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Pemphilimnadiopsis cheni sp. nov. (Branchiopoda: Diplostraca: Spinicaudata) from the Upper Carboniferous of East Hebei, China and its biostratigraphic significance

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Abstract

A new conchostracan species *Pemphilimnadiopsis cheni* **sp. nov.** is found in the upper section of the Pennsylvanian Benxi Formation in Kaiping, Tangshan City, Hebei Province, China and is closely related to the type species of the genus, *P. ortoni*. This finding is the fifth record of the Carboniferous conchostracans in China. Its finding gives evidence that the Benxi Formation in Kaiping, Tangshan City can be restricted into middle-late Moscovian to early Kasimovian and the present conchostracan layers more likely correspond to the early Kasimovian. Moreover, the first described Palaeozoic insects come from the same layers in the Kaiping Basin. This study indicates the age of these fossil insects would be close to the boundary of Moscovian and Kasimovian and more likely the early Kasimovian.

Keywords: Carboniferous, conchostracan, Benxi Formation, stratigraphic significance

Introduction

Conchostracans (clam shrimps) are a paraphyletic group of crustaceans known in the fossil records from the Devonian to recent times. They have been widespread in non-marine aquatic biotopes since the Carboniferous. The Carboniferous is an important time for the evolution and development of conchostracans. Though there are at least more than 20 conchostracan genera recorded in the Carboniferous around the world, records of China are still rare: only four records were noted in previous studies. *Lioestheria* ? *mathieui* Pruvost, 1927 was found in the Upper Carboniferous Benxi Formation in Kaiping, Tangshan City, Hebei Province (Pruvost, 1927; Zhang *et al*., 1976). This species possesses an oval carapace with about 40 growth bands (Zhang *et al*., 1976). *Protomonocarina huixianensis* Wang, 1987 was found in the Upper Carboniferous Benxi Formation in Chang Village, Hui County, Henan Province. It possesses a large larval valve with a coarse tubercle and only seven to eight growth bands on its carapace (Wang, 1987). *Retrofractus lingyuanensis* Liu & Fan, 1995 was found in the Upper Carboniferous Benxi Formation in Lingyuan City, Liaoning Province. Its main characteristic is the possession of an arched dorsal margin (Liu & Fan, 1995). Conchostracans from the Lower Carboniferous Lindi Formation in Lufeng Town, Shanghang County, Fujian Province were assigned into four genera *Rostroleaia* Novojilov, 1956, *Monoleiolophus* Raymond, 1946, *Lioestheria* Depéret & Mazeran, 1912 *and Qingxiestheria* Xi, 1981 (Zheng *et al.*, 1988). However, they were not described in detail and the original photographs were unclear and uninformative.

Herein we described a newly found species in the upper section of the Upper Carboniferous Benxi Formation in Tangshan City, Hebei Province (Figs. 1, 2). It possesses different characteristics than all the known species. This species has an oval to elongated oval carapace, a small larval valve with a curved drop-shaped tubercle, and about 15 growth bands that slightly recurve at the postero-dorsal area. The finding of this species broadens our knowledge on the Carboniferous conchostracans in China, and gives evidence that the age of the Benxi Formation in Tangshan City is middle-late Moscovian to early Kasimovian.

Material and methods

Specimens analyzed in this study were collected by Jian Gao from the upper section of the Upper Carboniferous Benxi Formation in Kaiping Basin, Tangshan City, Hebei Province, North China. The Benxi Formation is a set of

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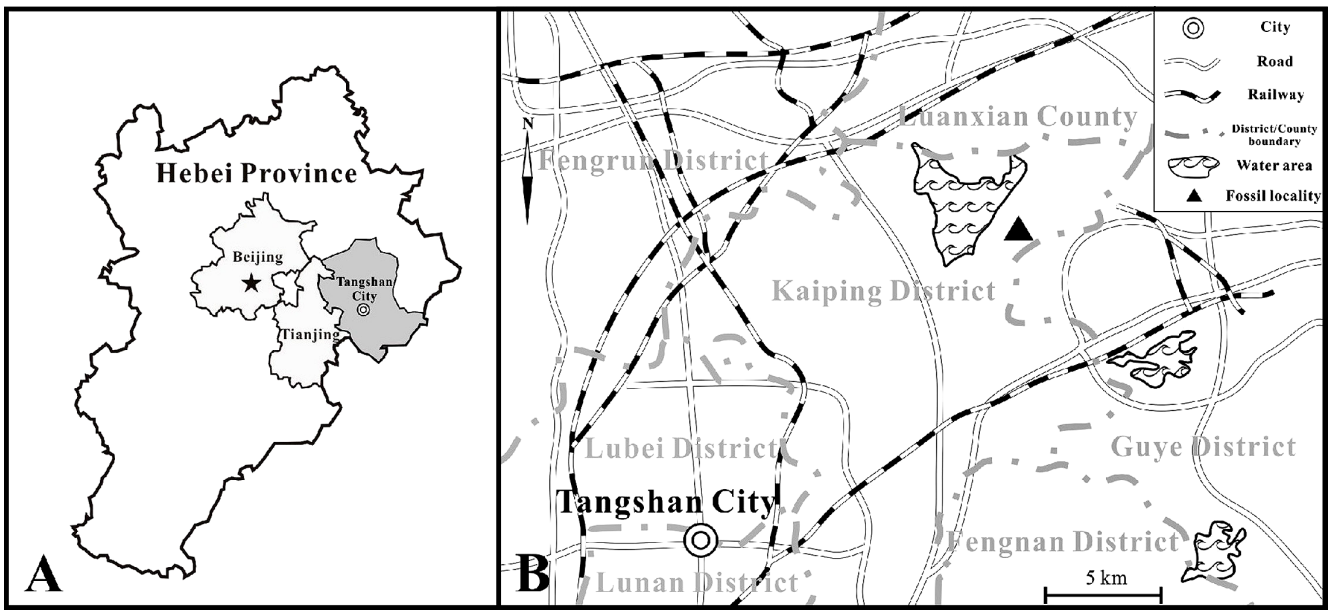

FIGURE 1. Maps of the fossil locality. **A**, Showing the location of Tangshan City in Hebei Province. **B**, Detailed map of the locality in Kaiping District, Tangshan City, with the black triangle indicating the locality.

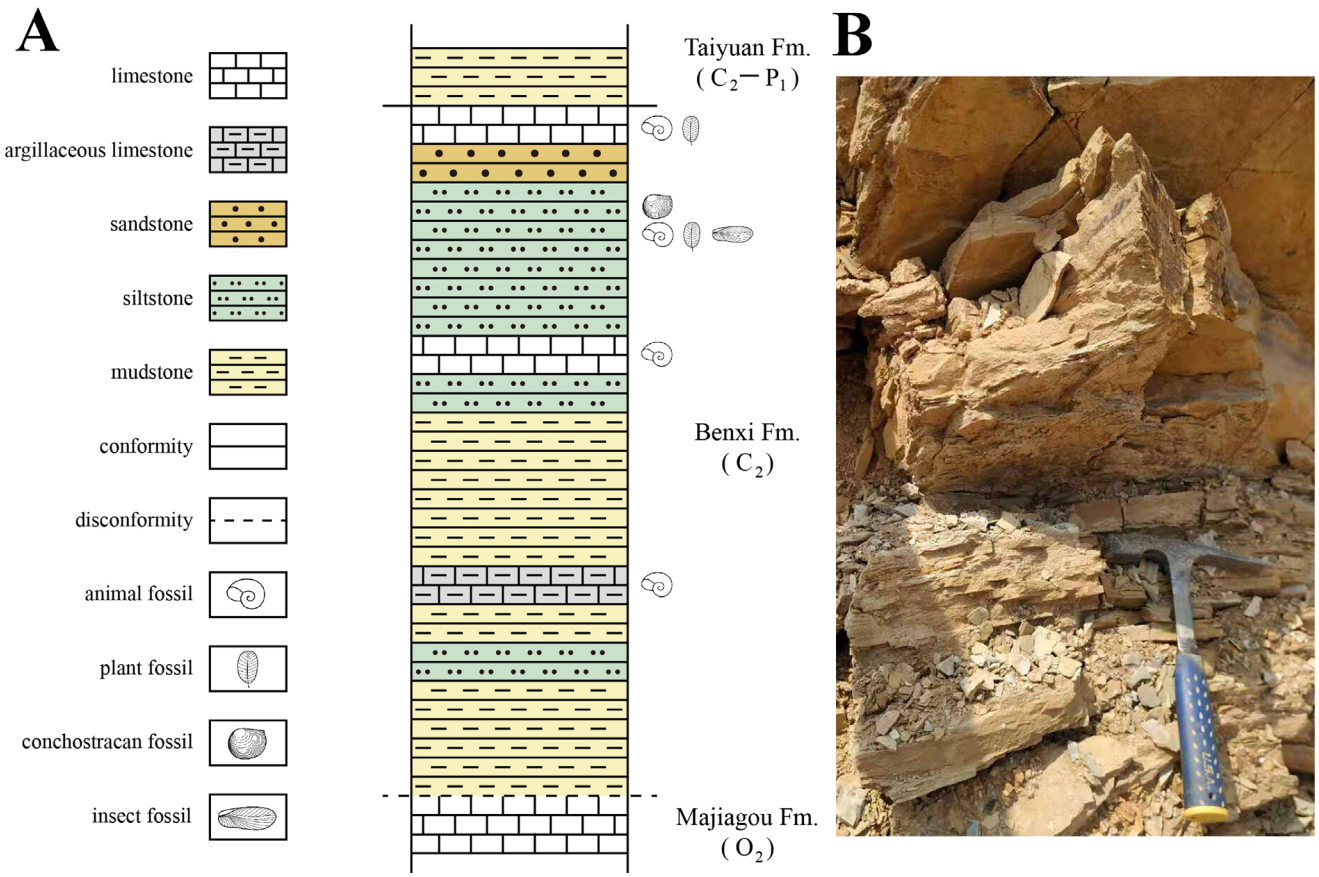

FIGURE 2. Stratigraphic information of the fossil locality. **A**, Stratigraphic column of the Benxi Formation in Kaiping Basin (modified after Hebei Bureau of Geology and Mineral Resources, 1989). **B**, Layers that yielded conchostracans.

continental sediments interbedded with marine sediments (Fig. 2). Abundant marine animal fossils including fusulinids, brachiopods, corals and conodonts were yielded in limestones and argillaceous limestones of this formation. These marine fossils indicate an age of Early to Middle Pennsylvanian (Hebei Bureau of Geology and Mineral Resources, 1989). Conchostracans are preserved in grayish green and grayish yellow siltstones of the upper

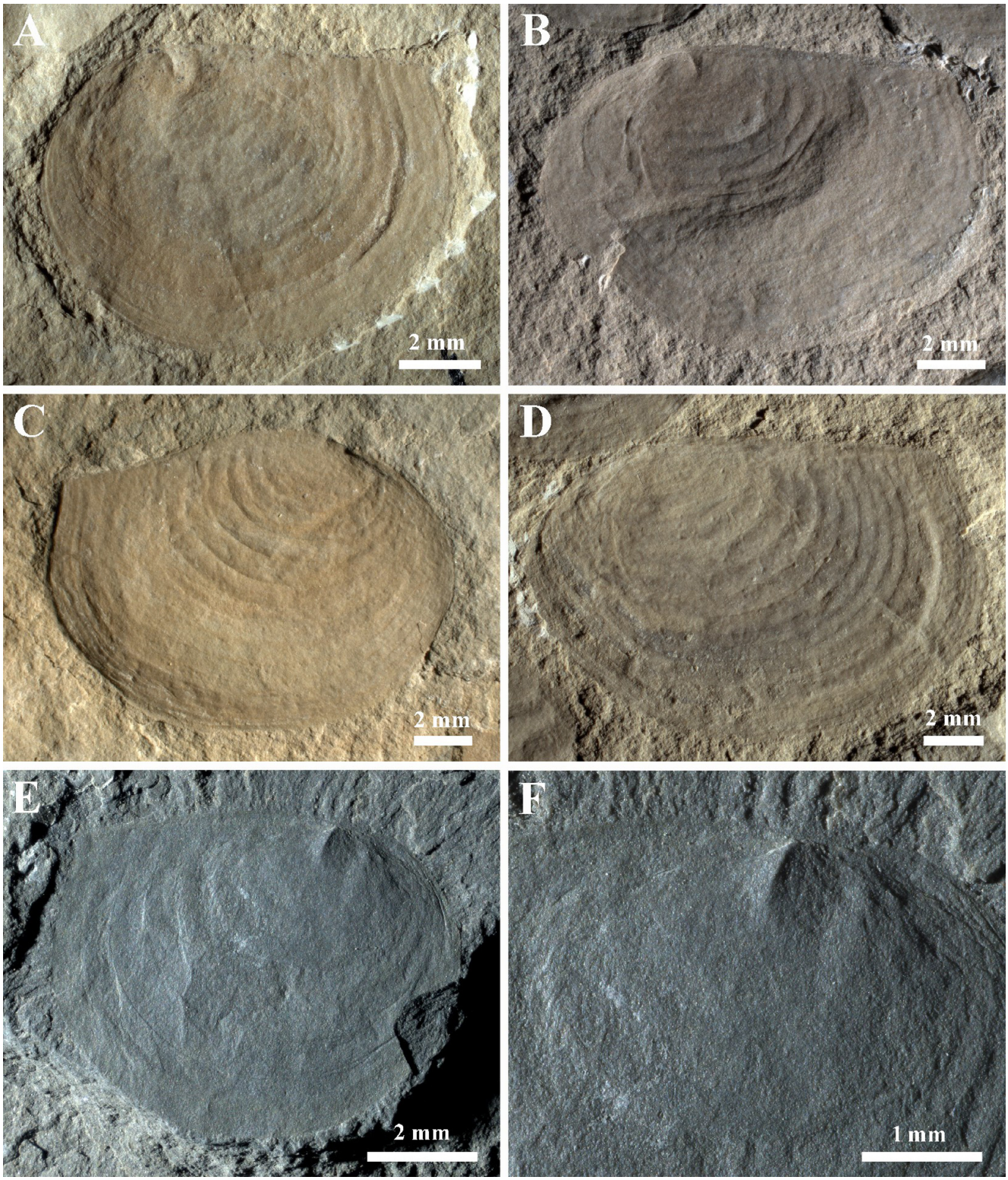

FIGURE 3. Carapaces of *Pemphilimnadiopsis cheni* **sp. nov.**. **A**, Holotype specimen, a supposed female individual, a left valve, NIGP171021. **B**, Paratype specimen, a supposed male individual, internal side of a right valve, NIGP171022. **C**, A supposed female individual, internal side of a left valve, NIGP171023. **D**, A supposed male individual, internal side of a right valve, NIGP171024. **E**, Paratype specimen, a juvenile individual, a right valve, NIGP171025. **F**, enlargement of the larval valve part of **E**, showing the tubercle.

section (Fig. 2). More than 180 conchostracan individuals preserved on 56 rock pieces were studied. Some of them were carefully prepared by using a sharp knife before detailed observation. They were observed and photographed under a Zeiss Discovery V16 microscope. A LEO 1530 VP scanning electron microscope (SEM)

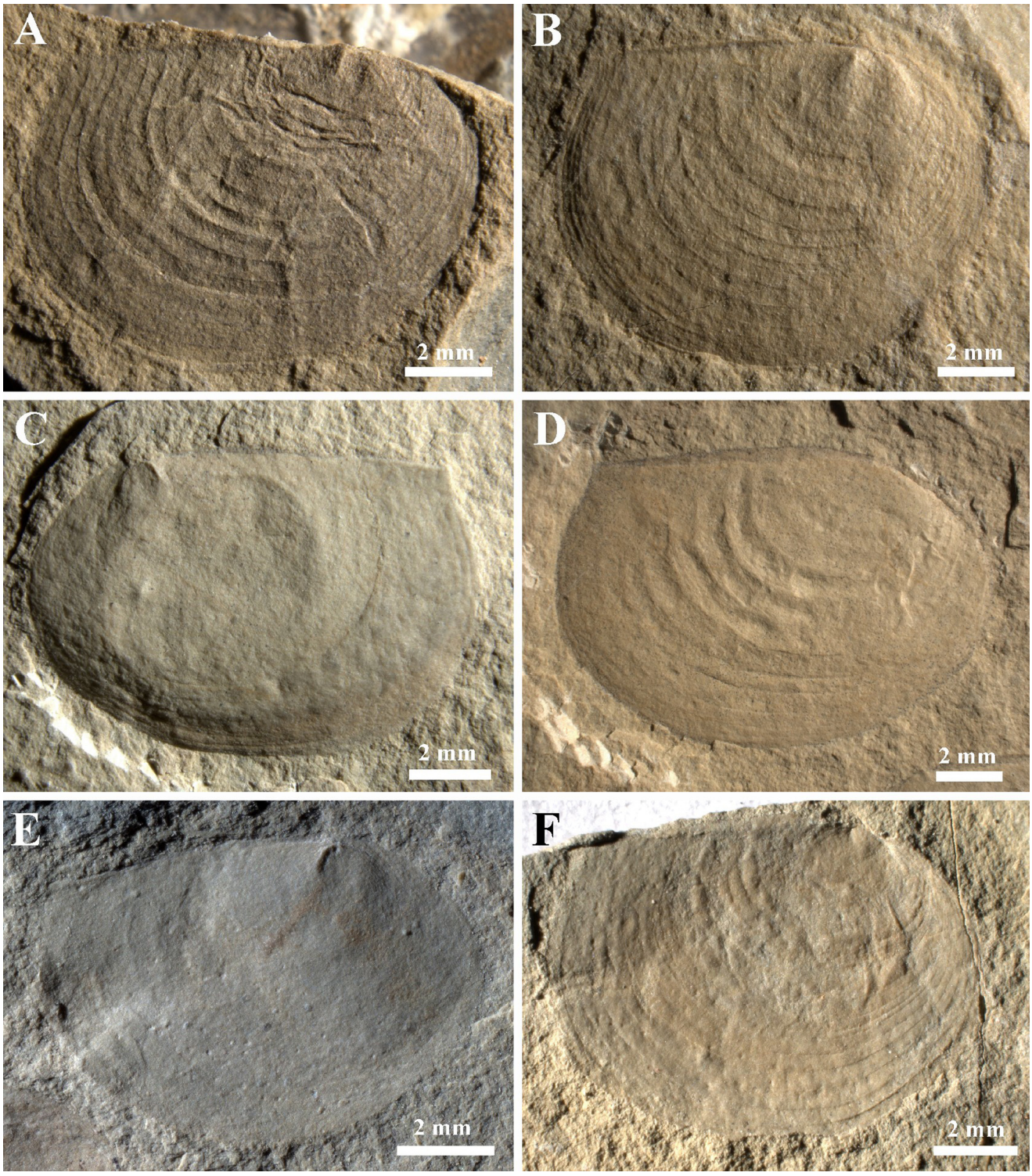

FIGURE 4. Carapaces of *Pemphilimnadiopsis cheni* **sp. nov.**. **A**, Paratype specimen, a supposed male individual, a right valve, NIGP171026. **B**, Paratype specimen, a supposed female individual, a right valve, NIGP171027. **C**, A supposed male individual, a left valve, NIGP171028. **D**, A supposed male individual, a right valve, NIGP171029. **E**, A supposed male individual, a right valve, NIGP171030. **F**, Paratype specimen, a supposed female individual, a right valve, NIGP171031.

was also used in observation; however, no microstructure of taxonomic value was found on the surface of these conchostracans. All the specimens studied in the present study are housed in the Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences, Nanjing, China. In the descriptions, we follow the suggestions of Scholze & Schneider (2015).

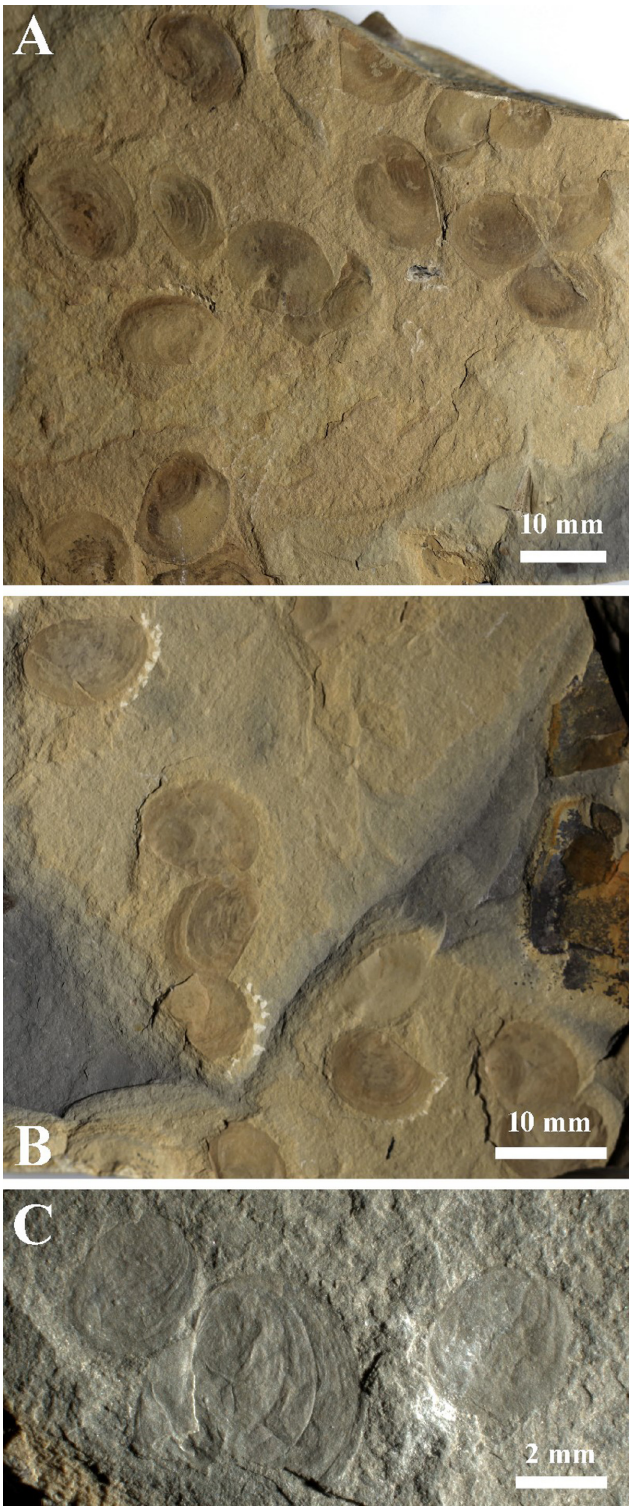

FIGURE 5. Several adult and juvenile individuals of *Pemphilimnadiopsis cheni* **sp. nov. A**–**B**, Adult individuals. **C**. Three juvenile individuals, NIGP171032.

Systematic palaeontology

Order Diplostraca Gerstaecker, 1866
Suborder Spinicaudata Linder, 1945
Superfamily Vertexioidea Kobayashi, 1954
Family Pemphilimnadiopsidae Tasch, 1961

Genus *Pemphilimnadiopsis* Tasch, 1961
Type species. *Pemphilimnadiopsis ortoni* Clarke, 1900

Pemphilimnadiopsis cheni Liao, Shen & Huang **sp. nov.**

Holotype. NIGP171021

Paratypes. NIGP171022, 171025–171027, 171031.

Etymology. In memory of the excellent Chinese palaeontologist Peiji Chen, who contributed significantly to the study of fossil branchiopods of the world and passed away on 9 July 2019.

Locality and horizon. Near the Wangnianzhuang Village, Kaiping District, Tangshan City, Hebei Province, China (Fig. 1); the upper section of the Benxi Formation.

Diagnosis. Carapace very large in size, oval to elongated oval in outline; dorsal margin straight and long; larval valve small; umbo in sub-medial position; a curved drop-shaped tubercle presents on larval valve; growth lines fine and sparse, about 15 in number; growth lines slightly recurved at postero-dorsal area. (Figs. 3–6).

Description. Carapace very large in size, 7.2–13.2 mm in length, 5.9–9.6 mm in height; oval to elongated oval in outline, with 14–16 growth bands (Fig. 3A–3D, 4, 5A, 5B); ratio of length/height between 1.22 to 1.65; dorsal margin long and straight; larval valve small, umbo slightly arched, situated in sub-medial position; a curved drop-shaped tubercle situated on the larval valve, middle part of the tubercle prominent, forming a sharp ridge (Figs. 3A, B, E, F, 4A–C, E, F, 6); anterior and ventral margins rounded; growth lines fine; growth bands relatively wide and sparsely distributed on the carapace, two to five growth bands close to the ventral margin narrowed and densely distributed (Figs. 3A–D, 4, 5, 6); six to eight growth lines slightly recurved at postero-dorsal area, forming a small cape at the postero-dorsal end of the carapace (Figs. 3–6). Juvenile individuals 3.3–7.0 mm in length, oval in outline, with less than 9 growth lines; recurving of growth lines inapparent in most of juvenile individuals (Figs. 3E, F, 5C).

Remarks. Among all adult individuals, two different carapace shapes were observed. According to our statistics, about 57% individuals possess an elongated oval outline (l/h>1.4), and the rest possess an oval (or even close to rounded) outline (l/h <1.4). This heteromorphic carapace (males usually elongated oval and females usually oval) has been observed in several modern and fossil species (*e.g.*, Mattox, 1937; Chen & Shen, 1985; Zhang *et al*., 1990). Therefore, we assume the individuals with oval carapaces in our fossil specimens are females, and the individuals with elongated oval carapaces are males. Male carapaces are 10.8–13.2 mm in length, 7.4–8.6 mm in height, and female carapaces are 7.2–12.7 mm in length, 5.9–9.6 mm in height. In

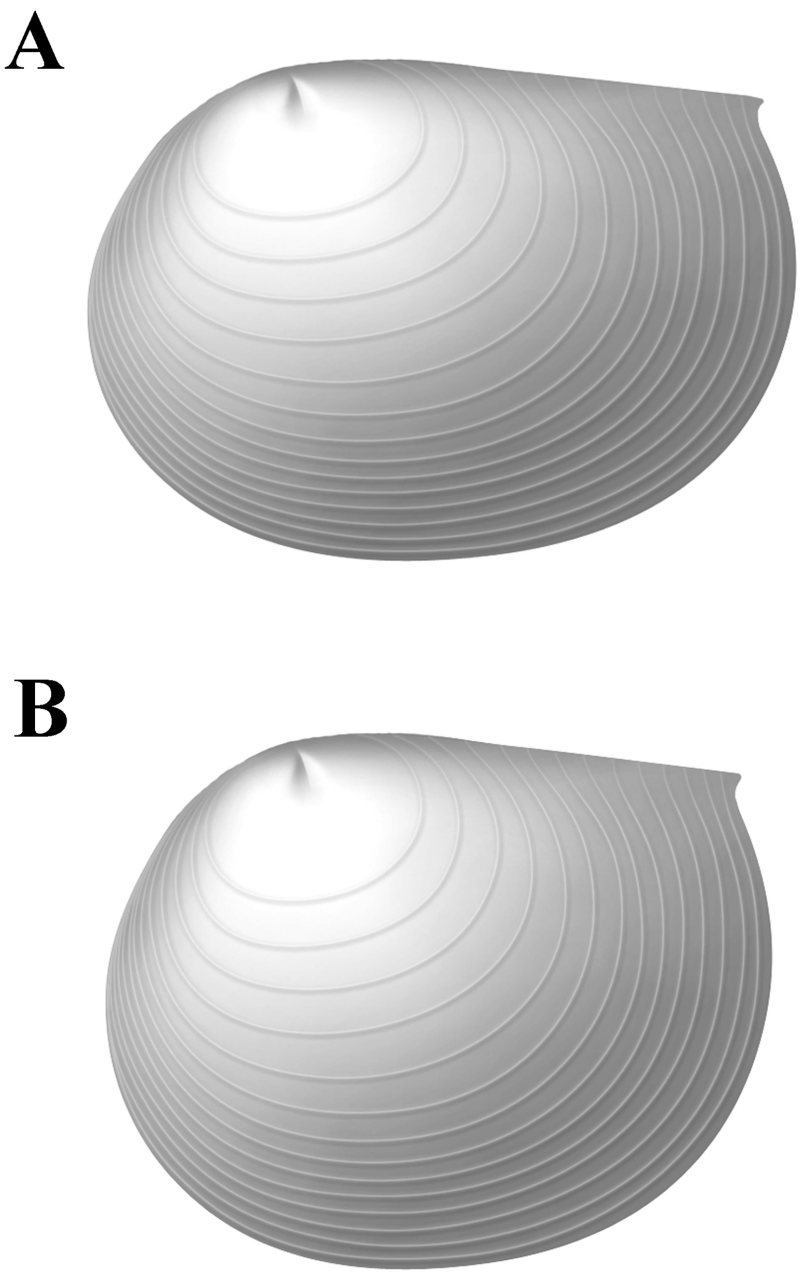

FIGURE 6. Reconstruction of the carapaces of *Pemphilimnadiopsis cheni* **sp. nov.**. **A**, Supposed male carapace. **B**, Supposed female carapace.

addition to this new species, only two other species of the genus have been recorded: 1) *Pemphilimnadiopsis ortoni* Clarke, 1900 from the Pennsylvanian of Carollton, Ohio (Clarke, 1900; Raymond, 1946; Tasch, 1961) and the east side of the Illinois Basin (Petzold & Lane, 1988), USA, which is also the type species of the genus; and 2) *P. anasuae* Ghosh, 2011 from the Upper Permian of Sohagpur, India (Ghosh, 2011). Specimens of the latter are very poorly preserved, making it difficult to compare with the other two species. Our new species differs from *P. ortoni* in having much larger carapace. *P. ortoni* specimens from Ohio are 1.5–3.9 mm in length, the largest one that is 3.9 mm long possesses 18 growth bands (Tasch, 1961). Specimens from the Illinois Basin are all less than 6 mm in length (Petzold & Lane, 1988). Some palaeolimnadiopsids share similar characteristics with *Pemphilimnadiopsis*. In particular, *Palaeolimnadiopsis* form Jessen from the the Pennsylvanian to lowest Permian (Gzhelian to Asselian) of Germany and North America, and *P. wettinensis* Laspeyres, 1870 from the Pennsylvanian (Gzhelian) of Europe share similar carapace size, outline and recurved growth lines with the new species (Schneider & Scholze, 2018); whereas neither possess a tubercle on their larval

valves. Moreover, *P.* form Jessen possess a relatively larger larval valve and less growth lines compared with the new species. However, it is worth mentioning that the absence or presence of the tubercle is highly determined by preservational variability. Hence, it might be difficult to distinguish the two genera *Pemphilimnadiopsis* and *Palaeolimnadiopsis* when fossils are not well preserved. *Lioestheria carinacurvata* Martens & Lucas, 2005 from the lower section of the Atrasado Formation (Kasimovian) in Socorro County, New Mexico, USA possesses a long or short curved tubercle on its larval valve and also recurved growth lines at its postero-dorsal area (Martens & Lucas, 2005). It differs from the new species by its smaller size (only 3–3.5 mm in length) and by the relatively larger larval valve. It seems that its growth lines are slightly recurved at the postero-dorsal area according to the original photographs and reconstruction while this characteristic was not mentioned in the diagnosis and description (Martens & Lucas, 2005). We hope that it could be re-studied in the future.

Discussion

Compared with the other three species *Lioestheria* ? *mathieui*, *Protomonocarina huixianensis* and *Retrofractus lingyuanensis*, that were found in the Benxi Formation, *Pemphilimnadiopsis cheni* **sp. nov.** differs in carapace size, growth line number, tubercle, and more importantly, possessing recurved growth lines at its postero-dorsal area. It shares many similarities and is closely related to *P. ortoni*. The latter is an important member of the Late Carboniferous Mazon Creek fauna (Petzold & Lane, 1988; Briggs & Gall, 1990; Wittry, 2012). Fossils of the fauna were yielded in the Francis Creek Shale (Westphalian D) and the Colchester Coal beds of the Linton Formation of the east side of the Illinois Basin, USA (Baird *et al*., 1985; Briggs & Gall, 1990; Wittry, 2012). Petzold & Lane (1988) noted that there were nine conchostracan-bearing horizons range in stratigraphic position from near the middle of the Desmoinesian Series into the lowest Virgilian Series in the east side of the Illinois Basin, and the Francis Creek Shale represented the lowest one. Except for the second (Bucktown Coal bed) and the third (Herrin Coal bed) horizons, *P. ortoni* was recorded in the remaining seven of nine horizons (see details in Petzold & Lane, 1988). Therefore, the occurrence of *P. ortoni* is restricted between the Middle Desmoinesian to earliest Virgilian. According to the newest global stratigraphic temporal framework, the occurrence of *P. ortoni* is restricted into middle-late Moscovian to early Kasimovian (Wang *et al*., 2019). The age of the Benxi Formation also corresponds the middle-late Moscovian to early Kasimovian (Wang *et al*., 2019). The conchostracans layer at the upper section of the Benxi Formation is possibly correlated the boundary of Moscovian and Kasimovian, and more likely the early Kasimovian. Moreover, the first described Palaeozoic insects come from the same layer in Kaiping Basin, refer to *Phyloblatta* Handlirsch, 1906 and *Soomylacris* Handlirsch, 1906 (Mathieu, 1939; Yin *et al*., 1966). This layer also yielded very rich fossil fishes, limulids, bivalves, gastropods and plants. In recent years, we have collected various fossil insects in this locality, a few meters below the conchostracan layer. Therefore, the present study provides obvious stratigraphic information that indicates these fossil insects are also in a geological age that is near the boundary of Moscovian and Kasimovian, and more likely the early Kasimovian.

The genus *Pemphilimnadiopsis* possesses characteristics linking it with both the Vertexiidae and Limnadiopsidae. The tubercle on larval valve is a pemphicycliid feature and hence of Vertexiidae relationship. The posterior recurvature of growth lines of the limnadiopsiid-type occurs in the adult portion of the valve and hence is of Limnadiopsidae relationship. Tasch (1961) thought that the most important characteristic of *Pemphilimnadiopsis* was the tubercle on larval valve, and the posterior recurvature of growth lines occurred in the genus independent of a similar development in palaeolimnadiopsids. We agree with Tasch's idea that the recurvature of growth lines occur in a lot of conchostracan clades with diverse characteristics in different ages, appearing to indicate the consequence of convergent evolution. The recurvature of growth lines occur mainly in species among five families: Palaeolimnadiopsidae, Sinoestheriidae, Ipsiloniidae, Vertexiidae and Pemphilimadiopsidae. Palaeolimnadiopsids are the most representative posterior-recurved-type conchostracans. Members of this family distribute in the Lower Devonian to the Upper Jurassic in North Eurasia and North America. *Belgolimnadiopsis* Novojilov, 1958 of the Lower Devonian age is the oldest member (Maillieux, 1939; Chen & Shen, 1985) and represents an ancestral type of the family. Sinoestheriids that include four genera distribute in the Upper Jurassic and the Cretaceous from China, South America and Africa (Defretin, 1967; Chen & Shen, 1985, 2014). Their key and common characteristics are the large carapace, stout growth lines which recurved at postero-dorsal area, and the serrated structures on growth lines. However, the serrated structures have been shown to be of no important taxonomic value (Shen, 2003; Liao *et al*., 2019). Hence their relationships are still ambiguous and needs further research. Ipsiloniids consist of four genera and are featured by the recurved growth lines which forms two capes at both the anterior and posterior dorsal

ends, respectively. The earliest representative of them is *Ipsilonia* Novojilov, 1953 from the Middle Devonian of Russia and Scotland (Chen & Morris, 1991), and the latest representative is *Aculestheria* Cardoso, 1962 from the Lower Cretaceous of Brazil (Cardoso, 1962). Vertexiidae consists of more than 10 genera which all possess tubercles or spines on their larval valves. However, it has to be noted that only two genera *Vertexia* Lutkevich, 1941 and *Tripemphigus* Novojilov, 1965 are posterior-recurved-type. These two genera distribute in the Upper Permian to the Lower Triassic in Russia (Scholze *et al*., 2019). Pemphilimadiopsids consist of four genera that are all featured by the recurved growth lines at the postero-dorsal area and the tubercle or shell gland on the larval valve (Shen *et al.*, 2001). The genus *Pemphilimnadiopsis* is distributed in the Pennsylvanian of China and USA, and the Upper Permian of India. The genus *Qingxiestheria*, with two node-like tubercles on its large larval valve was yielded in the Upper Devonian Wutong Formation in Anhui Province, China (Xi, 1981). The genus *Challaolimnadiopsis* Shen & Gallego, 2001 with two node-like tubercles that are separated by a ridge on its larval valve was yielded in the Middle to Upper Triassic in Mendoza Province, Argentina (Shen *et al.*, 2001). The most special genus of the family is *"Falsisca"* Novojilov, 1970 from the Upper Permian to Triassic in Russia. It possesses shell glands on its larval valve instead of a tubercle (Novojilov, 1970). It was conservatively assigned into the family (Shen *et al.*, 2001) and needs further study.

Acknowledgements

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