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Discovery of *Pemphilimnadiopsis cheni* (Branchiopoda: Diplostraca: Spinicaudata) from the Benxi Formation in Taiyuan, North China and its stratigraphic significance


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
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Clam shrimp (Spinicaudata) are worldwide distributed branchiopod crustaceans specialised in ephemeral freshwater habitats. The Carboniferous is an important period for the early evolution and diversification of clam shrimp. Compared with the rare and geographically confined fossil record of the Devonian, clam shrimp in the Carboniferous have a much wider geographical distribution and higher biodiversity. Over 20 genera of clam shrimp have been recorded in the Carboniferous all over the world, but they are sparse in China. To date, five records of Carboniferous clam shrimp have been reported from China (Pruvost, 1927; Zhang *et al.*, 1976; Wang, 1987; Zheng *et al.*, 1988; Liu & Fan, 1995; Liao *et al.*, 2019). Among them, four species *Lioestheria? mathieui* Pruvost, 1927, *Protomonocarina huixianensis* Wang, 1987, *Retrofractus lingyuanensis* Liu & Fan, 1995, and *Pemphilimnadiopsis cheni* Liao, Shen & Huang, 2019, are found in the Pennsylvanian Benxi Formation in North China (Pruvost, 1927; Zhang *et al.*, 1976; Wang, 1987; Liu & Fan, 1995; Liao *et al.*, 2019).

Pemphilimnadiopsis cheni has been first described from the Benxi Formation at the Kaiping Basin in Tangshan City, Hebei Province, east of North China (Liao *et al.*, 2019). Here we describe the occurrence of *P. cheni* in the Benxi Formation at a locality near Wangfeng Village, Taiyuan City, Shanxi Province, northern China. The *P. cheni* yielding locality is about 600 km southwest of the previous locality near Tangshan.

Geological setting

The strata exposed in the Western Hills of Taiyuan City are characterised by a set of coal-bearing sediments in China.

The strata include the Benxi, Taiyuan and Shanxi formations of the Carboniferous–Permian in ascending order. Some fossil insects were found in the Permian Shanxi Formation (Hong, 1985, the age was considered as Late Carboniferous in original paper). The Benxi Formation lies unconformably on the Ordovician Majiagou limestones. The lower part of the formation consists of ferroaluminites, and the upper part consists of sandstones and shales which are incidentally interbedded with limestones. The Benxi Formation is conformably overlain by the Taiyuan Formation. The bottom of the Taiyuan Formation is a set of thick sandstones with various thickness in different localities, usually called the Jinci Sandstone. The present described clam shrimp yields from the top layers of the Benxi Formation, just below the Jinci Sandstone (Fig. 2).



FIGURE 1. Map of the fossil localities. Locality 1 indicates the Kaiping Basin, from where *Pemphilimnadiopsis cheni* was first found. Locality 2 is the location yielding the new fossil studied herein.

Material and methods

The fossil clam shrimp preserved in black shale and yellow-greenish mudstone were collected from two localities at the Huangchanggou section of Western Hills (Taiyuan City, Shanxi Province, North China; Fig. 1). Clam shrimp were preserved in black shales and yellow-greenish mudstones at the top of the Benxi Formation, accompanying by abundant plants. No insects were found in the same, upper, or lower layers. However, abundant insects were found in similar layers of the *P. cheni* horizon in the Kaiping Basin, Tangshan City, Hebei Province.

Photomicrographs were taken using a Zeiss Discovery V16 microscope. All studied materials are housed in the Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences, Nanjing, China.

Result

The general characters of the newly discovered specimens, especially the small tubercle on the larval valve (Fig. 3), closely resemble those of *Pemphilimnadiopsis cheni* from

the type locality, but their body size are smaller (4.80–5.00 mm long, 3.33–3.67 mm high in Taiyuan specimens vs. 7.20–13.20 mm long, 5.90–9.60 mm high in Tangshan specimens). These clam shrimp are possibly sub-adults of *P. cheni* or small individuals developed in a different environment.

The age of Carboniferous–Permian (C–P) boundary in this area has been suggested by various authors. The previous opinion suggested that the entire Taiyuan Formation is Carboniferous in age and the C–P boundary is within the Shanxi Formation (*e.g.*, Hong, 1985). Recently, some researchers argued that the C–P boundary was located at the bottom of the Taiyuan Formation (Wang & Qi, 2003) or even lower (Sun *et al.*, 2014). Others considered the bottom of the Miaogou Limestones was very close to the C–P boundary according to conodont-based biostratigraphic studies (*e.g.*, Wang, 1991; Wang & Kang, 2000).

The clam shrimp were yielded from the top layers of the Benxi Formation, just below the Jinci Sandstones at the bottom of the Taiyuan Formation. Recent isotopic dating indicated that the age of the Jinci Sandstones is 294 ± 2 Ma or 296 ± 3 Ma (Sun *et al.*, 2014). The dating seems to correlate with the second opinion of the above opinions. *Pseudoschwagerina* are usually considered as index fossils

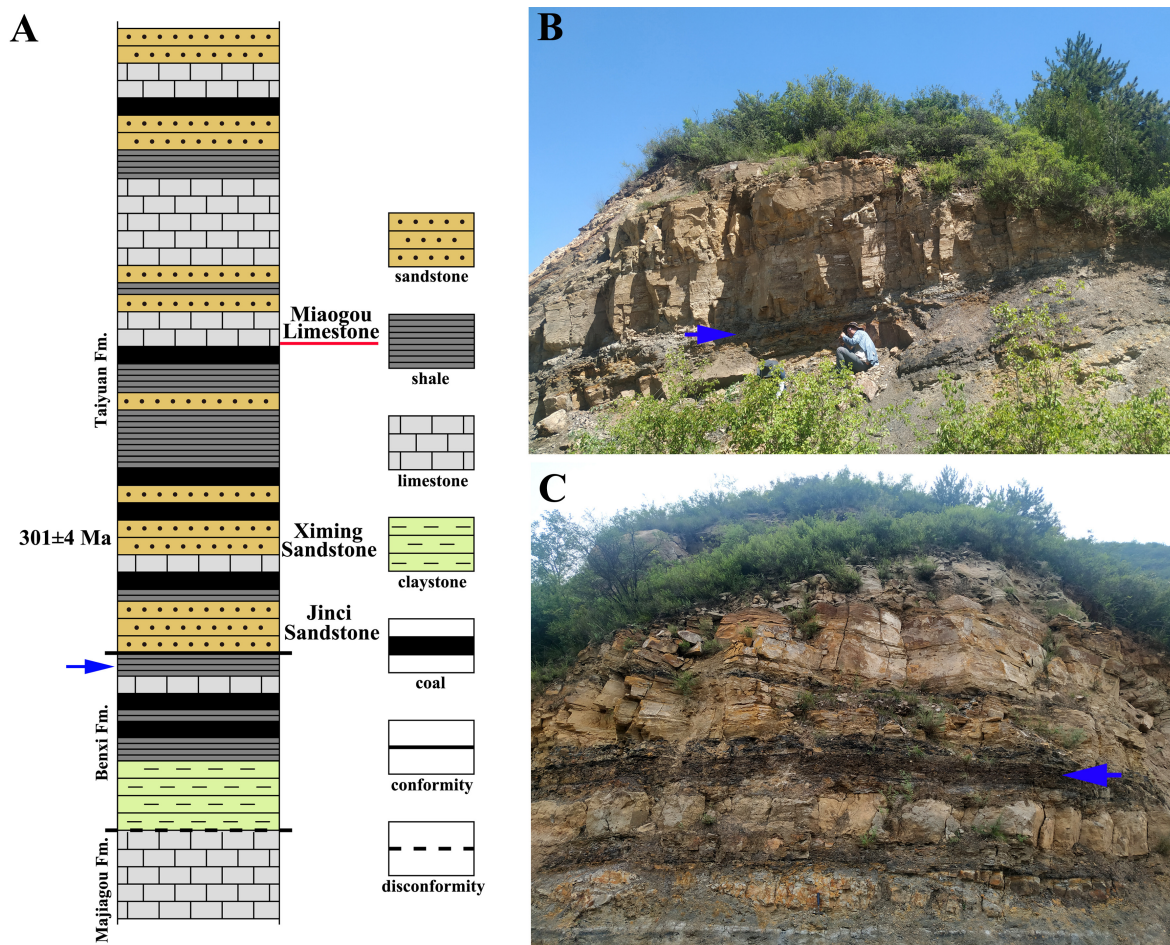


FIGURE 2. Stratigraphic column and outcrops. The blue arrow indicates the fossiliferous layer that yields **A**, Stratigraphic column at the Huangchanggou section near the Wangfeng Village, Taiyuan, North China. Red line represents the Carboniferous–Permian boundary. *Pemphilimnadiopsis cheni*. **B**, Fossil layer of locality 1. **C**, Fossil layer of locality 2.

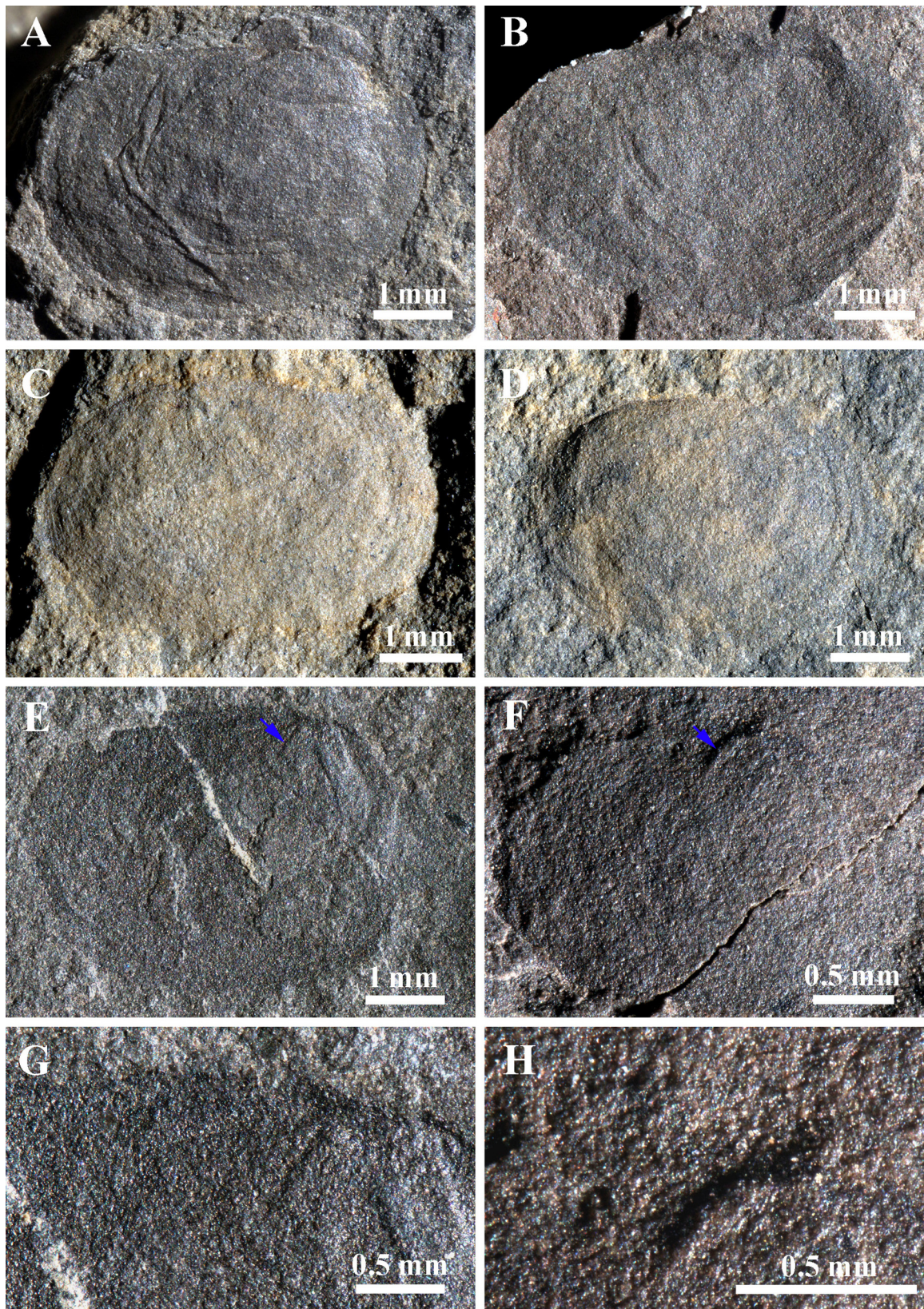


FIGURE 3. Carapaces of *Pemphilimnadiopsis cheni* from the uppermost of the Benxi Formation in Taiyuan, Shanxi Province. **A**, Right valve (NIGP173922), general habitus. **B**, Right valve (NIGP173923), general habitus. **C**, Left valve (NIGP173924) general habitus. **D**, Left valve (NIGP173925), general habitus. **E**, Imprint of left valve (NIGP173926), showing a small tubercle on the larval valve (blue arrow). **F**, Right valve (NIGP173927), showing a small tubercle on the larval valve (blue arrow). **G**, Enlargement of **E**, showing the imprint of the tubercle. **H**, Enlargement of **F**, showing the tubercle.

for the lowermost Permian in South China (Shen *et al.*, 2019). The fusulinid *Pseudoschwagerina vulgaris* in the Taiyuan Formation first appeared at the bottom of the Miaogou Limestones (Wang & Li, 1984), which supports the third opinion. Isotopic dating also indicated the age of the Ximing Sandstones at the lower part of the Taiyuan Formation (close to but below the Miaogou Limestones) is 301 ± 4 Ma (Sun *et al.*, 2014). Therefore, we agree that the C–P boundary in this area is near the bottom of the Miaogou Limestone. If the dating results mentioned above were correct, the age of the Jinci Sandstones would be distinctly older than 301 ± 4 Ma. Thus, the occurrence of *Pemphilmnadiopsis cheni* is more likely corresponding to the Kasimovian or Moscovian-Kasimovian (Liao *et al.*, 2019; Wang *et al.*, 2019). The occurrence of *P. cheni* indicates a distinct direction of sea transgression from east to west. Thus the upper *P. cheni* strata are much thicker in eastern locality at the Kaiping Basin than that of the present new locality.

This discovery indicates that *Pemphilmnadiopsis cheni* is a common species widely distributed in upper part of the Benxi Formation in North China. It also provides age constraint for the first marine-continental biota (including numerous fossil insects) following flooding of North China Platform in the Pennsylvanian.

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