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The Upper Ordovician Microfossil Assemblages from the Pagoda Formation in Zigui, Hubei Province

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ABSTRACT: The Pagoda Formation is a lithologically and biologically distinctive unit among the Upper Ordovician. The strata are characterized by a nodular limestone, which yields fossil assemblages of high diversity. Conodonts of 14 genera 20 species (6 undetermined species) and ostracods of 14 genera 26 species (16 undetermined species) are identified. In addition, spherical radiolarians and minute-walled foraminifers were first reported from this formation in South China. The conodont assemblage is attributed to the *Hamarous europaeus* Zone, which indicates the Early Katian Age. The conodont HDS biofacies, along with thin-shelled ostracods, spherical radiolarians and foraminifers, suggest relatively deep and quiet water depositional environment. Accordingly, these fossil materials not only enrich the diversity of the Pagoda biota, but also provide evidence for discussions of depositional environments and stratigraphic correlations for the Pagoda Formation.

KEY WORDS: South China, Ordovician, conodont, ostracod, radiolarians, foraminifer.

0 INTRODUCTION

The Pagoda Formation, a lithologically and palaeontologically unique unit among the Upper Ordovician formations (Chen et al., 2010; Zhan and Jin, 2007; Zeng et al., 1983), is characterized by distinctive nodular limestone and abundant fossil assemblages (Fang et al., 2015; Zhou and Zhou, 2005; Sun, 1988; An et al., 1985; Wang et al., 1983). The formation is widely distributed in the Middle and Upper Yangtze area, covering thousands of square kilometers (Zhan et al., 2016a; Xu et al., 2001). Owing to its distinctive lithology and wide distribution, the Pagoda Formation is regarded as an important stratigraphic marker unit of the Ordovician in South China (Zhan et al., 2016b). Also, global stratigraphic correlation of the Pagoda Formation is possible because of the recognition of the Guttenberg δ^{13}C Excursion (GICE) (Bergström et al., 2010, 2009, 2007a, b), the most well-known carbon isotope excursion in the Lower Palaeozoic deposits (Fan et al., 2015; Munnecke et al., 2011).

Despite its worldwide chemo- and litho-stratigraphic correlation, the depositional environment of the Pagoda Formation is still puzzling geologists. It has been interpreted as a low-tide shallow water environment (e.g., Shen, 1989; Chen and Qiu, 1986; Chen and Zhou, 1984; Liu and Chen, 1983), or an open platform environment of relatively deep water below the wave base (e.g., Wang A D, 2012; Xu et al., 2001; Wang Z Z, 1996; Rong and Chen, 1987), or a marine shelf environment of deeper and quieter water (e.g., Zhan et al., 2016a, b; Zhou and Xue, 2000). Meanwhile, the water depth of the Pagoda period is also controversial, ranging from less than 50 m to several hundred meters (Zhan et al., 2016b; Chen et al., 2010; Zhan and Jin, 2007; Ji, 1985).

Remarkably, fossil assemblages of the Pagoda Formation are quite abundant, for instance, trilobites (Zhou et al., 2007; Ji, 1985), brachiopods (Zhan et al., 2002), cephalopods (Fang et al., 2015), conodonts (Wang et al., 2011; An, 1987, 1981), etc. However, detailed reports about other microfossils are limited, i.e., ostracods, radiolarians and foraminifers. Herein, we present well-preserved, relatively thin-shelled ostracods, conodonts, radiolarians and foraminifers from nodular limestone, which diversify fossil assemblages of the Pagoda period. Moreover, these fossil observations also provide palaeontological evidence for discussion of depositional settings.

1 GEOLOGICAL SETTING

The Xilingxia Section is located in western Hubei Province, which is tectonically assigned to the northern part of the Yangtze Platform (Fig. 1a). The studied site (30°54′ N, 110°49′ E) is next to No. 334 provincial road, approximately 150 m north of Xilingxia Village in Quyuan Town, Zigui, Hubei Province (Fig. 1b). Before the middle Late Ordovician, the Yangtze Platform was the main carbonate sedimentary region in South China and experienced several evolutionary phases, ranging from the open platform in the Early Ordovician, to the carbonate gentle slope in the Middle Ordovician, and then submerged to carbonate platform in the early–middle Late Ordovician (Zhou et al., 1993). Generally, the eustatic sea-level rise occurred in the early Late Ordovician resulting in the deposition of nodular limestone of the Pagoda Formation (Yan et al., 2008).

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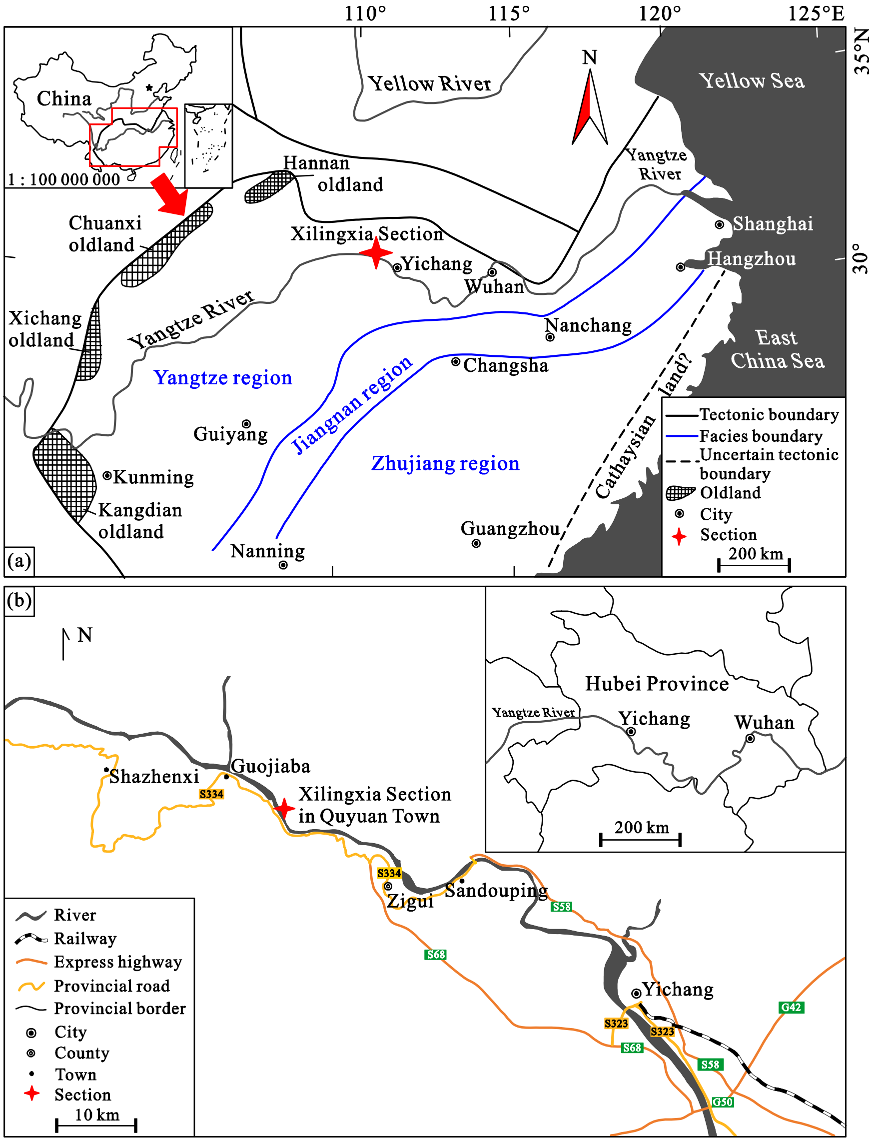

Figure 1. Geographic position of the Xilingxia Section (modified after Zhan and Jin, 2007; schetch map of China modified after http://bzdt.nasg.gov.cn/, No. GS(2016)1569); (b) detailed locality of study area.

The Upper Ordovician succession in the Xilingxia Section includes the Miaopo, Pagoda and Linhsiang formations in ascending order. The Pagoda Formation is characterized by carbonates with benthic shelly faunas (Munnecke et al., 2011). It consists of grayish yellow to purplish red, thick- to medium-bedded limestone, with nodules ranging from 5 cm to nearly 10 cm in diameter. It can be subdivided into two units (Fig. 2). The lower unit, conformably overlying the Miaopo Formation with dark grey shale and intercalated argillaceous limestone, comprises thick-bedded, greyish yellow micritic limestone with nodules (diameters >5 cm). Cephalopods (*Sinoceras*) (Fang et al., 2015), the characteristic fossil of the Pagoda Formation, are abundant in this unit. The upper unit, conformably underlying the Linhsiang Formation with argillaceous nodular limestone, consists of medium-bedded, purplish red bioclastic limestone with smaller nodules (diameters <5 cm).

The Pagoda Formation is dominated by calcareous deposits with bioclastic wackstone observed in thin sections (Zhan et al., 2016a, b). Shelly fossils are extremely abundant, characterized by cephalopods, trilobites, brachiopods and conodonts. Besides, ostracods, foraminifers, corals, echinoderms, etc., are also common but have been rarely reported. As part of the marine community, most of them live in the habitat of deeper water environments (Wang et al., 2011; Zhou et al., 2007; Ji, 1985).

2 MATERIAL AND METHODS

Ten nodular limestone samples (approximately 5 kg each) were collected from the Pagoda Formation at the Xilingxia Section. The samples were crushed into fragments (several cubic centimeters each) and divided into two parts. One part was etched in 5%–8% acetic acid solution for one month at room temperature, and the same concentration of acid was added every 3–4 days. The other part utilized the ‘hot acetolysis’ technique for retrieving the calcareous-shelled ostracods (Crasquin-Soleau and Kershaw, 2005; Lethiers and Crasquin-Soleau, 1988). The fragments were completely dried and then immersed in concentrated (>99.5%) acetic acid in glass pots. The pots were then placed on a heated sand-bath at a temperature

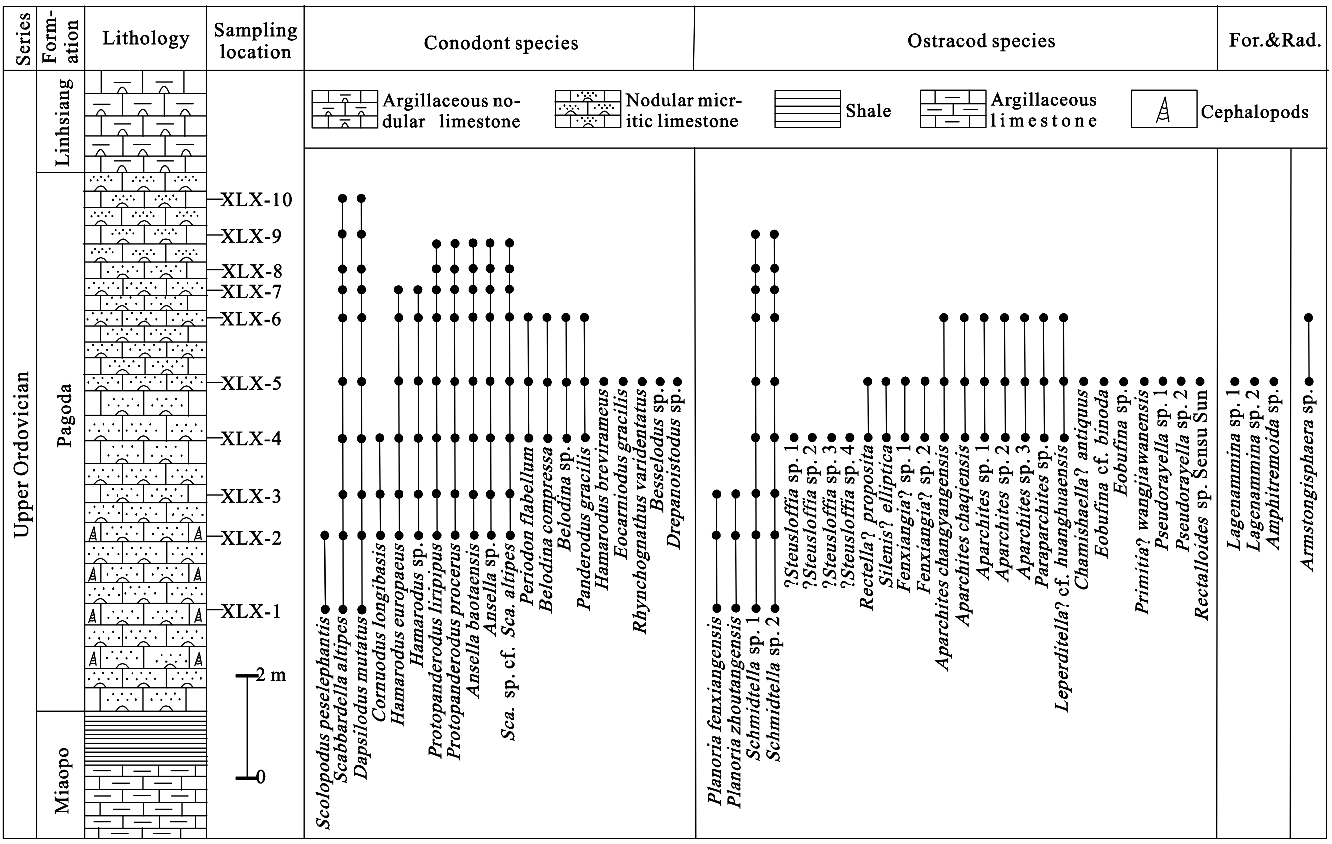

Figure 2. Stratigraphic sequence and the ranges of selected species at the Xilingxia Section in Zigui, Hubei Province (note: For.=foraminifera; Rad.=radiolarian; *Sca.*= *Scabbardella*).

of 60–80 ºC for 1–2 weeks till adequate muddy residues were deposited. The obtained residues from the two techniques were sieved (20 and 300 meshes) and then dried in a heating cabinet. Subsequently, microfossils were hand-picked from the dried residues with hairbrush or needle under a binocular microscope. Finally, the well-preserved specimens were mounted on stabs and photographed with a scanning electron microscope (SEM).

For this study, 1 126 specimens of conodonts, ostracods, radiolarians and foraminifers were recovered and 513 specimens were photographed. All the specimens and SEM photos were taken at the State Key Laboratory of Geological Process and Mineral Resources of China University of Geosciences (Wuhan).

3 RESULTS

The Pagoda assemblages reported herein are of relatively high diversification and good preservation. The samples yield 480 specimens of conodonts from 20 multi-element taxa, and 592 specimens of ostracods from 26 multi-element taxa. Moreover, 29 specimens of foraminifers and 25 specimens of radiolarians were first reported from this formation in South China. Their stratigraphic ranges are showed in Fig. 2.

3.1 Conodonts

Conodonts of 15 species and 6 undetermined species from 14 genera are identified (see Fig. 4 and illustration). Amongst them, *Hamarodus europaeus* Serpagli, 1967, *Hamarodus* sp., *Hamarodus brevirameus* Walliser, 1964, *Dapsilodus mutatus* Branson and Mehl, 1933 and *Scabbardella* sp. cf. *Scabbardella altipes* Orchard, 1980 are the dominant species, while *Protopanderodus liripipus* Kennedy, Barnes and Uyeno, 1979, *Ansella baotaensis* Ni, 1987, *Ansella* sp. and *Periodon flabellum* Lindström, 1955 are also common.

Taxonomically, representatives of *Hamarodus*, *Dapsilodus*, *Scabbardella* and *Protopanderodus* suggest that the Pagoda conodont assemblage represents the *Hamarodus-Dapsilodus-Scabbardella* (HDS) biofacies, which show closest affinity to those from the North Atlantic Conodont Province (Ortega et al., 2008; Bergström, 2007; Stouge and Rasmussen, 1996; Savage, 1990). This biofacies are defined by the dominance of *Hamarodus*, *Dapsilodus*, *Scabbardella* (Sweet and Bergström, 1984), which are broadly distributed in the outer shelf and are characteristic of relatively cold water deposits (Ferretti et al., 2014; Wang et al., 2007). In South China, similar conodont assemblage had also been reported from the Pagoda Formation in Shaanxi and Sichuan (Chen and Ji, 1986; Chen, 1983), the Yanwashan Formation in Zhejiang (Wang et al., 2015), and the Tangshan Formation in Anhui (Chen and Zhang, 1989). Whereas, the Pagoda conodonts have kept its local character that enigmatic species *Ansella baotaensis*, *Besselodus* sp. etc. only appear in Hubei.

3.2 Ostracods

Ostracods of 26 species (16 undetermined species) belonging to 14 genera are identified, composed of Palaeocopida and Metacopida. Amongst them *Planoria*, *Fenxiangia*,

Figure 3. Scanning electron micrographs of conodonts from the Pagoda Formation in Zigui, Hubei Province. Scale bar is 100 μm. A–B. *Hamarodus europaeus* Serpagli, 1967: A. lateral view of Pa element, collection number XLX15001; B. lateral view of Sc element, collection number XLX15002. C. *Hamarodus* sp.: lateral view of M element, collection number XLX15003. D. *Hamarodus brevirameus* Walliser, 1964: lateral view of M element, collection number XLX15004. E. *Scolopodus peselephantis* Lindström, 1955: lateral view of S element, collection number XLX15005. F. *Protopanderodus liripipus* Kennedy, Barnes and Uyeno, 1979: lateral view of S element, collection number XLX15006. G. *Protopanderodus procerus* An, 1987: lateral view of S element, collection number XLX15007. H–I. *Dapsilodus mutatus* Branson and Mehl, 1933: lateral view of S element, collection numbers XLX15008 and XLX15009, respectively. J. *Eocarniodus gracilis* Rhodes, 1955: lateral view of S element, collection number XLX15010. K–L. *Scabbardella altipes* Henningsmoen, 1948: lateral view of P element, collection numbers XLX15011 and XLX15012, respectively. M. *Scabbardella* sp. cf. *Scabbardella altipes* Orchard, 1980: lateral view of P element, collection number XLX15013. N. *Ansella baotaensis* Ni, 1987: lateral view of S element, collection number XLX15014. O. *Ansella* sp. (Löfgren, 1978: lateral view of S element, collection number XLX15015; P *Rhynchognathus varidentatus* Chen, 1965: lateral view, collection number XLX15016. Q. *Cornuodus longibasis* Lindström, 1955: lateral view of Sa element, collection number XLX15017. R. *Panderodus gracilis* Branson and Mehl, 1933: lateral view of S element, collection number XLX15018. S. *Belodina compressa* Branson and Mehl, 1933: lateral view of M element, collection number XLX15019. T. *Belodina* sp.: lateral view of M element, collection number XLX15020. U. *Periodon flabellum* Lindström, 1955: lateral view, collection number XLX15021. V–W. *Besselodus* sp.: lateral view of S element, collection numbers XLX15022 and XLX15023. X. *Drepanoistodus* sp.: lateral view of M element, collection number XLX15024.

Schmidtella and *Aparchites* are the dominant genera, and the specimens of *Fenxiangia* account for nearly one-tenth as a whole. The Pagoda ostracods are comparable to those from the Craighead limestone formation in Southwest Scotland, which are characterized by *Steusloffia* dominated association and form a 'high-diversity open marine assemblage', with species of *Schmidtella*, *Steusloffia*, *Aparchites*, *Longiscula*, *Balticella*, *Medianella*, *Krausella*, etc., and represent outer platform or deep shelf settings (Mohibullah et al., 2010). In South China, similar taxa have been documented from the Pagoda Formation in Fenxiang, Yichang and Liangshan, Shaanxi; the Yanwashan and Sanqushan formations in Jiangshan and Changshan, Zhejiang; with the common occurrence of *Aparchites changyangensis*, *A. chaqiensis*, *Planoria fenxiangensis*, *P. zhoutangensis* and *Fenxiangia* sp. (Wang, 2015; Jiang et al., 1995; Yuan and Ma, 1993; Li, 1989; Sun, 1987; Shi and Wang, 1985). Generally, most of them are typical species in the Late Ordovician.

Interestingly, relatively well-preserved radial decorations are recognized on the surface of the thin-shelled *Schmidtella* sp. (Fig. 4, D–E), which account for approximately a half of this species (30 carapace shells). However, the contributing factor is still unknown. Besides, it is crucial to note that several specimens with spinous ornaments were first reported in South China which is characteristic of relatively deep water environments (Wang, 2015; Zhao et al., 2014; Gou and Peng, 2011). According to carapace morphology, they are temporarily ascribed to ?*Steusloffia* sp. (Mohibullah et al., 2010). The genus *Steusloffia* with spinous ornaments is less common (Moore, 1961, p. 210).

3.3 Radiolarians and Foraminifers

Three radiolarian tests are recognized. One is identified as *Armstongisphaera* sp. (Fig. 6, A). This genus was first reported by Kozur (1984) from the lower Silurian series of Hungary. The other two tests (Fig. 6, B–C and D–F) are hardly assigned due to poor preservation. The order Spumellaria is dominating the radiolarian assemblage. In South China, studies on the Upper Ordovician radiolarians were limited, with documents only from the Wufeng Formation in Lunshan, Jiangsu (Wang and Zhang, 2011) and Leibo, Sichuan (Liu et al., 2010). Different from that in the Pagoda Formation, the Wufeng fauna was characterized by spherical radiolarians with long slender spines.

Agglutinated foraminifers of 3 undetermined species assigned to 2 genera *Lagenammina* and *Amphitremoida* are identified. The assemblage is dominated by thin-walled monothalamous (single-chambered) specimens. They possess regular to irregular rounded internal cavity and one or two conical apertural canals. The Late Ordovician foraminiferal fauna, which has been less known in South China, was first reported from the Pagoda Formation. Similar morphological species have been documented from the Lower to Middle Ordovician in northwestern Russia (Nestell and Tolmacheva, 2004) and Germany (Riegraf and Niemeyer, 1996).

4 DISCUSSION

4.1 Biostratigraphical Significance

As noted by An (1987), Chen (1983), Chen and Ji (1986), Wang et al. (2017, 2015, 2011), the conodont *Baltoniodus alobatus* Zone and *Hamarodus europaeus* Zone are recognized in ascending order. The base of the Pagoda formation in South China is in the conodont *Baltoniodus alobatus* Zone (Wang et al., 2011; An, 1987). Whilst the accurate biostratigraphic age of the top of this formation remains uncertain (Chen et al., 2010). In the studied section, only the index species *H. europaeus* is recognized, along with other species *Protopanderodus liripipus*, *Panderodus gracilis*, *Cornuodus longibasis*, *Scabbardella altipes* etc. The conodont assemblage suggests that they belong to the *H. europaeus* Zone, which is typical for the Lower Katian Stage (Ferretti et al., 2014; Wang and Wu, 2009; Bergström et al., 2000; Stouge and Rasmussen, 1996).

Because of close affinity within conodonts from successions in South China and coeval successions in the North Atlantic area (Wang et al., 2015, 2011, 2007; Tolmacheva et al., 2009), inter-continental biostratigraphic correlations between these regions are possible. The *Baltoniodus alobatus* Zone is equivalent to the *B. alobatus* Subzone of the *A. tvaerensis* Zone in the North Atlantic conodont zonation (Wang et al., 2017, 2015, 2011; Bergström, 1971). Besides, it is noted that the *Amorphognathus superbus* Zone is well recorded in the North Atlantic region, with frequent co-occurrence of species *H. europaeus* (Fan et al., 2015), thus the *H. europaeus* Zone can be well correlated to the *Amorphognathus superbus* Zone. *A. superbus* Zone was rarely reported from the Pagoda Formation in South China, apart from initially been distinguished by Chen and Zhang (1989) from the Lower Tangshan Formation in Shitai, Anhui.

In South China, similar *H. brevirameus* Zone was documented from the Yanwashan Formation in Jiangxi and the Tangshan Formation in Anhui, the zonal index species of which is considered as the senior synonym of *H. europaeus* (e.g., Wang et al., 2015; Ferretti et al., 2014; Dzik, 1994; Chen and Zhang, 1989). Thus, the Yanwashan and part of the Tangshan formations can be well correlated with the Pagoda Formation by the *H. europaeus* Zone (Wang et al., 2015; Chen et al., 2010).

4.2 Palaeoenvironmental Significance

The grayish yellow to purplish red nodular limestone of the Pagoda Formation is widely distributed in the middle and upper Yangtze area. Interpretations of the depositional settings of this formation are mainly based on lithological characteristics (Zhan et al., 2016a, b; Wang et al., 2012; Xu et al., 2001). Herein, more palaeontological evidence will be discussed. Major faunal associations from the Pagoda Formation are common, characterized by smooth and small-shelled *Leangella- Foliomena* brachiopod association (Rong et al., 1999), the main components of which are commonly found in deeper water environments. Moreover, based on *Cyclopyge-Symphysops-Psilacella* trilobite association and *Sinoceras* nautiloid fauna, the minimum depth of 150 m for the Pagoda Formation was proposed (Rong et al., 1999; Wang, 1996).

Sweet and Bergström (1984) initially distinguished conodont *Hamarodus-Dapsilodus-Scabbardella* (HDS) biofacies widely distributed in the North Atlantic faunal region and suggested relatively cold water deposits (Wang et al., 2015, 2007, 1996; Bergström et al., 2007a, b; Tolmacheva et al., 2009; Stouge and Rasmussen, 1996). The nodular limestone of the Pagoda Formation yields abundant conodonts, which are

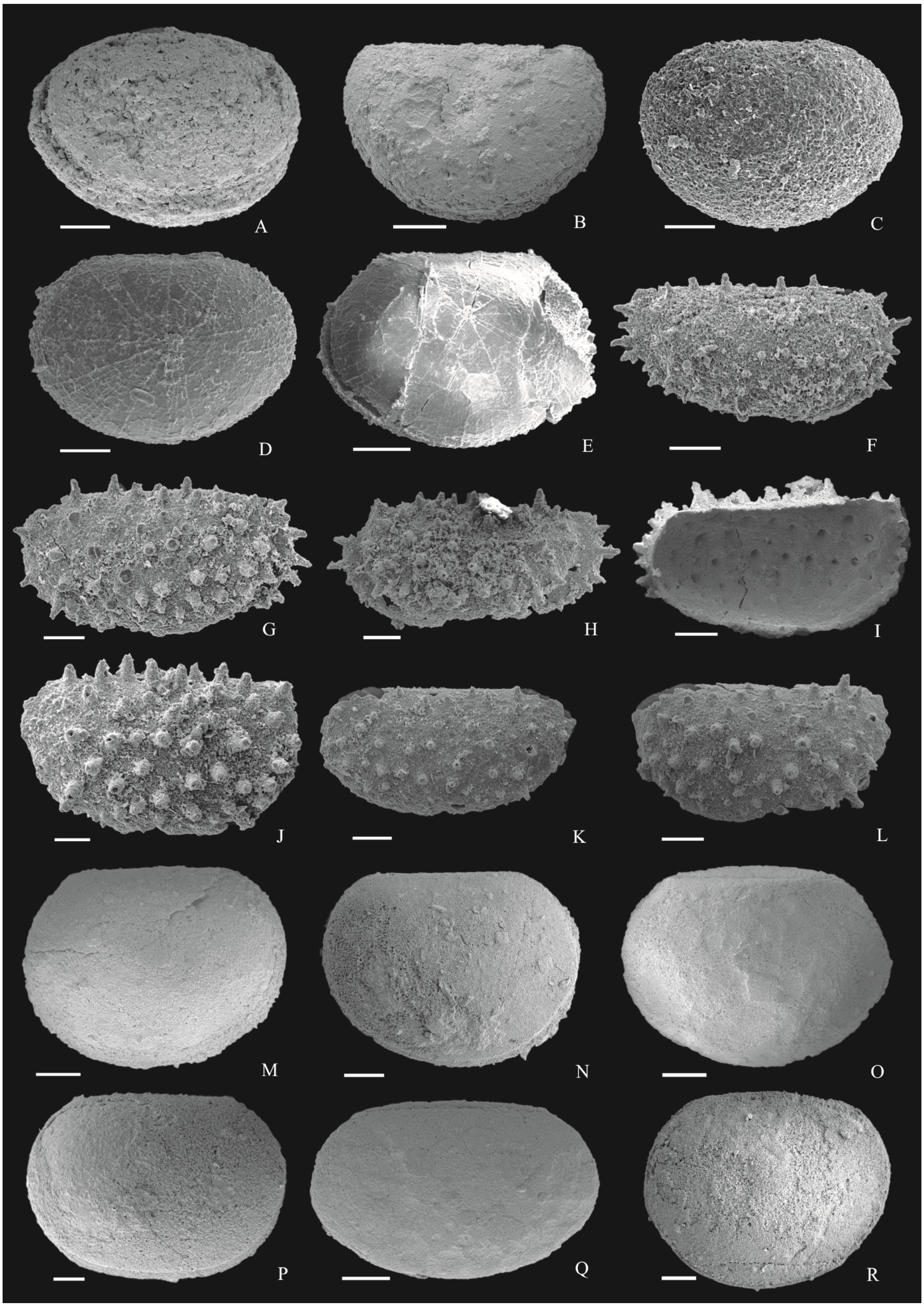

Figure 4. Scanning electron micrographs of ostracods from the Pagoda Formation in Zigui, Hubei Province. Scale bar is 100 µm. A. *Leperditella*? cf. *huanghuaensis* Sun, 1988: right lateral view of carapaces, collection number XLX15025. B. *Primitia*? *wangjiawanensis* Sun, 1983: right lateral view of carapaces, collection number XLX15026. C. *Schmidtella* sp. 1: lateral view of right valve, collection number XLX15027. D–E. *Schmidtella* sp. 2: D. lateral view of right valve, collection number XLX15028; E. left lateral view of carapace, collection number XLX15029. F, I. ?*Steusloffia* sp. 1: F. lateral view of right valves, collection number XLX15030; I. lateral view of left valves, collection number XLX15031. G–H. ?*Steusloffia* sp. 2: G, H. lateral view of left valves, collection numbers XLX15032 and XLX15033, respectively. J. ?*Steusloffia* sp. 3: lateral view of right valves, collection numbers XLX15034. K–L. ?*Steusloffia* sp. 4: K, L. lateral view of left valves, collection numbers XLX15035 and XLX15036. M. *Aparchites changyangensis* Sun, 1988: left lateral view of carapace, collection number XLX15037. N. *Aparchites chaqiensis* Sun, 1988: right lateral view of carapace, collection number XLX15038. O. *Aparchites* sp. 1: left lateral view of carapace, collection number XLX15039. P. *Aparchites* sp. 2: right lateral view of carapace, collection number XLX15040. Q. *Aparchites* sp. 3: left lateral view of carapaces, collection number XLX15041. R. *Paraparchites* sp.: right lateral view of carapaces, collection number XLX15042.

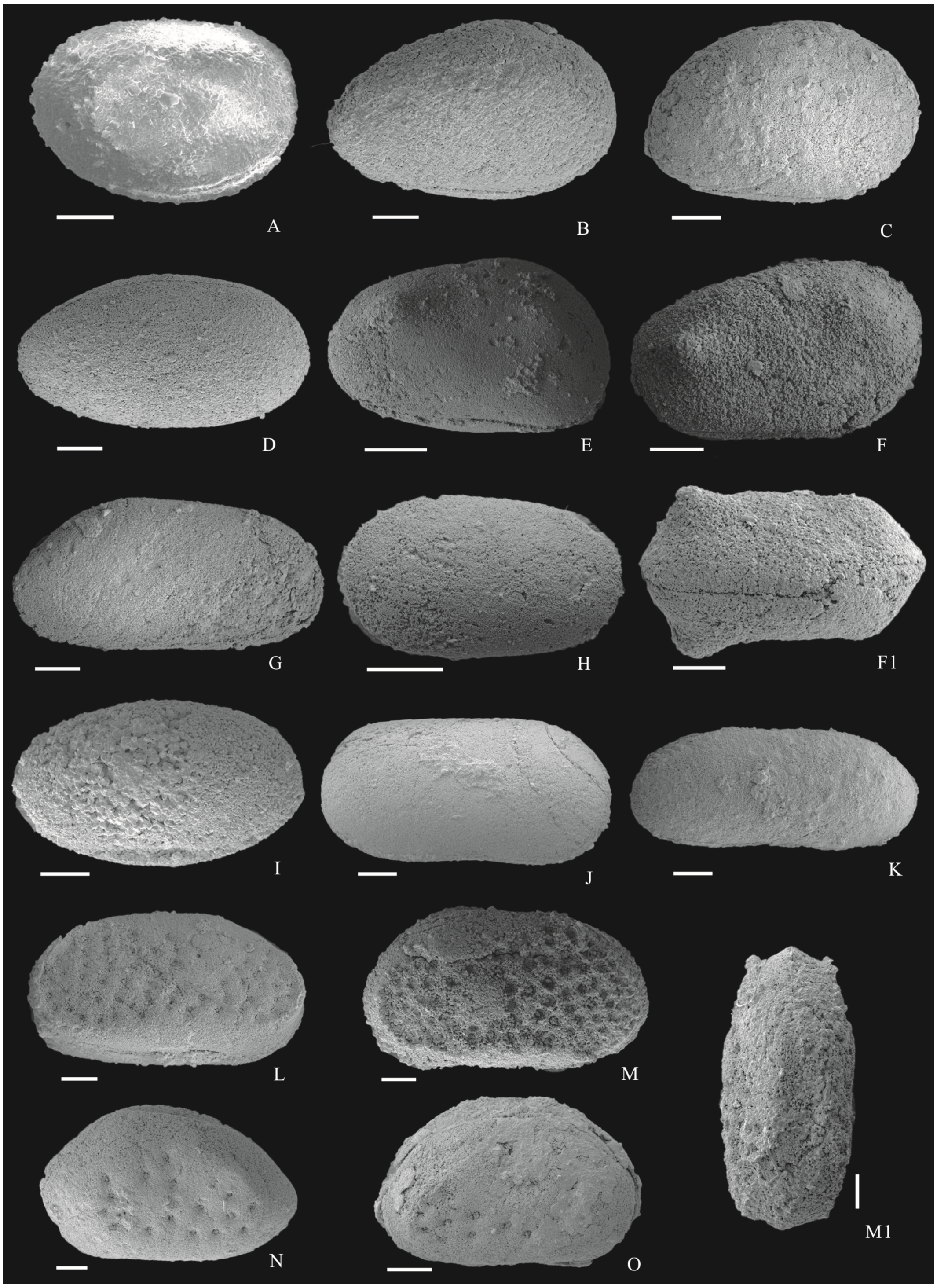

Figure 5. Scanning electron micrographs of ostracods from the Pagoda Formation in Zigui, Hubei Province. Scale bar is 100 µm. A. *Chamishaella*? *antiquus* Shi and Wang, 1985: left lateral view of carapace, collection number XLX15043. B–C. *Pseudorayella* sp. 1: right lateral view of carapaces, collection numbers XLX15044 and XLX15045, respectively. D. *Pseudorayella* sp. 2: right lateral view of carapace, collection number XLX15046. E. *Eobufina* cf. *binoda* Jiang, 1995: right lateral view of carapaces, collection number XLX15047. F. *Eobufina* sp.: F. right lateral view of carapace, collection number XLX15048, F1-ventral view of carapace. G. *Silenis*? *elliptica* Sun, 1978: right lateral view of carapaces, collection number XLX15049. H. *Fenxiangia*? sp. 1: left lateral view of carapace, collection number XLX15050. I. *Fenxiangia*? sp. 2: right lateral view of carapaces, collection number XLX15051. J. *Rectalloides* sp. Sensu Sun, 1988: right lateral view of carapace, collection number XLX15052. K. *Rectella*? *proposita* Abushik and Sarv, 1983: left right lateral view of carapace, collection number XLX15053. L–M. *Planoria fenxiangensis* (Sun), 1978: left lateral view of carapaces, collection numbers XLX15054 and XLX15055, respectively, M1-ventral view of carapace. N–O. *Planoria zhoutangensis* Wang, 2015: N. left lateral view of carapace, collection number XLX15056; O. right lateral view of carapace, collection number XLX15057.

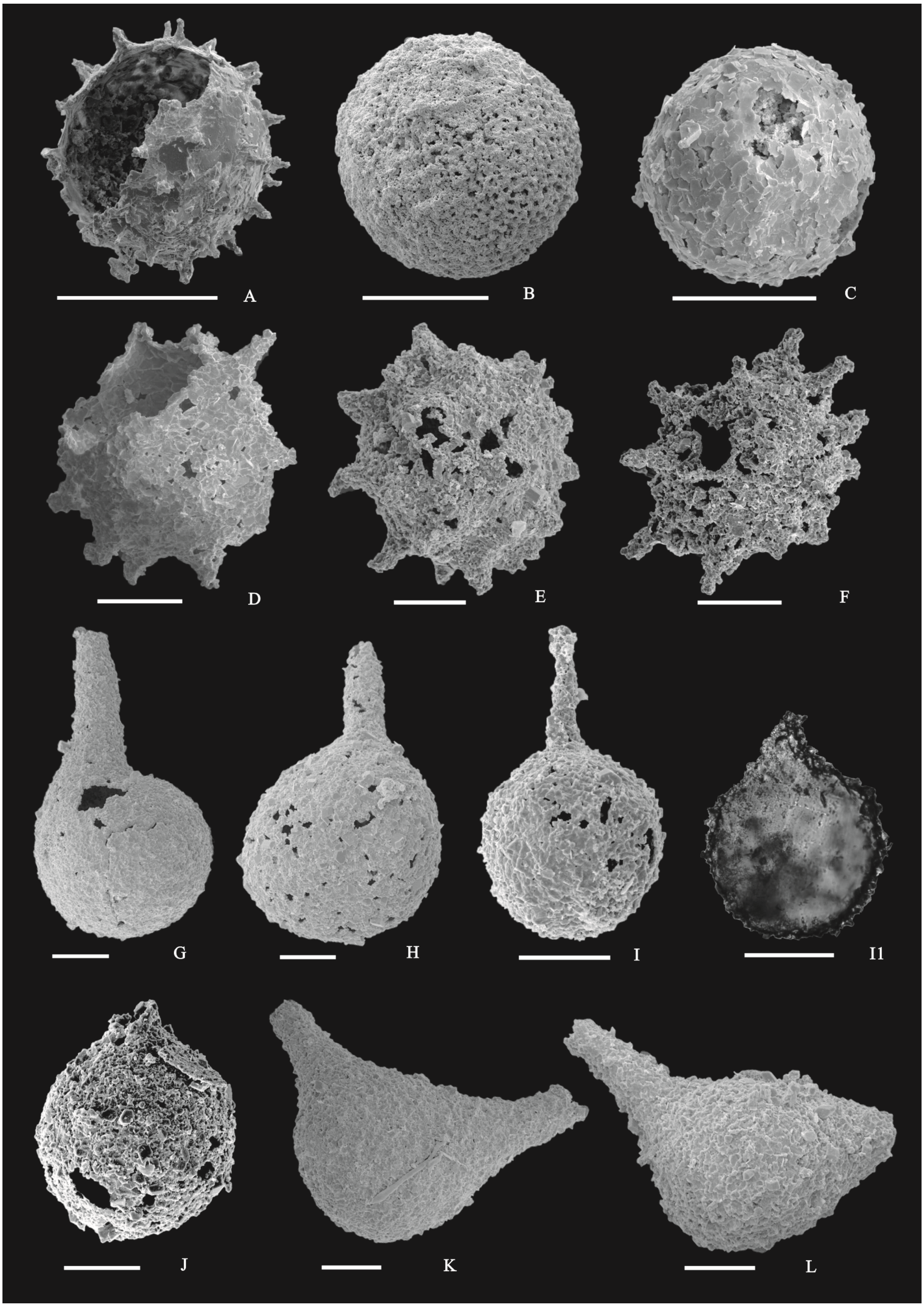

Figure 6. Scanning electron micrographs of radiolarians and foraminifers from the Pagoda Formation in Zigui, Hubei Province. Scale bar is 100 μm. A. *Armstongisphaera* sp., collection number XLX15058. B–C. Spumellaria, gen et sp. indet., collection number XLX15059 and XLX15060, respectively. D–F. Radiolarians, gen et sp. indet., collection numbers XLX15061, XLX15062 and XLX15063, respectively. G–H. *Lagenammina* sp. 1, collection number XLX15064 and XLX15065, respectively. I–J. *Lagenammina* sp. 2: I1. axial section, collection number XLX15066 and XLX15067, respectively. K–L. *Amphitremoida* sp., collection number XLX15068 and XLX15069, respectively.

Series	Stages	North Atlantic (Wang et al., 2011 Bergström, 1971)		South China: Yichang, Hubei (An, 1987)		South China: Wuning, Jiangxi (Chen and Zhang, 1984)		South China: Shitai, Anhui (Chen and Zhang, 1989)	
		Conodont Zone		Fm.	Conodont Zone	Fm.	Conodont Zone	Fm.	Conodont Zone
Upper Ordovician	Katian	*Amorphognathus superbus*		Pagoda	*Hamarodus europaeus*	Yanwashan	*H. brevirameus* =(*H. europaeus*)	Tangshan	*H. europaeus*
Upper Ordovician	Katian	*Amorphognathus superbus*		Pagoda	*Hamarodus europaeus*	Yanwashan	*H. brevirameus* =(*H. europaeus*)	Tangshan	*A. superbus*
Upper Ordovician	Sandbian	*A. tvaerensis*	*B. alobatus*	Miaopo	*B. alobatus*	Hulo		Datianba	*A. tvaerensis*
Upper Ordovician	Sandbian	*A. tvaerensis*	*B. gerdae*	Miaopo	*B. alobatus*	Hulo		Datianba	*A. tvaerensis*
Upper Ordovician	Sandbian	*A. tvaerensis*	*B. variabilis*	Miaopo	*B. alobatus*	Hulo		Datianba	*B. variabilis*
Upper Ordovician	Sandbian	*Pygodus anserinus*		Miaopo	*Pygodus anserinus*	Hulo		Datianba	*P. anserinus*

Figure 7. Conodont zonation between the Pagoda Formation and coeval units of North Atlantic and South China (Note: Fm.=formation; *A.=Amorphognathus*; *B.=Baltonidus*; *H.=Hamarodus*; *P.=Pygodus*).

characterizedby the HDS biofacies. The typical species *H. europaeus* occurs in relatively deep water sequences of the Northern Europe, Southeast and Northeast Asia, especially in South China (Chen et al., 2010; Zhang and Barnes, 2007; Ferretti and Serpagli, 1999; Dzik, 1994). Besides, *Dapsilodus* and *Scabbardella* often co-occurred with *Hamarodus*. Though these two genera are cosmopolitan and present in various depths, associations with *H. europaeus* are considered as indicative of deep water facies. Moreover, associated species of genus *Periodon* were present in outer shelf areas of colder and deeper water environments (Wu et al., 2014; Tolmacheva et al., 2009; Wang et al., 2007). Thus, the Pagoda conodont assemblage may indicate relatively deep and cold water, outer shelf environments.

According to Whatley (1988, 1983), ostracod diversity and assemblage compositions vary with environments. Their morphological features may reflect water temperature and depths, and thus be utilized as environmental indicators (Holms and Chivas, 2002; Casier et al., 2005, 2003). Copeland (1982) recognized aparchitid and schmidtellid rich assemblage from Ordovician Lower Esbataottine Formation in Canada, restricted to a deeper shelf marine environment. Consequently, smooth and thin-shelled *Aparchites* and *Schmitella*, as dominating genera of ostracod assemblage from the Pagoda Formation, are regarded as characteristics of quieter and deeper water depositional settings (Mohibullah et al., 2010; Williams and Siveter, 1996; Williams and Vannier, 1995). As for shell ornaments, similar nubbles and spines were typically documented in deep water environments (Si et al., 2010; De Deckker, 2002, De Deckker and Forester, 1998).

Radiolarians are widely reported from siliceous rocks of relatively deep water environments (Feng and Algeo, 2014; Kozur, 1993). Although the radiolarian assemblage in the Pagoda Formation comprises limited specimens that are of lower diversity and abundance, spherical radiolarians with short spines indicate relatively deep water shelf environments (Nie et al., 2012). Besides, the foraminifers' faunal composition of low diversity and species abundance are similar to those from the Siberian region (Nestell et al., 2009; Nestell and Tolmacheva, 2004), which belongs to cold water assemblage. According to their morphological preservation, small and thin-walled fauna could be living in the relatively deep water environments (Dixon and Haig, 2004; Kaiho, 1991). In general, the relatively deep water plankton and benthic shelly faunas are widely preserved in the Pagoda Formation, along with lithological characteristics, which indicates the rselatively cold and deep water of outer shelf depositional settings.

5 CONCLUSION

The Pagoda Formation exhibits fossil assemblages of high diversity, with conodonts of 14 genera 20 species (6 undetermined species) and ostracods of 14 genera 26 species (16 undetermined species). In addition, radiolarians and minute-walled foraminifers reported here represent their first records in South China. The occurrence of *H. europaeus* suggests that the conodont assemblage can be attributed to the *Hamarous europaeus* Zone, which indicates the Early Katian Age. The conodont HDS Biofacies (Sweet and Berrström, 1984), together with morphological evidence from thin-shelled ostracods, spherical radiolarians and foraminifers, indicate relatively deep and cold water, outer shelf depositional settings, which are in accordance with previous research on lithological characteristics (Zhan et al., 2016a, b). Accordingly, our materials enrich the diversity of the Pagoda biota in South China, and also provide palaeontological evidence for the depositional settings and stratigraphic correlations for the Pagoda Formation.

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