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Upper Darriwilian (Middle Ordovician) Radiolarians and Ostracods from the Hulo Formation, Zhejiang Provicnce, South China

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ABSTRACT: Considerable research has been done on the Ordovician marine fossils from South China, including macrofossils such as brachiopods, graptolites, bivalves, trilobites, some microfossils like conodonts and acritarches. However, radiolarians and ostracods that are also important constituents of the Ordovician marine ecosystem have been paid little attention in this region. In this study, ten radiolarians species belonging to four genera and sixteen ostracods species grouped into nine genera were found from the Hulo Formation at the Hengdu Section of the Jiangshan District, western Zhejiang Province, South China. The fossil-bearing strata belong to the graptolite *Pterograptus elegans* Zone which indicates the Late Darriwilian Age. This radiolarian fauna is the first record of the Middle Ordovician radiolarian body fossils and also the earliest Ordovician radiolarian fauna reported from South China. The occurrence of Beothuka in this fauna extends the stratigraphic range of the genus to the Upper Darriwilian. Reviews of previous literatures suggest that the diversity of Beothuka was greater during the Early Ordovician, and then declined gradually from the Early Ordovician to the Middle Ordovician before its extinction. The co-occurring ostracod fauna belongs to a shallow-water ecotype. This is contrary to the host lithofacies of the ostracod fauna which represent a deep-water environment. Therefore, these ostacods may have been transported from the shallow-water environment, most likely from the Yangtze carbonate platform. If this conjecture is the truth, then the Jiangshan District was near the shallow-water carbonate platform and received its sediments during the Darriwilian. It is still essential to do more work in the future to better understand the ecology of the Ordovician ostracod fanuas and their role in the sedimentary system of South China.

KEY WORDS: radiolarians, ostracods, ecotype, Ordovician, Hengdu Section, South China.

0 INTRODUCTION

The Ordovician marine fossils have already been well studied in South China. Until now, more studies have been focused on macrofossils such as brachiopods (e.g., Zhan et al., 2013, 2007, 2005; Zhan and Harper, 2006), graptolites (e.g., Zhang et al., 2009, 2007; Zhang and Chen, 2008), bivalves (e.g., Fang, 2006) and trilobites (e.g., Zhen and Zhou, 2008; Zhou et al., 2007). Research into the Ordovician microfossils such as conodonts (Wu et al., 2012) and acritarchs (e.g., Yan et al., 2011; Li et al., 2007) has also been undertaken in South China. The overall number of radiolarian and ostracod species was growing during the Ordovician (Braddy et al., 2004; Noble and Danelian, 2004). Radiolarians are the only planktonic fauna with the great biostratigraphic significance and known from the Phanerozoic (Nazarov and Ormiston, 1986). Radiolarians had already been important constituents of planktonic communities by the Ordovician (Servais et al., 2010, 2008). Like radiolarians, ostracods have also been abundant and diverse during the Ordovician (Salas and Vaccari, 2012; Salas, 2011; Servais et al., 2010, 2008; Schallreuter and Hinz-Schalleuter, 2009; Schallreuter et al., 2008; Salas et al., 2007). However, little attention has been paid to the Ordovician radiolarians and ostracods especially in South China. A few radiolarian fossils were only reported from the Upper Ordovician in Sichuan Province (Liu et al., 2010) and Jiangsu Province (Wang and Zhang, 2011). The research of the ostracod fossils from the Ordovician strata was also limited. Hou (1956a, b) firstly presented the Middle Ordovician ostracods including nineteen genera and thirty-four species from Zhejiang Province, although most of them were not well-preserved. Eight genera and twelve species ostracods

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were then found from the Middle Ordovician in Gansu Province (Shi and Wang, 1985). Sun (1988) collected abundant ostracod fossils from the Ordovician in Hubei Province as well. A number of the Middle Ordovician ostracods were also reported in Shanxi Province (Yuan and Ma, 1993). This paper reports ten species radiolarian fossils assigned to four genera and sixteen species ostracods of nine genera in the Ordovician from the Hengdu Section of Jiangshan District, western Zhejiang Province, South China, and also discusses their evolutionary and ecological implications.

1 GEOLOGICAL SETTING

Studies of the Ordovician lithological facies, biota and tectonic combination characters in South China have been carried on for several years. Based on the previous work, South China could be divided into three paleogeographic units including the Yangtze carbonate platform, the Jiangnan shelf-slope and the Zhujiang Basin during the Middle Ordovician (Fig. 1). The recognition that the Yangtze region mainly consisted of carbonate facies with shell fossils suggesting the shallow-water environments has been widely accepted (Hu et al., 2016; Wang, 2016; Zhou et al., 2008, 1979; Feng et al., 2003, 2001; Lai et al., 1993). The area between the Yangtze carbonate platform and the Zhujiang region was usually called the Jiangnan shelf- slope, which was characterized by cherts with sponge spicules, black shales with graptolites, siliceous shales, slity shales and some limestones with a few shelly fossils representing the relatively deep-water environments (Wang, 2016, 1989; Feng et al., 2003, 2001; Guo, 1998, 1994; Lai et al., 1993). The Zhujiang region was a deep basin during the Middle Ordovician for it mainly consisted of black shales with graptolites, siliceous shales and cherts, while the carbonate rocks were very rare (Wang, 2016, 1989; Zhou et al., 2008, 1979).

The Hengdu Section (28°44′52″N, 118°32′45″E) is in a quarry situated about 1 km northeast of Hengdu Country, in Jiangshan City, Zhejiang Province (Fig. 2). This section exposes the Darriwilian–Sandbian strata assigned into two formations—the Hulo and Yenwashan formations (Fig. 3). The Hulo Formation is about 10 m thick and its lower boundary is covered by the Quaternary sediments. It consists of thinly layered cherts together with siliceous limestones and some black shales, and is subdivided into three parts. The lower part of the Hulo Formation is black shales and cherts with siliceous limestone intercalations. In the middle part, it is characterized by alternating cherts and siliceous limestones containing black shales, while the upper part is mainly alternating cherts and shales. The studied section had already been reported by Song et al. (2013) and they recognized four graptolites zones, in an ascending order, the *Nicholsonograptus fasciculatus*, the *Pterograptus elegans*, the "*Hustedograptus teretiusculus*", and the

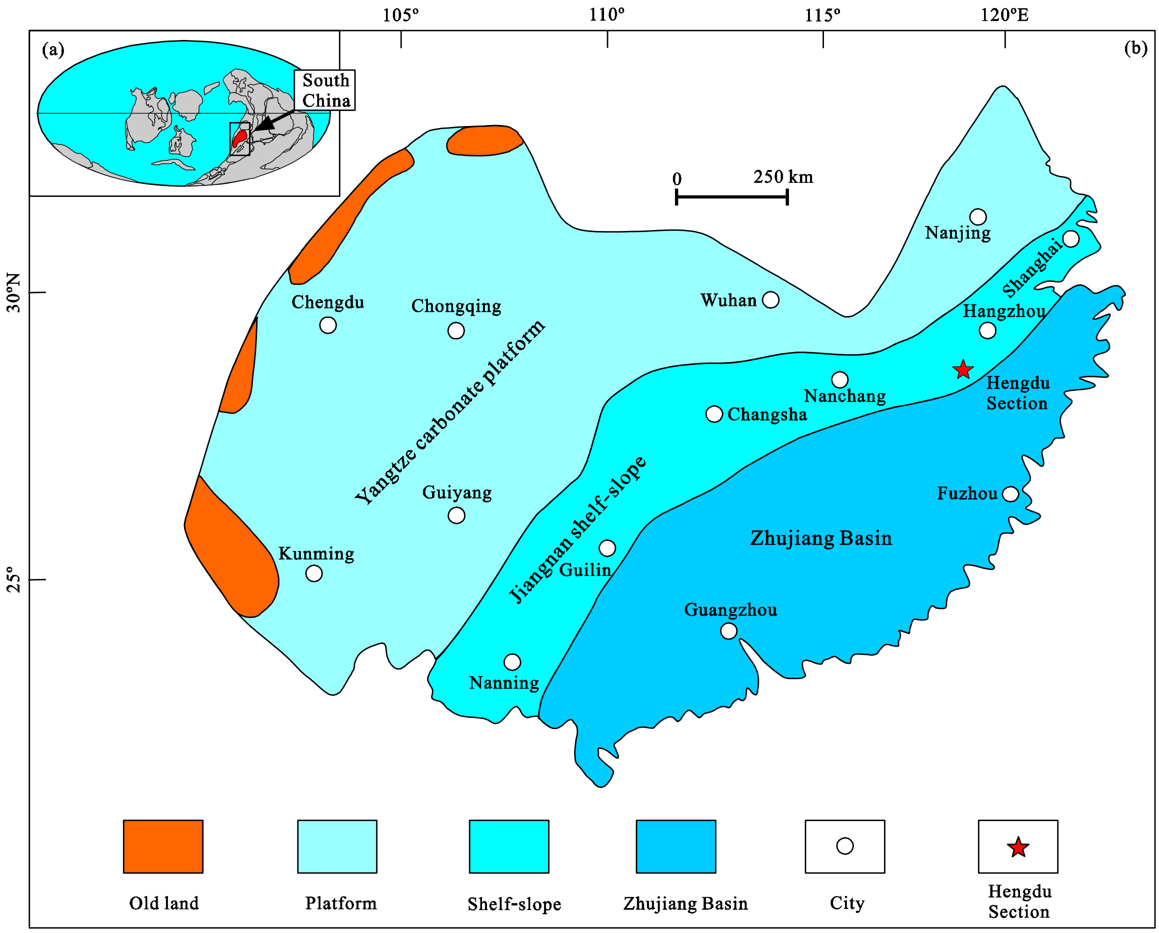
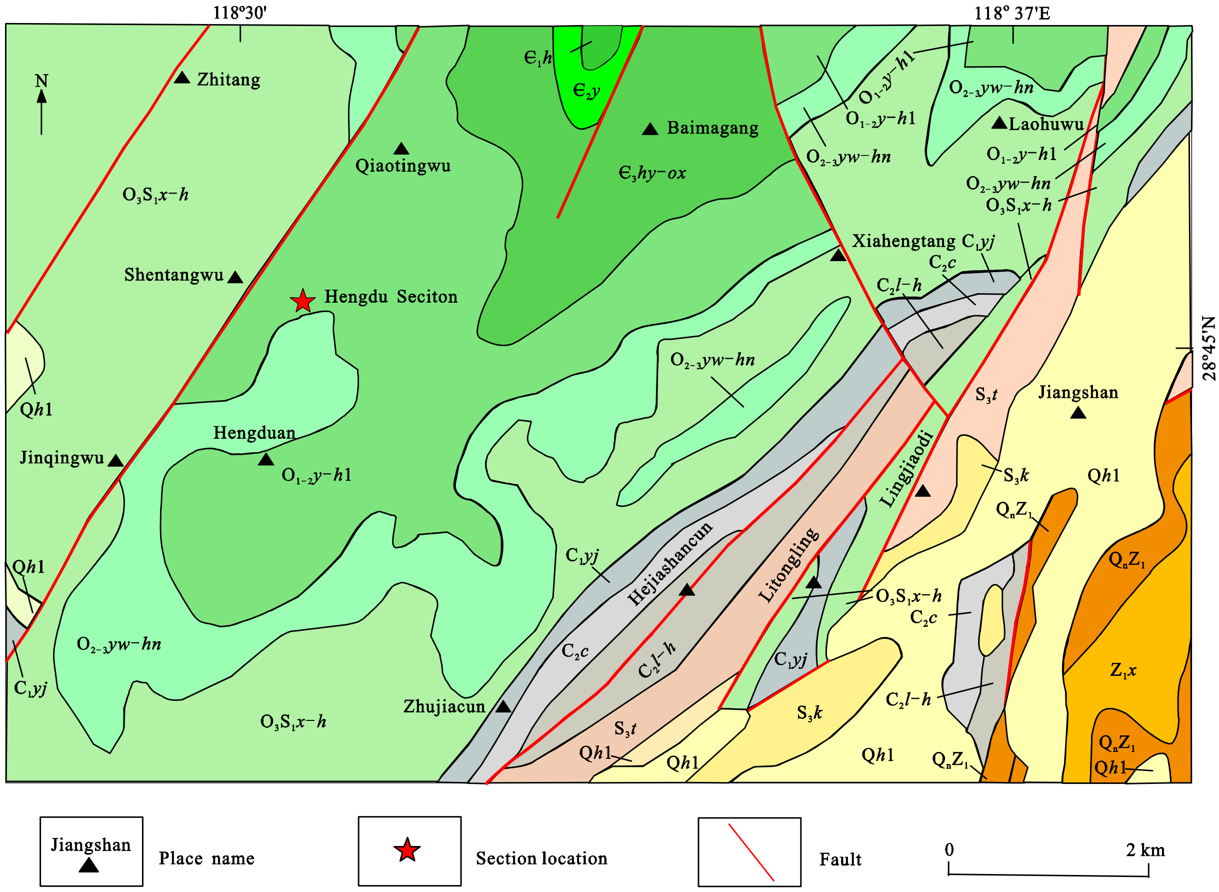


Figure 1. (a) The global Middle Ordovician paleogeographic map showing the location of South China; Middle Ordovician paleogeographic map of South China modified from Scotese (2001). (b) The Middle Ordovician paleogeographic map of South China (modified from Zhan and Jin, 2007).



Figuge 2. Regional geological map of the Hengdu Section in Jiangshan City, Zhejiang Province. Formation names: Z_1x. Xiuning Formation; Є$_1h$. Hetang Formation; Є$_2y$. Yangliugang Formation; Є$_3hy$-ox. Huanyansi and Xiyangshan formations; $O_{1\text{-}2}y$-$h1$. Ningzhubu, Ningguo and Hulo formations; $O_{2\text{-}3}yw$-hn. Yenwashan and Huangnigang formations; O_3c. Changwu Formation; S_3k. Kangshan Formation; S_3t. Tangjiawu Formation; C_1yj. Yejiatang Formation; C_2l-h. Laohudong and Huanglong formations; C_2c. Chuanshan Formation; Q$h1$. Lianxu Formation. Geological period: Z. pre-Cambrian (Sinian); Є. Cambrian; O. Ordovician; S. Silurian; C. Carboniferous; Q. Quaternary.

Nemagraptus gracilic biozones, based on the graptolites from the section. Compared with lithological characters that are mainly cherts and black shales given by Song et al. (2013), we conclude that the fossiliferous part in the section belongs to the *Pterograptus elegans* Zone from the lower part of the Hulo Formation which indicates the Upper Darriwilian (the upper Middle Ordovician).

According to Fig. 1, this section is located in the Jiangnan shelf-slope during the Darriwilian and its lithological characters is consisted with the paleogeographical setting of this area meaning a relatively deep-water environment. The Yenwashan Formation conformably overlies the Hulo Formation and is composed of gray limestones together with black siliceous limestones, which may suggest a shallow-water environment (Lu et al., 2017; Liu et al., 2016; Song et al., 2013; Guo, 1998). Only the lower part of the Yenwashan Formation is exposed in the Hengdu Section and is assigned to the Sandbian Age based on the *Pygodus anserinus* Zone (Wang et al., 2015).

2 MATERIALS AND METHODS

Thirteen samples were collected at evenly spaced intervals through the Hulo Formation in the Hengdu Section. The samples reported herein are from dark red thinly layered cherts. The hydrofluoric acid (HF) technique was utilized to extract radiolarians and ostracods. Samples were crushed into small pieces about 1 cm^3 and put in separate beakers that were placed into a fume hood and immersed in 5% HF acid solution for 8–10 hours at room temperature. Acid residues were decanted into other beakers, which were filled with water until neutral. The beakers holding the samples were refilled with fresh 5% HF acid solution and this process was repeated for about one month. Residues were washed through the sieves and dried. Microfossils were then picked for examination under a binocular microscope and preliminary taxonomic determinations. The best-preserved specimens were later mounted on stubs and photographed with scanning electronic microscope (SEM) for more precise determination. All the specimens are housed in the State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences (Wuhan).

3 RESULTS

Approximately 800 radiolarian and 300 ostracod specimens were recovered. Over 500 specimens were imaged using scanning electronic microscope. After detailed study of these radiolarians, ten morphotypes assignable to four genera were recognized from four samples (HD-R-2, HD-R-3, HD-R-4 and HD-R-6). Sixteen ostracod species of nine genera were recovered from a single sample (HD-R-1). Details of the recognized fossils are described as follows (Fig. 3).

3.1 Radiolarians

Ten morphotypes are recognized: *Syntagentactinia* sp. aff. *excels* Nazarov and Ormiston, *Syntagentactinia* sp. A, *Syntagentactinia* sp. B, *Syntagentactinia* sp. C, *Beothuka* sp. aff. *terranova*, *Beothuka* sp., *Haplotaeniatum* sp. A, *Haplotaeniatum* sp. B, *Haplotaeniatum*? sp. and *Antygopora*? sp. (Fig. 4). There are also a number of nondescript spherical forms. The important characteristics of *Syntagentactinia* are multi-layer shells including one medullary shell centrally or slightly eccentrically located inside the internal cavity and a number of cortical shells, different layers of which are connected by radial beams, and the main spines on the surface of the outermost shell. Some specimens share the same features of *Syntagentactinia* and some of them just resemble *Syntagentactinia excelsa* especially in the skeleton structure and dimensions, but their medullary shells inside the cavity are not so eccentrically, and due to poor preservation some main spines are broken or can only be partially observed. *Haplotaeniatum* is mainly formed by several shells that are concentrically or spirally positioned and an inner small microsphere. The shells around the microsphere are formed by the apophyses from main spines and the

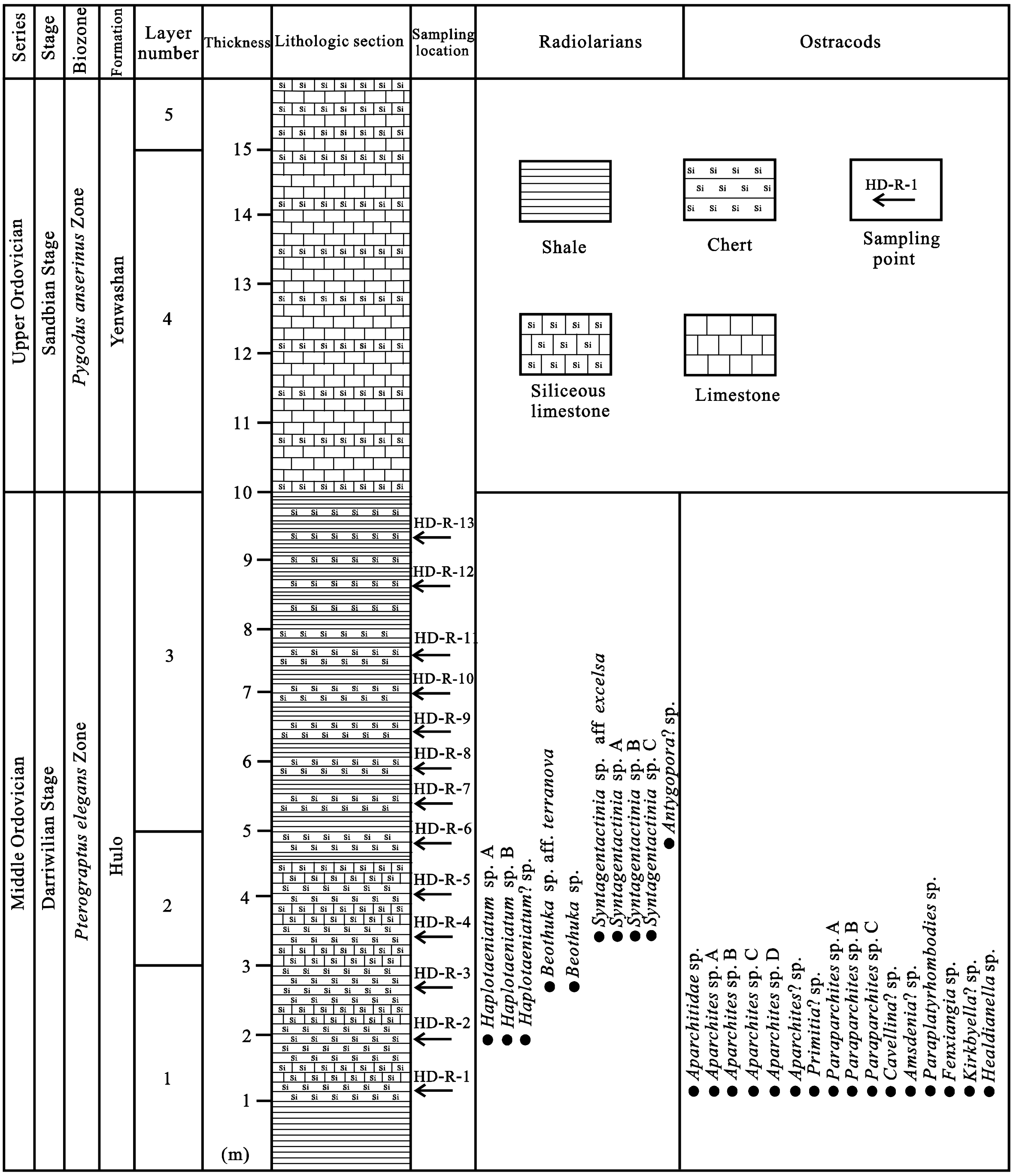


Figure 3. Occurrences of radiolarians and ostracods identified from the Hengdu Section and its biostratigraphic subdivision.

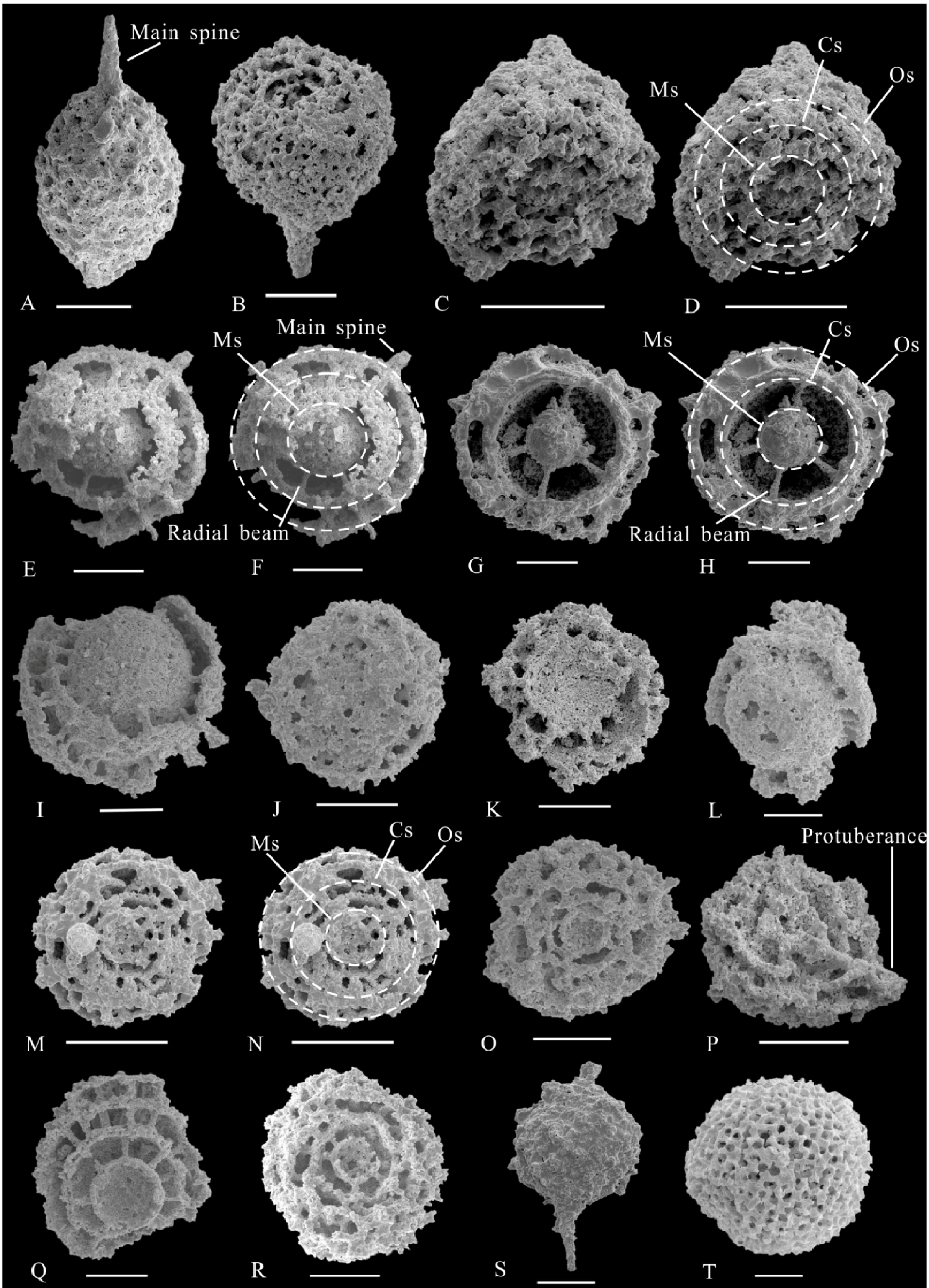


Figure 4. Scanning electron micrographs of radiolarians from samples HD-R-2, HD-R-3, HD-R-4 and HD-R-6 (Hulo Formation, Hengdu, Jiangshan in Zhejiang Province, South China). Scale bar is 100 μm (the scale bar for T is 20 μm). Abbreviation: Os. outer shell; Cs. cortical shell; Ms. medullary shell. A–B. *Beothuka* sp. aff. *terranova* aitchison, flood and malpas, sample HD-R-3. C–D. *Beothuka* sp., sample HD-R-3. E–H. *Syntagentactinia* sp. aff. *excels* Nazarov and Ormiston, sample HD-R-4. I, J. *Syntagentactinia* sp. A, sample HD-R-4. K. *Syntagentactinia* sp. B, sample HD-R-4. L. *Syntagentactinia* sp. C, sample HD-R-4. M–O. *Haplotaeniatum* sp. A, sample HD-R-2. P. *Haplotaeniatum* sp. B, sample HD-R-2. Note the protuberance on the surface of the outermost shell. Q. *Haplotaeniatum*? sp., sample HD-R-2. R. *Antygopora*? sp., sample HD-R-6. S, T. Radiolarians, sample HD-R-4. gen. et sp. indet.

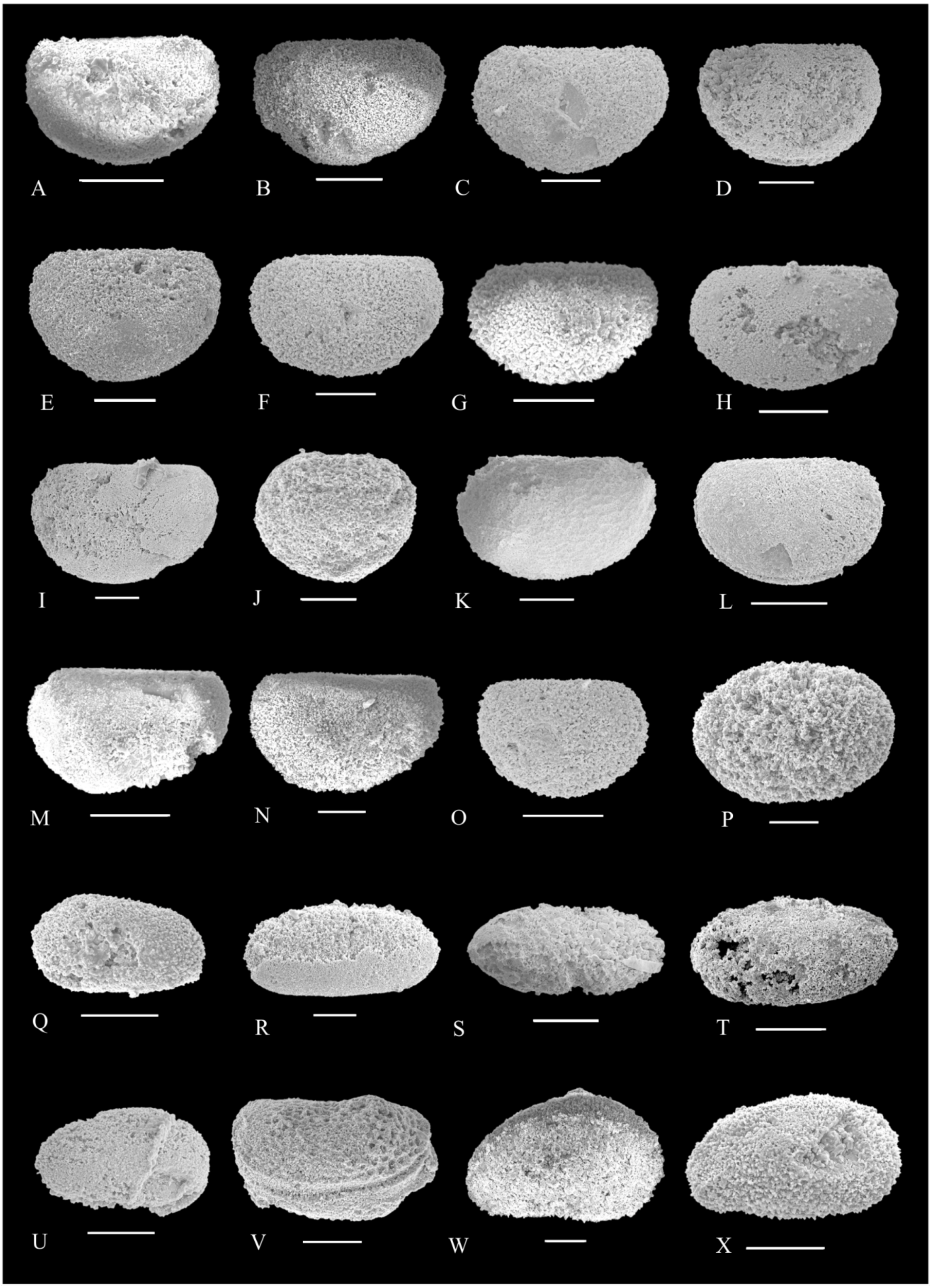


Figure 5. Scanning electron micrographs of ostracods from Sample HD-R-1 (Hulo Formation, Hengdu, Jiangshan in Zhejiang Province, South China). Scale bar is 100 μm. A. *Aparchites* sp. A, lateral view of incomplete valve. B. *Aparchites* sp. B, right view of right valve. C–D. *Aparchites* sp. C, C. right view of right valve; D. left view of left valve. E. *Aparchites* sp. D, right view of right valve. F–I. *Aparchites* sp. E, F. right view of right valve; G. right view of right valve; H. right view of right valve; I. right view of right valve. J. *Aparchites*? sp., right view of right valve. K. *Primitia*? sp., right view of right valve. L. *Paraparchites* sp. A, lateral view of incomplete valve. M–N. *Paraparchites* sp. B, M. right view of right valve; N. right view of right valve. O. *Paraparchites* sp. C, left view of left valve. P. *Cavellina*? sp., lateral view of incomplete valve. Q. *Amsdenia*? sp., left view of left valve. R-S. *Paraplatyrhombodies* sp., R. lateral view of incomplete valve; S. lateral view of incomplete valve; T–U. *Fenxiangia* sp., T. lateral view of incomplete valve; U. lateral view of incomplete valve. V. *Kirkbyella*? sp., lateral view of incomplete valve. W. *Healdianella* sp., left view of left valve. X. Ostracods, gen. et sp. indet.

shells are connected by the radial beams. Some specimens have the common features of *Haplotaeniatum* and some of them have a special structure that called "protuberance", which might be formed by the rod-like spines from the middle of the radiolarian. However, the specimens are not determinable to the species level.

The radiolarian fauna also consists of a bi-polar form which is very similar to *Beothuka terranova*. For example, this form is characterized by coarsely porous ellipsoidal cortical shell and two polar spines or main spines. The bi-polar rodded spines taper over their entire length to a point. Internal structures of some broken specimens consist of multi-layer shells formed by few cortical shells and one small central medullary shell. However, this form differs from *Beothuka terranova* in its shorter and weaker bi-polar spines. For these reasons, it is more appropriate to assign this form into *Beothuka* aff. *terranova* rather than *Beothuka terranova*.

3.2 Ostracods

Although most ostracods found from the Hulo Formation have suffered relatively intense recrystallisation, their identifycation remains possible. Sixteen ostracod species identified from nine genera are recognized including: *Aparchites* sp. A, *Aparchites* sp. B, *Aparchites* sp. C, *Aparchites* sp. D, *Aparchites* sp. E, *Aparchites*? sp., *Primitia*? sp., *Paraparchites* sp. A, *Paraparchites* sp. B, *Paraparchites* sp. C, *Cavellina*? sp., *Amsdenia*? sp., *Paraplatyrhombodies* sp., *Fenxiangia* sp., *Kirkbyella*? sp., *Healdianella* sp. (Fig. 5).

4 DISCUSSION

4.1 Radiolarian Fauna

4.1.1 Distribution

Radiolarians are an important constituent of marine life throughout the Paleozoic. The fossil record of radiolarians is significant for better understanding of early eukaryote evolution and also indicates that a diversification took place during the Ordovician (Maletz, 2011; Noble and Danelian, 2004). The Ordovician radiolarians have been reported from numerous localities worldwide, and significant progress has been made in the past decades (e.g., Won and Iams, 2015a, b, 2013, 2011; Pouille et al., 2014; Danelian et al., 2013; Noble and Danelian, 2004). The Middle Ordovician radiolarians have been investigated in some regions, such as Kazakhstan (Pouille et al., 2014; Maletz, 2011; Danelian and Popov, 2003; Nazarov and Popov, 1980; Nazarov et al., 1977; Nazarov and Popov, 1976), Australia (Iwata et al., 1995; Goto et al., 1992; Umeda et al., 1992; Goto and Ishiga, 1991), Scotland (Danelian and Floyd, 2001; Danelian, 1999; Danelian and Clarkson 1998), South America (Maletz et al., 2009), Kyrgyzstan (Danelian et al., 2011). In western China, the Middle Ordovician radiolarians have been reported from western Junggar and Kuruktag, Xinjiang Uygur Autonomous Region (Zong et al., 2015; Wang et al., 2008; Buckman and Aitchison, 2001), Ningxia Hui Autonomous Region (Wang, 1991), Qinghai Province (Li, 1995), and Gansu Province (Wang, 1993).

South China is a good place to undertake research into the Ordovician marine fossils due to its exposed complete marine strata and long history of detailed research into paleontology (Liu et al., 2016; Peng et al., 2016; Zhan et al., 2007). However, previous studies were mainly focused on macrofossils (Zhan et al., 2013, 2007, 2005; Zhang et al., 2009, 2007; Zhang and Chen, 2008; Zhen and Zhou, 2008; Zhou et al., 2007; Fang, 2006; Zhan and Harper, 2006). Microfossils such as radiolarians have not been paid enough attention. Luo et al. (2002) and Zheng et al. (2012) reported the possible existence of radiolarian fossils in the thin sections from the Early to Middle Ordovician of Hunan. Poorly-preserved radiolarians have been reported from the Wufeng Formation in the Upper Ordovician in Yichang, Hubei (Wang and Zhang, 2011) and the Sichuan area (Liu et al., 2010) from South China. Generally the well-preserved Early and Middle Ordovician radiolarian body fossils have not previously been reported from South China.

4.1.2 Taxonomic implications

Based on the *Pterograptus elegans* Zone (Song et al., 2013), it is clear that the radiolarian fossils found in the Hengdu Section belong to the Upper Darriwilian (the upper Middle Ordovician). The Lower to Middle Darriwilian radiolarians are generally included in the *Proventocitum procerulum* assemblage (Maletz et al., 2009). It is notable that the Lower Darriwilian faunas usually showed low diversity and were dominated by radiolarians with some spherical and thin shells made of irregularly oriented bars or rods (Maletz, 2011). Most of the Upper Darriwilian radiolarian faunas could also be referred to the *Proventocitum procerulum* assemblage, which usually included many spherical spumelarians and the genus *Proceratoikiscum* (Maletz, 2011).

For the Upper Darriwilian radiolarian fauna in this paper, four genera have been identified, including *Syntagentactinia*, *Haplotaeniatum*, *Antygopora* and *Beothuka*. The genus of *Syntagentactinia* has already been reported both from the Middle (Pouille et al., 2014) and Upper Ordovician (Cui et al., 2000). *Haplotaeniatum* has been described from the Lower Ordovician (Maletz, 2007), the Middle Ordovician (e.g., Pouille et al., 2014; Maletz and Bruton, 2008) and the Upper Ordovician (e.g., Noble and Webby, 2009; Goto et al., 1992). *Antygopora* was first reported and named by Maletz and Bruton (2005) from Spitsbergen and has also been found in the Lower (e.g., Won and Iams, 2013, 2011; Maletz 2007) and the Middle Ordovician (Maletz and Bruton, 2008). In general, these three genera are common within the Middle Ordovician. However, the presence of *Beothuka* in our samples is unusual as this genus is generally absent in other Middle Ordovician faunas globally (Won and Iams, 2015a, b, 2013; Maletz, 2007; Maletz and Bruton, 2005; Aitchison et al., 1998). This genus is a special form in spherical radiolarians and represents the oldest known spherical bipolar radiolarian, which is widely regarded as a typical taxon of the Lower Ordovician (Maletz, 2007; Maletz and Bruton, 2005). Numerous identified spherical radiolarians have been recorded from the Ordovician but only rare ones from the Cambrian. A faunal turnover of radiolarians in the Early Ordovician had been discussed and there had been no common faunal elements between the Cambrian and Ordovician ones (Noble and Danelian, 2004). Thus, research on a closer relationship of the Lower Paleozoic radiolarians and a progressive turnover between the Cambrian and

Ordovician should be undertaken in details. More investigations into *Beothuka* could possibly provide us with further understanding of the Early Paleozoic radiolarian evolution.

The characteristic bipolar species *Beothuka terranova* was first described by Aitchison et al. (1998) from the Little Port complex in western Newfoundland, and assigned to the basal Tremadocian. Maletz and Bruton (2007, 2005) reported a radiolarian fauna from Spitsbergen, in which they found *B. terranova*. Maletz (2007) then described a radiolarian fauna from Newfoundland that also contained *B. terranova*. The Little Port complex radiolarian fauna was regarded as the Upper Floian by Maletz (2011) based on the biostratigraphic range of the two radiolarian faunas from Spitsbergen and Newfoundland above. Won and Iams (2013) also reviewed and studied the radiolarian fauna from the red cherts in the Little Port complex and confirmed an "Early Arenig" (the Middle Floian) age assignment. Other Floian radiolarian faunas in Newfoundland also yielded various species of *Beothuka* (Won and Iams, 2015a, b, 2011). *Beothuka* has not been reported from younger strata in Newfoundland.

Wang et al. (2008) introduced a new species of *Beothuka* (*B. longispinforma*) from the Dapingian (the lower Middle Ordovician) from Xinjiang Uygur Autonomous Region in western China. Although the figured specimens appear to have the characteristics of *Beothuka*, it seems that they are still insufficient to allow the establishment of a new species which is regarded as *nomen dubium* (Maletz, 2011). Combined with its occurrence from Xinjiang, it is concluded that the global range of *Beothuka* is likely to be greater than the interval from the Early to Middle Arenig suggested by Won and Iams (2015b). The distribution of radiolarians assigned to *Beothuka* from different areas has been listed in Table 1. It is clear that *Beothuka* exhibits greater diversity in the Lower rather than the Middle Ordovician, which may indicate a gradual decline from the Early Ordovician to the Middle Ordovician.

4.2 Ostracod Fauna

4.2.1 Distribution

Ostracods are an abundant and diverse organism of the marine biosphere since the Ordovician with a well-documented fossil record (Salas and Vaccari, 2012; Salas, 2011; Servais et al., 2010, 2008; Salas et al., 2007). In the Lower Ordovician, ostracods were found from Russia (Melnikova, 1999; Öpik, 1935), Estonia (Öpik, 1935), Sweden (Hessland, 1949), Denmark (Tinn and Meidla, 1999), England (Siveter et al., 1995), Argentina (Salas and Vaccari, 2012; Salas, 2011; Salas et al., 2007), Kazakhstan (Melnikova et al., 2010) and Iran (Ghobadi Pour et al., 2011). The first major diversification of ostracods occurred during the Middle Ordovician, and reached a peak during the Late Ordovician (Braddy et al., 2004). Ostracods from the Middle Ordovician are mainly documented from Norway (Henningsmoen, 1953), Sweden (Tinn and Meidla, 2001; Jaanusson, 1957), America (Williams and Siveter, 1996; Berdan, 1988, 1984, 1976; Swain, 1962, 1957; Levinson, 1961; Kesling et al., 1960; Kesling, 1960), Poland (Olempska, 1994), Estonia (Tinn and Meidla, 2003), Iran (Ghobadi Pour et al., 2006) and Canada (Landing et al., 2013). The Upper Ordovician ostracods have been found from Estonia (Meidla, 1996a), Denmark (Meidla, 1996b), England (Williams et al., 2001), Himalaya (Schallreuter et al., 2008, 2005), Sweden (Meidla, 2007), Russia (Melnikova, 2010), Scotland (Mohibullah et al., 2011), America (Siveter et al., 2014; Spivey, 1939). Studies of the Ordovician ostracods in China are quite limited with only a few reports of low diversity and poorly-preserved assemblages. In South China, only the Lower Ordovician ostracod assemblages have been reported from western Hubei Province (Sun, 1988; Hou, 1956a) and western Zhejiang Province (Hou, 1956b). In North China, the Lower Ordovician ostracods only occurred in Liaoning (Hou, 1956b), Gansu (Shi and Wang, 1985) and Shanxi provinces (Yuan and Ma, 1993). Generally there have been already some records of the Ordovician ostracods, but a detailed biostratigraphic framework for the Ordovician ostracods has not yet been established in China.

4.2.2 Composition

Although the ostracods from the Hengdu Section are not well-preserved enough and some of them are difficult to be identified to the specific level, they still could provide new fossil materials of the Ordovician ostracods in South China. Totally, the fauna consists of three orders including Palaeocopida (*Aparchites*, *Parapatchites*, *Primitia*, *Kirkbyella*), Metacopida (*Healdianella*, *Fenxiangia*, *Amsdenia*, *Paraplatyrhombodies*) and Platycopida (*Cavellina*). There are quite a number of fossils belonging to the genera *Aparchites* and *Paraparchites* found in the studied section. Although most of them are not preserved well enough, they still could be assigned to the genus level according to their characteristic outline. *Aparchites* is very common during the Ordovician in China especially in Hubei and Zhejiang provinces (Wang, 2015; Sun, 1988; Shi and Wang, 1985; Hou, 1956a, b). *Paraparchites* only appears in the Lower and Upper Ordovician in South China but is the general genus from the Permain in other areas (Wang, 2015; Molostovskaya, 2010; Kempf, 2009; Sun, 1988; Frank, 1969; Scott, 1959; Hou, 1956a, b). *Paraplatyrhombodies* is the genus with long and narrow carapaces and has only been reported from the Middle Ordovician in North China (Shi and Wang, 1985). *Primitia* only has been found from the Lower and Upper Ordovician in China (Shi and Wang, 1985; Hou, 1956a, b). The features of *Fenxiangia* include the spindle-shape in the later view and the arched dorsal border and this genus could be found from the Ordovician strata in China (Wang, 2015). *Healdianella* and *Cavellina* are not common genera from the Ordovician in South China but general in the Silurian especially in Yunnan Province (Wang, 2015).

4.2.3 Paleoenvironmental analysis

The Paleozoic ostracods distributed from the shallow to deep environments and their compositions could be important indicators to their ecotypes (Williams and Siveter, 1996; Vannier et al., 1995; Wang, 1988). Bandel and Becker (1975) firstly presented the possible ecotype of the Paleozoic ostracods and its distribution model, including Eifelian Ecotype (from tidal zone to fore-reef environment), Thüringen Ecotype (slope environment in the inter-platform basins) and Entomozoacean Ecotype (basin). Wang (1988) subsequently presented a more detailed division of the Late Paleozoic ostracod

Table 1 Comparisons of *Beothuka* species from different areas (modified from Won and Iams, 2015b)

Location	Age	Graptolite biozone	Reference	*B. terranova*	*B.* sp. aff. *terranova*	*B. aitchisoni*	*B. grosmornensis*	*B. stougei*	*B.? stellata*	*B. robusta*	*B. spongiosa*	*B. echinata*	*B.? concreta*	*B. spissa*	*B. inexpectata*	*B. maletziana*	*B. longispinforma*
Newfoundland	E. Ar	*Tetragraptus approximatus*	Won and Iams (2011)	Y		Y	Y	Y	Y								
Newfoundland	E. Ar	*Pendeograptus fruticosus*	Aitchison et al. (1998)	Y		Y				Y							
Newfoundland	E. Ar	*Pendeograptus fruticosus*	Won and Iams (2013)	Y		Y	Y			Y	Y	Y	Y				
Spitsbergen	E/M. Ar	*Didymograptellus bifidus*	Maletz and Bruton (2005)	Y													
Spitsbergen	E/M. Ar	*Didymograptellus bifidus*	Maletz and Bruton (2007)	Y													
Newfoundland	E/M. Ar	*Didymograptellus bifidus*	Won and Iams (2015a)	Y		Y	Y			Y	Y			Y			
Spitsbergen	M. Ar	*Isograptus victoriae lunatus*	Maletz and Bruton (2007)							Y					Y		
Newfoundland	M. Ar	*Isograptus victoriae lunatus*	Maletz (2007)							Y	Y					Y	
Newfoundland	M. Ar	*Isograptus victoriae lunatus*	Won and Iams (2015b)	Y						Y	Y					Y	
Xinjiang	L. Dp.	*Exigraptus clavus*	Wang et al. (2008)														Y
Xinjiang	E. Da.	*Pterograptus elegans*	This study		Y												

Y. Species present; E. Early; M. Middle; Ar. Arenig; Dp. Dapingian; Da. Darriwilian.

ecotypes and classified them into five associations, which were Leperdittid Association, Palaeocopid-platycopid Association, Smooth-podocopid Association, Spinose-podocopid Association and Entomozoacean Association. The former three associations are subdivisions of the Eifelian Ecotype of Bandel and Becker (1975) representing the nearshore shallow-water environments, while Spinose-podocopid Association was consisted with Thüringian Ecotype and Entomozoacean Association was similar to Entomozoacean Ecotype (Wang, 1988; Bandel and Becker, 1975). As the fossil materials had been accumulated, Wang's five associations appeared to be applicable almost globally such as in Australia (Reynolds, 1987), Japan (Kuwano, 1987), China (Wang, 1988) and South America (Vannier et al., 1995), within a much broader time span from the Ordovician to the Trassic (e.g., Wang, 2015; Kozur, 1972; Knüpfer, 1968). Leperdittid Association dominated by leperditiacean in a low diversity and abundance was an assemblage typical of the very shallow-water tidal flat, lagoonal, or deltaic environments (Vannier et al., 1995; Wang, 1988). Palaeocopid Association represented a broad range from nearshore to subtidal open shelf environments and it mainly consisted of palaeocopids and platycopids especially cavellinaceans with little or no podoropids (Vannier et al., 1995; Wang, 1988). Smooth-podocopid Association and Spinose-podocopid Association were both dominated by podocopids, but the differences between them were distinctive. The former one often consisted of large-size podocopids with little spines and a few palaeocopids like kikbyaceans and paraparchitaceans, living in the off-shore, shallow-water environments, while the latter one's compositions were the podocopids with smaller body size and spinose ornamentation, indicating the relatively low-energy and deep-water environments (Vannier et al., 1995; Wang, 1988; Bandel and Becker, 1975). Entomozoacean Association contained a great many entomozoids often preserved in the basin, which was deeper than Spinose-podocopid Association (Wang, 1988).

The composition of the ostracod fauna in this paper consists of Palaeocopida (*Aparchites*, *Parapatchites*, *Euprimitia*, *Kirkbyella*), Metacopida (*Healdianella*, *Fenxiangia*, *Amsdenia*, *Paraplatyrhombodies*) and Platycopida (*Cavellina*), which is very close to the constitutes of Palaeocopid Association (Wang, 1988) with prevailing palaeocopids, some platycopids especially cavellinaceans (e.g., *Cavellina*) and no podoropids. It means that the ostacod fauna from the Hengdu Section may had lived in a shallow-water environment (e.g., from nearshore to subtidal open shelf facies) during the Darriwilian (Vannier et al., 1995; Wang, 1988). However, these ostracods are found in the cherts accompanied by radiolarians and sponge spicules representing a deep-water environment. In addition, in the regional paleogeographical context, the studied section is in the shelf-slope, also a relatively deep-water environment. Therefore, the living environment based on the ecotypes of ostracods is different from their burial environment. It might be able to conclude that this ostracod fauna in this paper was transported from the shallow-water environments. If this inference is true, the Jiangshan District was close to a shallow-water platform, probably the Yangtze carbonate platform (according to Fig. 1) during the Darriwilian and could receive the sediments from it. More detailed work in the future will contribute to a better understanding of the ecology of the ostracod fanuas in the Ordovician of South China and their role in the sedimentary system.

5 CONCLUSION

1. Relatively well-preserved radiolarian fossils occur in the Upper Darriwilian from the Middle Ordovician of the Jiangshan District, western Zhejiang Province, South China. This is the first record of the Middle Ordovician radiolarians and also the Earliest Ordovician radiolarian fauna from South China. Four genera and ten species of radiolarians were identified from the succession. These fossils contribute to filling the faunal gap regarding the Middle Ordovician radiolarians in this region.

2. The occurrence of *Beothuka* (*B.* sp. aff. *terranova*) in this Middle Ordovician radiolarian fauna is noteworthy and indicates that the range of the genus may be greater than what has been previously suggested. Diversity of this genus appears to have gradually declined from the Early to Middle Ordovician.

3. Nine genera and sixteen species ostracods were also found in the same horizon. The composition of the ostracod fauna is close to the Palaeocopid Association, which belongs to a shallow-water ecotype. The ecotype of the fauna suggests that the Jiangshan District was close to a shallow-water platform, probably the Yangtze carbonate platform during the Darriwilian and could receive the sediments from it.

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