New Siliceous Microfossils from the Terreneuvian Yanjiahe Formation, South China: The Possible Earliest Radiolarian Fossil Record

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ABSTRACT: Radiolarians form an important part of the planktonic realm in the ocean of Early Paleozoic, but their origin and evolutionary processes has long been enigmatic. The ancestral representatives of radiolarians have been considered to belong to the order Archaeospicularia, whose unquestionable fossil records were dated back to the Middle Cambrian. Here we report ?Blastulospongia and unnamed spherical radiolarians in the Terreneuvian from the Yanjiahe Formation in Hubei Province, South China. Blastulospongia is an enigmatic siliceous microfossil genus, with affinities proposed amongst the radiolarian, sphinctozoan-grade sponges and uncertain protists. As for the newly discovered unnamed radiolarians, morphologically they possess latticed shell, spherical shape and are all small in size. Our discoveries support the idea that spherical radiolarians is an ancient representative, whose origin and diversification was probably much earlier than generally accepted. The hypothesis that the oldest radiolarians belong to the order Archaeospicularia needs to be re-examined.

KEY WORDS: Cambrian, radiolarian, ?Blastulospongia, silica-biminerализation.

0 INTRODUCTION

Apart from exquisite skeletons and astonishing biodiversity, radiolarians are one of the key components in the marine system with silica-biminerализational skeletons. Their origin and early history has long been studied extensively, including molecular data and the fossil record (Decelle et al., 2012; Ishitani et al., 2011; Pouille et al., 2011; Danelian and Moreira, 2004; Nazarov, 1975, 1973). Identifying the earliest record of radiolarians is undoubtedly important in regard to the rise of siliceous biominerализation in eukaryotic lineages and its impact on the evolution of the silica cycle (Zhang et al., 2013 and references therein). Moreover, they provide information on the origin and initial establishment of “modern”-type marine ecosystems during the transitional interval between the Ediacaran and Cambrian, since they constitute the main representatives of the heterotrophic plankton (De Wever et al., 2001; Anderson, 1983). However, little is known concerning the morphology of the earliest radiolarians, since fossil records are scarce, especially in old sequences. Despite their origin can be dated back to the Neoproterozoic by molecular data (Decelle et al., 2012), the earliest convincing fossil record of radiolarians is from the Middle Cambrian (Won and Below, 1999). The ancestor of radiolarians has been considered to belong to the order Archaeospicularia, and the spicular or needle-like morphology has been postulated to represent an ancient characteristic (Malitz, 2011).

However, history of radiolarians in the Early Cambrian or the Neoproterozoic is still poorly known. So far, reports concerning Early Cambrian radiolarians are still highly incomplete, among them, few specimens have been described (e.g., Braun et al., 2007a; White, 1986), some of the specimens are misinterpreted as nonbiologic objects or skeletal plates of the lobe-pod animal Microdictyon (Zhang and Aldridge, 2007; Lippis, 1992; Shu and Chen, 1989; Peng, 1984), some specimens are poorly preserved (Cao et al., 2014, Fig. 4I therein; Braun et al., 2007a). Besides, ambiguous age of some sequences in the Lower Cambrian poses another challenge since there are neither proper fossil zones nor geochemical data.

Here we report new siliceous microfossils recovered from the Yanjiahe Formation in the Luojiaxian Section, Zigui County, Hubei Province, South China. According to SSFs biostratigraphy, the Yanjiahe Formation belongs to Early to Middle Meishucunian in age, corresponding to the Terreneuvian internationally (Guo et al., 2014). The fossils, recovered from the limestone nodules in the middle of Yanjiahe Formation, include ?Blastulospongia sp. and unnamed spherical radiolarians, they both represent the possible earliest radiolarian fossil record. These fossils are less likely to be contamination because Blastulospongia is a genus that only reported from the
Cambrian; the unnamed radiolarians are very similar to those reported from the Kuanchuanpu Formation (Terreneuvian) and the Shuijingtuo Formation (Series 2) (Cao et al., 2014; Braun et al. 2007a). Our findings support the idea by Braun et al. (2007a) that spherical radiolarian is an original representative and has an older history than previous thought. Along with sponges (e.g., Chang et al., 2017; Braun et al., 2007b), it is likely that the Cambrian invasion of siliceous skeleton-bearing radiolaria in the oceanic realm altered profoundly oceanic silica cycle during the Ediacaran–Cambrian transition. Their early biomineralization and flourish might be related to the high concentration of silica in the seawater caused by the breakup of the Rodinia supercontinent.

1  GEOLOGICAL SETTING AND STRATIGRAPHY

The studied section crops out in a quarry (30°47′40.95″N, 110°54′49.81″E) closed to the Luojiaucun Village, western Yichang, Hubei Province, China (Fig. 1). The Ediacaran to Lower Cambrian succession is well exposed. It includes, in ascending order, the Dengying, the Yanjiahe, the Shuijingtuo, and the Shipai formations. The basal Cambrian Yanjiahe Formation, disconformably overlies the Baimatuo Member of the Ediacaran Dengying Formation. There is a hiatus between the Yanjiahe and the Shuijingtuo formations (Fig. 2).

In biostratigraphy, Chen (1984) identified two small shelly fossils (SSFs) assemblage zones within the Yanjiahe Formation: Circotheca-Anabarites-Protohertzina assemblage zone and Lophotheca-Aldanella-Maidipingoconus assemblage zone. Guo et al. (2014) revised the SSFs into three assemblage zones, namely: the Anabaritestrisulcatus-Protohertzinaanabarica assemblage zone (Zone I), the Purellaantiqua assemblage zone (Zone II) and the Aldanellayanjiaheensis assemblage zone (Zone III) in ascending order (Fig. 2). Based on SSFs, the Yanjiahe Formation was deposited in the Early to Middle Meishucunian and corresponds to the Cambrian Terreneuvian internationally.

In the studied area, the Yanjiahe Formation can be subdivided into 5 parts. Bed 1, characterized by basal dolomitic conglomerates, mostly consists of dolostone to sandy dolostone and banded black cherts. Bed 2 is dominated by siliceous phosphatic dolostone with flat pebble conglomerates. It is followed by a thick succession of alternation of shale, in which carbonate and phosphatic nodules are common, and limestone (Bed 3). Bed 4 comprises carbonaceous limestones. The uppermost Bed 5 is characterized by cherts and siliceous phosphatic dolostone with flat pebble conglomerates. The radiolarian fossils were recovered from the limestone nodules in Bed 3, which belongs to the Purellaantiqua Zone (Zone II) in the Yanjiahe Section. This bed can be further correlated with the Upper Zhongyicun Member in eastern Yunnan, the Upper Maidipingo Formation in western Sichuan, the Upper Gezhongwu Member in northern Guizhou (Guo et al., 2014).

2  MATERIAL AND METHODS

Recrystallization in cherts during diagenesis process can strongly influence the microstructures of radiolarian fossils. This study focused on limestone nodules to detach radiolarians. A large amount of limestone nodules were collected from the middle part of the Yanjiahe Formation (Bed 3) in the field work. Sample was then crushed into small pieces of about 1 cm³. The fragments were placed in plastic barrels with 10% acetic acid solution (nine parts water to one part acid) for a period of about one week, the upper acid is discarded and the sample is washed until enough residues were detached. Subsequently, the residue was sieved (diameter=0.038 and 0.083 mm) carefully, dried at room temperature, and then hand-picked under a binocular microscope. Isolated specimens were mounted on stubs with latex then examined on stereoscan electron microscope (SEM) and electronic differential system (EDS) analysis in the State Key Laboratory of Geological Process and Mineral Resources (Wuhan).

Figure 1. Geological map of Zigui County in South China and location of the studied area (schetch map of China modified after http://bzdt.nasg.gov.cn/, No. GS(2016)1569).
In our study, abundant microfossils have been recovered, including radiolarians, SSFs, sponge spicules, etc. Among them, six radiolarian fossils were described. According to small shelly fossil biostratigraphy, the radiolarian fossils, including *Blastulospongia* sp. and unnamed spherical radiolarians, belong to *Purellaantiqua* assemblage zone of the Yanjiahe Formation (Guo et al., 2014), which can be correlated with the second SSF biozone, *Siphonochitestrangularis–Purellasquamulosa* assemblage zone in eastern Yunnan (Steiner et al., 2007), corresponding to the Early Meishucunian Stage of Chinese usage, Upper Nemakit–Daldynian in Siberia and Terreneuvian, Fortunian Stage of international scheme (Peng et al., 2012; Khomentovsky and Karlova, 1993).

3 SYSTEMATIC PALEONTOLOGY

All of the specimens described here are deposited in the Geological Museum of China University of Geosciences (Wuhan), China.

*Phylum uncertain*
*Class uncertain Family uncertain*
*Genus Blastulospongia* Pickett and Jell, 1983
**Diagnosis:** Spherical to oval shell, perforated by numerous pores which are usually evenly distributed. Wall thin, interior of tests empty, the primary composition is uncertain.

*Blastulospongia* sp.

*Material:* Two specimens: YJH03-11, YJH03-12.

*Occurrence:* Early Cambrian–South China, Siberia; Middle Cambrian, West Utah; Late Cambrian, Queensland.

*Description:* Globular tests, single and small shell, about 70 μm in diameter, with rounded or angular perforations evenly distributed all over the specimen. Spineless, wall thin. Composed of microcrystalline silica. Most of the perforations are nearly circular in outline, fairly and evenly spaced, about 5–8 μm in diameter, some angular ones might partially be attributed to recrystallization.

*Remarks:* *Blastulospongia* is an enigmatic genus that only receives specimens from Cambrian strata, with siliceous wall and varied diameter. It was originally interpreted as sponge by Pickett and Jell (1983). The type species, *B. monothalamos*, was described to be extremely large (1–1.9 mm in diameter). Bengston (1986) reported *B. mindyallica* from the Late Cambrian of Queensland and proposed that this genus would be a radiolarian, if the original composition could have been siliceous. White (1986) reported an unnamed spumellarian from the Middle Cambrian, which is recognised as *Blastulospongia* for its strong similarities with this genus. In South China, Conway Morris and Chen (1990) reported *B. polytreca* from the Shuijingtuo Formation (the Cambrian Series 2). The *B. polytreca* was characterized by thin wall, bearing dimples and folds of varying openness. However, possibility of post-mortem damage cannot be ruled out for these dimples and folds, since the shells of *B. polytreca* are rather thin and would be easily influenced by sedimentary compaction. Conway Morris and Chen (1990) further provided evidence that the *Blastulospongia* was unlikely to be sponge for its siliceous composition that probably being primary. Kouchinsky et al. (2017) reported specimens recovered from Cambrian Terreneuvian in Siberia, by experiments of energy-dispersive X-ray analyses and their co-occurrence with calcitic shelly fossils, the siliceous composition of *Blastulospongia* was further confirmed to be original, rather than reflecting selective replacement by silica during diagenesis.

New materials described here are siliceous (Fig. 4a), co-occurred with calcitic shelly fossils. However, our specimens have some differences with those mentioned above. The specimens reported from Medvezhya Formation (Terreneuvian, Stage 2) in Siberia includes 2 specimens, the smaller specimen is ca. 350 μm and the larger one ca. 800 μm in diameter (Kouchinsky et al., 2017). Our specimens are rather small in diameter, the perforations are evenly spaced, and shows no deformation in the wall. Compared to *B. polytreca*, the
perforations of our specimens are more sparsely distributed; compared to *B. mindyallica*, the shell of our specimens are thicker. The diameter of specimens from the Shuijingtuo Formation reported by Conway Morris and Chen (1990) is between 350 to 370 μm; the specimen described by White (1986) from the Middle Cambrian was about 380 μm, but the size range of his materials was not provided; the diameters of specimens reported from the Late Cambrian were between 280–520 μm (Bengtson, 1986). The diameter of this genus varies from 280 to 1 900 μm, some of the specimens have rather thin wall and tend to be deformed with dimples and folds (e.g., *B. polytreca* and one specimen from Siberia) but others do not show deformation. Our specimens share the morphology of single chambered, asiphonate, porate, without others do not show deformation. Our specimens share the internal skeletal structures with *Blastulospongia*, but is rather small in size, it’s possible that these differences represent two different lineages, so they are tentatively assigned to *Blastulospongia*.

As to this controversial question of whether *Blastulospongia* belongs to a sponge, radiolarian, or something else, observations of this study are in accordance with Conway Morris and Chen (1990) and Kouchinsky et al. (2017), which shows that *Blastulospongia* are less similar to spongozoan grade. In morphology our specimens are most similar to that reported by White (1986) and they might belong to one species. In addition, if it is a radiolarian, to the familiar latticed architecture, radiolarians can also produce spherical tests of denser material with perforations, it is possible that radiolarian could have been diversified as a part of the ‘Cambrian explosion’.

*Blastulospongia* is similar to a small shelly fossil, assigned as *Aetholicopallaadnata* (Conway Morris and Chen, 1990), in the round shape with perforations. *Aetholicopallaadnata* have been widely reported from the Lower Cambrian strata (Yang et al., 2014; Kouchinsky et al., 2013; Wrona, 2004; Elicki, 1998). But *Aetholicopallaadnata* is characteristic of double-walled shells connected by hollow pillars and preserved as phosphate (Wrona, 2004), which can be distinguished from *Blastulospongia*.

**Suborder, family and genus unknown**

**Spherical radiolarian**

Figure 3. 4–7

**Material:** Six specimens: YJH03-21, YJH03-22, YJH03-31, YJH03-32, YJH03-33, YJH03-34.

**Occurrence:** Early Cambrian, South China.

**Description:** Spherical, latticed shell, small in diameter, about 125 μm. The perforations are circular with pentagonal or hexagonal frames. Inner structure unclear. Siliceous in composition (Fig. 4b).

**Remarks:** These spherical radiolarians are very similar to those reported from the Kuanchuanpu Formation in Ningqiang, Shanxi Province, China (Braun et al., 2007a), they possessed latticed shell and spherical shape with small sizes, while the latter specimens possess short spines. In the Shuijingtuo Formation, Cao et al. (2014) reported similar spherical radiolarian, but its age is younger (Series 2, Stage 3) and its diameter is bigger (240 μm). The specimens described here are from the same region with those reported by Cao et al. (2014), not only validating the presence of radiolarians in the Early Cambrian sequences, but also providing opportunities to reveal characteristics of early radiolarian. The spherical morphology might represent an original characteristic of radiolarian, which was evolved much earlier than that has been generally accepted. The frame structure displayed similarities to some genera occurred in Ordovician, but due to recrystallization its inner structure was unclear. However, its systematic position and nomenclature requires additional material and more conspicuous characters showing the inner structure.

**4 DISCUSSION ON SIZE AND MORPHOLOGY OF RADIOLARIANS IN THE EARLY CAMBRIAN**

In the Yanjiahe Formation, all these siliceous fossils yielded are small in size, with the average diameter being approximately 100 μm. The specimens reported from the Kuanchuanpu Formation are also relatively small, about 160 μm in diameter (Braun et al., 2007a). The specimens reported by Obut and Iwata (2000) from the Botomian (Lower Cambrian) in the Altai Mountains (Siberia) are even smaller. Indeed, the shell diameter of species *Archaeocenosphaeramuricata* Obut and Iwata ranges between 80 and 100 μm (Obut and Iwata, 2000). The specimens of *Spongomasanannosphaera* Won, described from the Middle Cambrian of Australia, varies between 93 and 130 μm in diameter (Obut and Iwata, 2000). The relationship of body size with oxygen availability has been discussed widely, with lots of studies showing that the increase of oxygen level is a critical trigger for evolution of life (Li et al., 2017; Zhang and Cui, 2016; Zhang et al., 2014; Payne et al., 2009; Canfield et al., 2007; Cloud, 1968). Specifically increased oxygen availability leads to increased sizes, as demonstrated by fossil records of protists (primarily in aerobic het-
istry show that oxygen availability was still very low in South China (e.g., Liu et al., 2017; Jin et al., 2016), lithologically the wide spread black shales and cherts composition also indicate a relatively poor redox condition in the lower sequences of South China (e.g., Zhou and Jiang, 2009; Li et al., 1999). The small size of the ?Blastulospongia and the spherical radiolarian fossils in the Yanjiahe Formation might be an original character and the low oxygen availability might be a factor that limited their size, but considerable complexity remains.

The ancestral representatives of radiolarians have been considered to belong to the order Archaeospicularia, and the simple spicular or needle-like morphology has been postulated as described by Maletz (2011) could be easily confusing with Hexactinellida sponge spicules or some abiogenetic minerals for their similar outline, size and siliceous composition.

The record of radiolarians from the Lower Cambrian or even the Late Neoproterozoic would certainly provide a great breakthrough as regards to the radiolarian research as well as the Cambrian research. Recently there have been multi-disciplinary works on the Ediacaran–Cambrian transition from South China (e.g., Ding et al., 2017; Mason et al., 2017; Hu et al., 2016; Yin et al., 2016; Zhang et al., 2016), as the Proterozoic to Early Cambrian strata are well exposed there, many publications provided evidence of radiolarian fossils shown in thin sections (He et al., 2013; Zheng et al., 2012; Zhao, 1999; Yin et al., 1994), and all of them possess spherical shell. But due to recrystallization the inner structures are difficult to observe. Reports regarding old radiolarian fossils from South China have a potential for our knowledge on the early history of radiolarians. Morphologically they possess latticed shell and spherical shape that are quite different from the postulated ancestral radiolarians (Archaeospicularia). The original character of radiolarian is still open to question, but evidence from both thin sections and acid etching analysis shows that the morphology of radiolarian in South China is different from that of Australia specimens during Cambrian. The hypothesis that oldest radiolarians belong to the order Archaeospicularia needs to be re-examined, and a phylogenetic analysis concerning old radiolarians must await more investigations.

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REFERENCES CITED

English Abstract


