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New siliceous microfossils from the Terreneuvian Yanjiahe Formation, South China: the possible earlist radiolarian fossil record

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ABSTRACT:Radiolarians form an important part of the planktonic realm in the ocean of early Palaeozoic, but their originand evolutionary processes has long been enigmatic. The ancestral representatives of radiolarians have been considered 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 discoveriessupportthe idea thatsphericalradiolarians is an ancient representative, whose origin and diversification was probably much earlier than generally accepted; the hypothesisthat the oldest radiolarians belong to the order Archaeospicularia needs to be re-examined.

KEYWORDS: Cambrian, Radiolarian, ?*Blastulospongia*,silica-biomineralization

0 INTRODUCTION

Apart from exquisite skeletons and astonishing biodiversity,radiolarians are one of the key components in the marine system with silica-biomineralized 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, 1973, 1975). Identifying the earliest record of radiolarians is undoubtedly important in regard to the rise of siliceous biomineralization in eukaryotic lineages and its impact on the evolution of the silica cycle (Zhang et al., 2013 and references cited 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 et al., 1999). The ancestor of radiolarians has been considered tobelong to the order Archaeospicularia, and the spicular or needle-like morphology has been postulated to represent an ancient characteristic (Maletz, 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 described (e.g., Braun, 2007a; White, 1986), some of the specimens are misinterpretations of nonbiologic objects or skeletal plates of the lobopod animal *Microdictyon*(Zhang and Aldridge, 2007; Lipps, 1992;Peng, 1984; Shu and Chen, 1989), some specimens are poorly preserved (Cao et al., 2014, fig. 4L; Braun et al. 2007a). Besides,ambiguous age of somesequences in the lower Cambrian poses another challengesince there are neither proper fossil zones nor geochemical data.

Here we report new siliceous microfossils recovered from the Yanjiahe Formation in the Luojiacun 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, includes ?*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 II) (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 previously 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 during the Neoproterozoic-Cambrian transition.

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 Luojiacun village, western of 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).

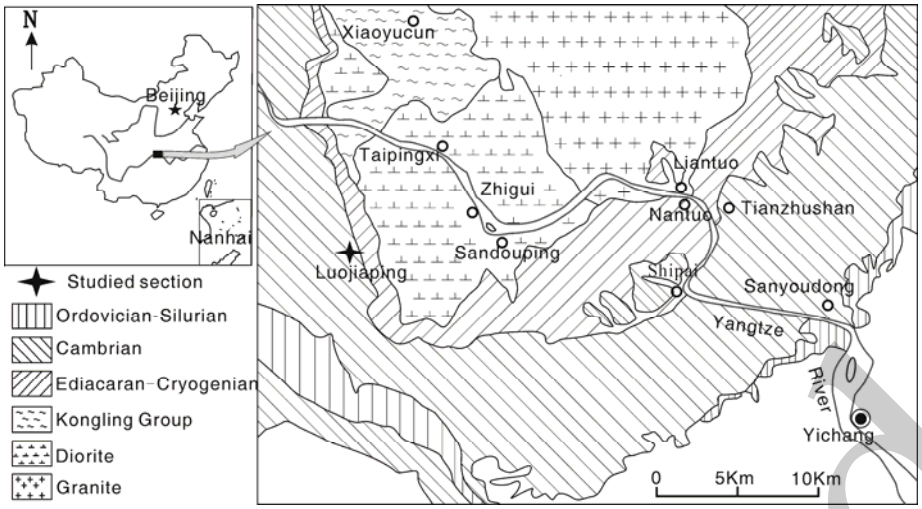

Figure 1. Geological map of Zigui city in South China and location of studied area.

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 SSFsinto threeassemblage zones, namely: the *Anabarites trisulcatus–Protohertzina anabarica* assemblage zone (Zone I),the *Purella antiqua* assemblage zone (Zone II) and the *Aldanella yanjiaheensis*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. 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 *Purella antiqua* zone (Zone II) in the Yanjiahe section.This bed can be further correlated with the upper Zhongyicun Member in eastern Yunnan, the upper Maidiping Formation in western Sichuan, the upper Gezhongwu Member in northern Guizhou (Guo et al., 2014).

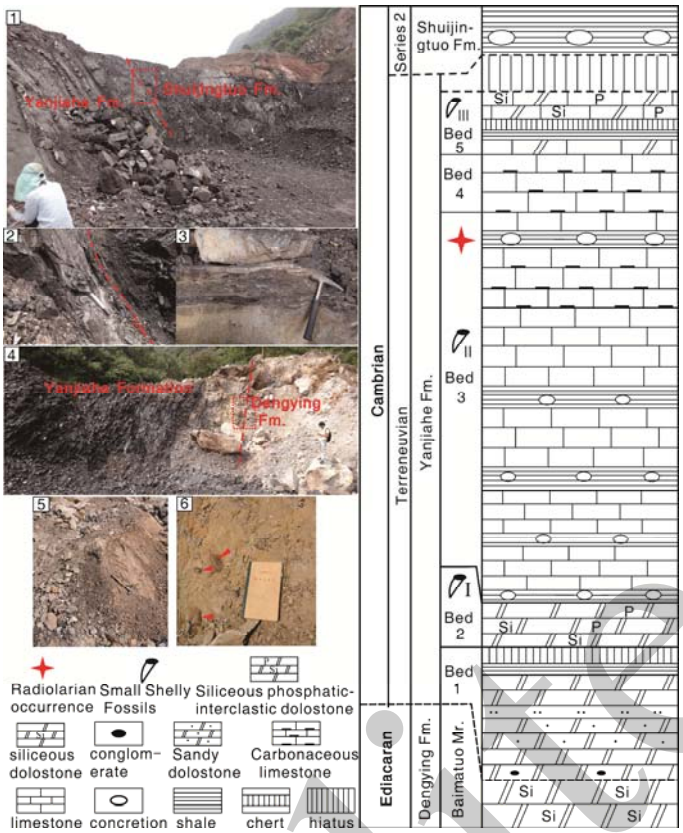

Figure 2. Stratigraphic column of the Luojiaping section and field photos. **(1)**, field photo shows the contact relationship of the Yanjiahe Fm. with the Shuijingtuo Fm., **(2)** shows the magnified picture of the rectangle area in**(1)**, **(3)** shows siliceous phosphatic-interclastic dolostone in Bed 5; **(4)**, field photo shows the contact relationship of the Yanjiahe Fm. with the Dengying Fm., **(5)** shows the weathering crust, **(6)** shows conglomerates (marked by the arrows) in the base of the Yanjiahe Fm.

2MATERIAL AND METHODS

Recrystallization in cherts duringdiagenesisprocess 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 smallpieces of about 1cm^3. The fragments were placed in plastic barrels with 10% acetic acidsolution (nine parts water to one part acid) for a period of about one week,the upper acidis discarded and the sample is washeduntil enough residue was detached. Subsequently, the residue was sieved (diameter=0.038mm and 0.083mm) carefully, dried at room temperature, and then hand-picked under A binocular microscope.Isolated specimens were mounted on stubs withlatex then examined onStereoscan Electron Microscope(SEM) and Electronic Differential System (EDS) analysis in the State Key Laboratory of Geological Process and Mineral Resources.

In our study, abundant microfossils have been recovered, including radiolarians, SSFs, sponge spicules,etc. Among them, sixradiolarian fossils were described.According to small shelly fossil biostratigraphy, the radiolarian fossils, including ?*Blastulospongia* sp. and unnamed spherical radiolarians, belongs to *Purella antiqua* assemblage zone of the Yanjiahe Formation (Guo et al., 2014), which can be correlated with the second SSF biozone, *Siphogonuchites triangularis–Purella squamulosa* 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).

3SYSTEMATIC PALEONTOLOGY

All of the specimens described here are deposited in theGeological 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.

Figure 3.1-3

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 70μm in diameter, with rounded or angular perforationsevenly distributed all over the specimen.Spineless, wall thin. Composed ofmicrocrystalline silica.Most of the perforations are nearly circular in outline, fairly and evenly spaced, about 5-8μm 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 originallyinterpreted as sponge by Pickett and Jell (1983).The type species,*B.monothalamos*, wasdescribed to beextremely large (1-1.9mm in diameter). Bengtson (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 unnamedspumellarian 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 characteristic bythin wall, bearing dimples and folds ofvarying openness. However, possibility of post-mortem damage cannot be ruled out for thesedimples and folds, since the shells of *B. polytreca*are rather thin and would be easily influenced bysedimentary 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.

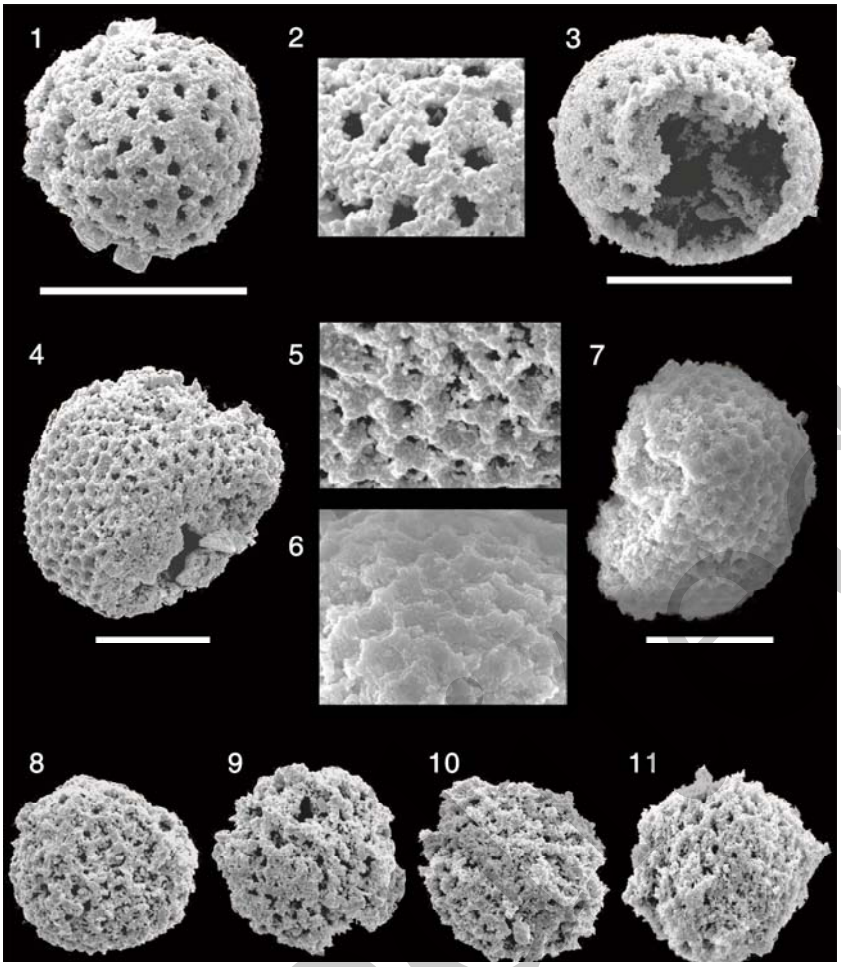

Figure 3. Radiolarian fossils from the Yanjiahe Formation in the Loujiaping section. **(1, 3)**, *Blastulospongia* sp., **(1)**, YJH03-11; **(2)** shows the magnified picture of the perforations; **(3)**, YJH03-12. **(4, 7)**, spherical radiolarian **I**. **(4)**,YJH03-21, with thepentagonal or hexagonal frames amplified in **(5, 6)**;**(7)**, YJH03-22. **(8-11)**, Spherical radiolarian **II**, poorly preserved. **(8)**, YJH03-31; **(9)**, YJH03-32; **(10)**, YJH03-33; **(11)**, YJH03-34. Scale bars length: 50μm.

New materialsdescribed here are siliceous (Fig. 4-1), 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 specimensare thicker. The diameter of specimens from the Shuijingtuo Formation reported by Conway Morris and Chen (1990) is between 350μm to 370μm; the specimen described by White (1986) from the Middle Cambrian was about 380μm, but the size range of his materials was not provided; the diameters of specimens reported from the late Cambrian were between 280-520μm (Bengtson, 1986). The diameter of this genus varies from 280μm to 1900μm, 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 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 tosphinctozoan-grade sponges.In morphology our specimens are most similar to that reported by White (1986) and they might belongs to one species. In addition, if it is a radiolarian, to the familiar latticed architecture,radiolarians can also producespherical 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 *Aetholicopalla adnata* (Conway Morris, 1990), in the round shape with perforations. *Aetholicopalla adnata* have been widely reported from the lower Cambrian strata (Yang et al., 2014; Kouchinsky et al., 2013; Wrona 2004; Elicki, 1998). But *Aetholicopalla adnata* is characteristic ofdouble-walled shells connected by hollow pillars and preserved as phosphate (Wrona 2004), which can be distinguished from *Blastulospongia*.

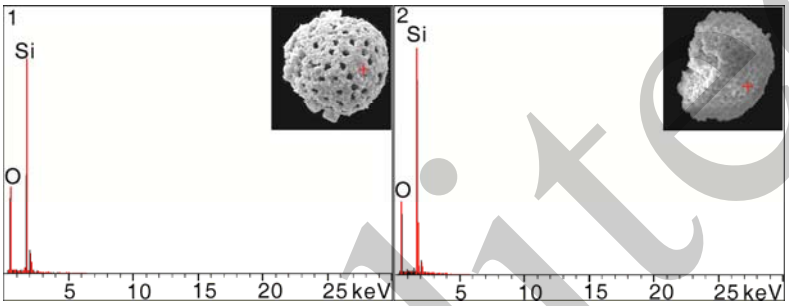

Figure 4. Electronic Differential System (EDS) analysis for the siliceous microfossils from the Yanjiahe Foramtion. **(1)**, EDS result of the specimen of *Blastulospongia* shown in Figure **3(1)**; **(2)**, EDS result of the specimen of the unnamed spherical radiolarianshown in Figure **3(7)**.

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, about125μm. The perforations are circular withpentagonal or hexagonal frames. Inner structure unclear. Siliceous in composition (Fig. 4-2).

Remarks: These sphericalradiolariansarevery similar to those reported from the Kuanchuanpu Formation in Ningqiang, Shanxi province, China(Braun et al., 2007a), they possess latticed shell and spherical shape withsmall sizes,while the latter specimenspossess short spines.Inthe Shuijingtuo Formation,Cao et al.(2014) reported similar spherical radiolarian,butits age is younger (Series 2, Stage 3) and its diameterbigger (240μm). 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 characteristicsof early radiolarian.The spherical morphology might represent an original characteristic of radiolarian, which was evolved much earlier than has been generally accepted.The frame structure displayed similarities to some genera occurred in Ordovician, but due to recrystallizationits inner structure was unclear. However, its systematic position and nomenclaturerequires additional material and more conspicuous characters showing the inner structure.

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

In the Yanjiahe Formation, all these siliceous fossils yielded are small in size, with theaverage diameter being approximately100μm.The specimens reported from the Kuanchuanpu Formation are also relatively small, about 160μm 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 *Archaeocenosphaera muricata* Obut and Iwata ranges between 80 and 100μm(Obut and Iwata, 2000). The specimens of *Spongomassa nannosphaera* Won, described from the middle Cambrian of Australia, varies between 93 to 130μm 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 heterotrophs) and animals (Payne et al., 2010) and experiments in laboratory settings (Klok et al., 2009). Studies from geochemistry shows that oxygen availability was still very low in South China (e.g. Jin et al. 2016), lithologically the wide spread black shall 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 Formationmight 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 has been considered to belong to the order Archaeospicularia, and the simple spicular or needle-like morphology has beenpostulatedto represent an ancient characteristic (Maletz, 2011). However, no elements of Archaeospicularia has been found in the lower Cambrian till now, moreover, the simple, ‘original’ morphology 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 workson the Edicaran-Cambrian transition from South China (e.g. Ding et al., 2017; Mason et al., 2017; Yin et al., 2016),as the Proterozoic to early Cambrian strata are well exposed there, many publications provided evidence of radiolarian fossilsshown 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 structure 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 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

An, Z., Jiang, G., Tong, J. et al., 2015. Stratigraphic position of the Ediacaran Miaohe biota and itsconstrains on the age of the upper Doushantuo $\delta^{13}C$ anomaly in the Yangtze Gorges area, South China. *Precambrian Research*, 271(2015): 243–253

Anderson, O. R., 1983. Radiolaria. Springer, New York. 271

Bengtson, S., 1986.Siliceous microfossils from the Upper Cambrian of Queensland.*Alcheringa*, 10: 195–216

Braun, A., Chen J., Waloszek, D., Maas, A., 2005.Micropalaeontological studies in Lower Cambrian rocks of the Yangtze Plate, China: methods and results.*Studia Geologica Polonica*, 124: 11–20

Braun, A., Chen, J., Waloszek, D., et al., 2007a. First early Cambrian Radiolaria.In: Vickers-Rich, P. Komarower, P., eds., The Rise and Fall of the Ediacaran Biota. *Geological Society*, *London*, 286: 143–149

Braun, A., Chen, J., Waloszek, D.,et al., 2007b. Siliceous microfossils and biosiliceous sedimentation in the lowermost Cambrianof China. In:Vickers-Rich, P., Komarower, P., eds., The Rise andFall oftheEdiacaranBiota.GeologicalSociety,London,286: 423–424

Canfield, D.E., Poulton, S.W., Narbonne, G.M., 2007.Late-Neoproterozoic deep-ocean oxygenation and the rise of animal life.*Science*, 315(5808): 92–95

Cao, W., Feng, Q., Feng F., Lin, W., 2014.Radiolarian *Kalimnasphaera* from the Cambrian Shuijingtuo Formation in South China.*Marine Micropaleontology*, 110(2): 3–7

Chang, S., Feng, Q., Clausen, S., et al., 2017. Sponge spicules from the lower Cambrian in the Yanjiahe formation, South China: the earliest biomineralizing sponge record. In: Chen, Z., Zhou, C., Stanley, G., eds., Biosedimentary records of China from the Precambrian to present. *Palaeogeography Palaeoclimatology Palaeoecology*, 474: 36–44

Chen, P., 1984. Discovery of lower Cambrian small shelly fossils from Jijiapo, Yichang, West Hubei and its significance.*Professional Papers of Stratigraphy and Palaeontology*, 2: 49–65(in Chinese)

Cloud, P.E., 1968, Pre-metazoan evolution and the origins of the Metazoa.In Drake, E.T. eds., Evolution and environment. New Haven, Yale University Press, 72

Conway Morris, S., Chen, M., 1990.*Blastulospongia polytreta* n. sp., an enigmatic organism from the Lower Cambrian of Hubei, China.*Journal of Paleontology*, 64(1): 26–30

Danelian, T., Moreira, D., 2004.Palaeontological and molecular arguments for the origin of silica-secreting marine organisms.*Comptes Rendus Palevol*, 3(3): 229–236

De Wever, P., Dumitrica, P., Caulet, et al., 2001. Radiolarians in the Sedimentary Record. Gordon and Breach Science Publishers. 525

Decelle, J., Suzuki, N., Mahé, F., et al., 2012.Molecular Phylogeny and Morphological Evolution of the Acantharia (Radiolaria): *Protist*, 163(3), p. 435–450

Ding, R., Zou, H., Min, K. et al., 2017. Detrital Zircon U-Pb Geochronologyof Sinian-Cambrian Strata in the Eastern Guangxi Area, China. *Journal of Earth Science*, 28(2):295-304

Elicki, O., 1998. First report of *Halkieria* and enigmatic globular fossils from the central European Marianian (Lower Cambrian, Görlitz Syncline, Germany). *Recista Españo;a de Paleontología*, n° extr., 51-64.

Guo, J., Li, Y., Li, G., 2014.Small shelly fossils from the early Cambrian Yanjiahe Formation, Yichang, Hubei, China.*Gondwana Research*, 25(3): 999–1007

He, T., Ling, H., Chen, Y., et al., 2013. Geochemical character and formation of cherts from the Ediacaran Piyuancun Formation of Lantian section in Xiuning, southern Anhui. *Geological Journal of China Universities*, 19(4): 620–633 (in Chinese)

Ishitani, Y., Ishikawa, S.A., Inagaki, Y., et al., 2011.Multigene phylogenetic analyses includingdiverse radiolarian species support the "Retaria" hypothesis—the sister relationship of Radiolaria and Foraminifera.*Marine Micropaleontology*, 81(1): 32–42

Jin, C., Li, C., Algeo, T. J., et al., 2016. Evidence for marine redox control on spatial colonization of early animals during Cambrian Age 3 (c. 521–514 Ma) in South China. *GeologicalMagazine*,https://doi.org/10.1017/S0016756816001138

Khomentovsky, V.V., Karlova, G.A., 1993. Biostratigraphy of the Vendian–Cambrian beds and the lower Cambrian boundary in Siberia. *Geological Magazine*,130(1), 29–45

Klok, C.J., Hubb, A.J., Harrison, J.F., 2009.Single and multigenerational responses of body mass to atmospheric oxygen concentrations in Drosophila melanogaster: evidence for roles of plasticity and evolution.*Journal of evolutionary biology*, 22(12): 2496–2504

Kouchinsky, A., Bengtson, S., Landing, E., et al., 2017. Terreneuvian stratigraphy and faunas from the Anabar Uplift, Siberia. *Acta Palaeontologica Polonica*,62(2): 311–440

Kouchinsky, A., Bengtson, S., Clausen, S., et al., 2015. An early Cambrian fauna of skeletal fossils from the Emyaksin Formation, northern Siberia. *Acta Palaeontologica Polonica*, 60(2): 421–512

Li C, Jin C, Planavsky N J, et al., 2017. Coupled oceanic oxygenation and metazoan diversification during the early–middle Cambrian?. *Geology*,45(8):743-746.

Li, R., Lu, J., Zhang, S., et al., 1999. Organic carbon isotopes of the Sinian and Early Cambrian black shales on Yangtze Platform, China. *Science in China*, 42(6): 595–603

Lipps, J. H., (1992). Proterozoic and Cambrian skeletonized protists. In: Schopf, J. W. and Klein, C., ed., The Proterozoic Biosphere: a Multidisciplinary Study. Cambridge University Press, Cambridge. 237-240

Maletz, J., 2011,Radiolarian skeletal structures and biostratigraphy in the early Palaeozoic (Cambrian–Ordovician).*Palaeoworld*, 20(2-3): 116–133

Mason, R., Li, Y., Cao, K. et al., 2017. Ediacaran macrofossils in Shunyang Valley, Sixi, Three Gorges District, Hubei Province, China. *Journal of Earth Science*, 28(4), 1–8

Nazarov, B.B., 1973.Radiolarians from the Lowermost Horizons of the Batenev Mountain Ridge. In: Problems of Paleontology and Biostratigraphy of the Lower Cambrian of Siberia and the Far East. Novosibirsk, Nauka, 5–13(in Russian)

Nazarov, B.B., 1975. Lower and Middle Paleozoic radiolarians of Kazakhstan (methods of investigation, systematics and stratigraphic significance). In Raaben, M.E. eds., Trudy Akademiya Nauk SSSR, Geologicheskii Institut. Izdatelstvo Nauka, Moscow, USSR, 1–203 (in Russian)

Obut, O. T., Iwata, K., 2000. Lower Cambrian Radiolaria from the Gorny Altai (Southern west Siberia). *News of Paleontology and Stratigraphy*, 2-3: 33–38

Payne, J.L., Boyer, A.G., Brown, J.H., Finnegan, S., Kowalewski, M., Krause, R.A., Lyons, S.K., McClain, C.R., McShea, D.W., Novack-Gottshall, P.M., Smith, F.A., Stempien, J.A., Wang, S.C., 2009.Two-phase increase in the maximum size of life over 3.5 billion years reflects biological innovation and environmental opportunity.*Proceedings of the National Academy of Sciences*, 106(1): 24–27

Peng, L., 1984. The age and tectonic significance of ophiolites of the Undorsum Group, Nei Mongol Autonomous Region. *Science Bulletin*, 29(7): 936–939

Peng, S.C., Babcock, L.E., Cooper, R.A., 2012. The Cambrian Period. In Gradstein, F.M., Ogg, J.G., Schmitz, M.D., Ogg, G.M. eds., The Geologic Time Scale 2012, vol. 2. Elsevier BV, Amsterdam, 437–488.

Pickett, J.W. and Jell, P.A., 1983.Middle Cambrian Sphinctozoa (Porifera) from New South Wales.*Memoirs of the Association of Australasian Paleontologists*, 1: 85–92

Pouille, L., Obut O., Danelian T. et al., 2011, Lower Cambrian (Botomian) polycystine Radiolaria from the Altai Mountains (southern Siberia, Russia).*Competes Rendus Palevol*, 10(8): 627–633

Shu, D., Chen, L., 1989. Discovery of Early Cambrian radiolarian and its significance. *Science in China*, 32(8): 986–994

White, R.D., 1986, Cambrian Radiolaria from Utah.*Journal of Paleontology*, 60(3): 778–780

Wrona, R. 2004. Cambrian microfossils from glacial erratics of King George Island, Antarctica. *Acta Palaeontologica Polonica*, 49 (1): 13–56

Wu, W., Zhu, M., Steiner, M., 2014. Composition and tiering of the Cambrian sponge communities. *Palaeogeography Palaeoclimatology Palaeoecology*, 398(398): 86–96

Won, M.Z., Below, R., 1999. Cambrian Radiolaria from the GeorginaBasin, Queensland, Australia. *Micropaleontology*, 45(4): 325–363

Yang, B., Steiner, M., Li, G., et al., 2014. Terreneuvian small shelly faunas of East Yunnan (South China) and their biostratigraphic implications. *Palaeogeography Palaeoclimatology Palaeoecology*, 398(2014): 28-58

Yin, H., Zeng, Y., Xia, W., 1994. Chert on the Southeast continental margin of the Yangtze platform. *Acta Geologica Sinica*, 68(2): 132–141 (in Chinese with English abstract)

Yin, L., Wang C., Zhao, Y. et al., 2016. Early–Middle Cambrian Palynomorph Microfossils and Related Geochemical Events in South China. *Journal of Earth Science*, 27(2): 180–186

Zhang, L., Danelian, T., Feng, Q.L., et al., 2013.On the Lower Cambrian biotic and geochemical record of the Hetang Formation (Yangtze Platform, South China): evidence for biogenic silica and possible presence of Radiolaria.*Journal of Micropaleontology*, 32(2): 207–217

Zhang, X., Aldridge, R. J., 2007. Development and diversification of trunk plates of the lower Cambrian lobopodians. *Palaeontology*, 50(2): 401–415

Zhang, X., Cui, L., 2016. Oxygen requirements for the Cambrian explosion. *Journal of Earth Science*, 27(2):187–195

Zhang, X., Pratt, B., 1994. New and extraordinary Early Cambrian sponge spicule assemblage from China. *Geology*, 22(1): 43–46

Zhang, X., Shu, D., Han, J., et al., 2014.Triggers for the Cambrian explosion: Hypotheses and problems.*Gondwana Research*, 25(3): 896–909

Zhao, G., 1999. The influence of biogenic procession on the accumulation and precipiation of silica—an example from south of Anhui and west of Zhejiang. *Acta Sedimentologica Sinica*, 17(1): 30–37 (in Chinese with English abstract)

Zheng, N., Song, T., Li, Y., et al., 2012. The discovery of the Lower Cambrian and Middle Ordovician Radiolaria in the Souuth China orogenic belt. *Geology in China*, 39(1): 260–265 (in Chinese with English abstract)

Zhou C., Jiang S., 2009. Palaeoceanographic redox environments for the lower Cambrian Hetang Formation in South China: Evidence from pyrite framboids, redox sensitive trace elements, and sponge biota occurrence.*Palaeogeography, Palaeoclimatology, Palaeoecology*, 271(4): 279–286