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Source: Paleontological Research, 23(4) : 261-280

Published By: The Palaeontological Society of Japan

URL: https://doi.org/10.2517/2018PR025

Paleontological Research, vol. 23, no. 4, pp. 261–280, October 1, 2019

doi:10.2517/2018PR025

The Guadalupian (Permian) Gufeng Formation on the north margin of the South China block: A review of the lithostratigraphy, radiolarian biostratigraphy, and geochemical characteristics

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Received March 23, 2018; Revised manuscript accepted December 17, 2018

Abstract. The Guadalupian (Permian) Gufeng Formation, distributed over the north margin of the South China block, is characterized by siliceous rock and muddy rock and yields several representative radiolarian fossils. The lithostratigraphy, radiolarian occurrences and biostratigraphy, and geochemical characteristics of the Gufeng Formation are reviewed and summarized in this paper. The distributional area of the Gufeng Formation is subdivided into the Lower, Middle, and Upper Yangtze regions. The Gufeng Formation in the Lower Yangtze region is lithostratigraphically characterized by muddy rock, chert, and nodule-bearing muddy rock in descending order. The Gufeng Formation in the Middle Yangtze region is lithostratigraphically characterized by chert, muddy rock with carbonate, and muddy rock in ascending order. The lithostratigraphic characteristics of the "Gufeng Formation" in the south margin of the South China block greatly differ from the typical Gufeng Formation in containing fewer siliceous rocks and a large amount of clastic rocks and in having a significantly greater total thickness; therefore, this article considers that the "Gufeng Formation" in the block's south margin should be isolated from the Gufeng Formation in the block's north margin. The radiolarian biostratigraphy of the Lower and Middle Yangtze regions is composed of the *Pseudoalbaillella globosa*, *Ps. monacantha*, and *Follicucullus scholasticus-Ruzhencevispongus uralicus* assemblage zones in ascending order. The lower Gufeng Formation has abundantly yielded the Albaillellaria; however, its occurrence ratio with respect to other radiolarian orders decreases stratigraphically upward. The geochemical characteristics indicate the following facts: (1) the siliceous rocks are generally biogenic; (2) even though a previous study concluded that the organic matter within the chert was originated from terrestrial or reworked organic matter, the origin remains debatable; and (3) the Gufeng Formation was formed on a continental shelf. The geochemical characteristics, in addition to the lithological characteristics, indicate that the redox conditions of the Gufeng Formation in the Lower Yangtze region changed from aerobic to suboxic to anoxic, while that in the Middle Yangtze region changed from oxic to anoxic to suboxic.

Key words: Gufeng Formation, lithology, radiolarian biostratigraphy, sedimentary environment, South China block

Introduction

The Permian period is one of the most diverse intervals during Earth's history (e.g. Hein, 2004) because a number of notable events occurred during this period, such as the most severe mass extinction in the Phanerozoic at the Guadalupian–Lopingian boundary and the end-Permian (Jin *et al.*, 1994; Stanley and Yang, 1994), multiple glaciations (e.g. Isbell *et al.*, 2011), a global cooling event termed the Kamura event (e.g. Isozaki *et al.*, 2007a, b), and a large amount of chert accumulation in the middle Permian termed the mid-Permian chert event (Murchey

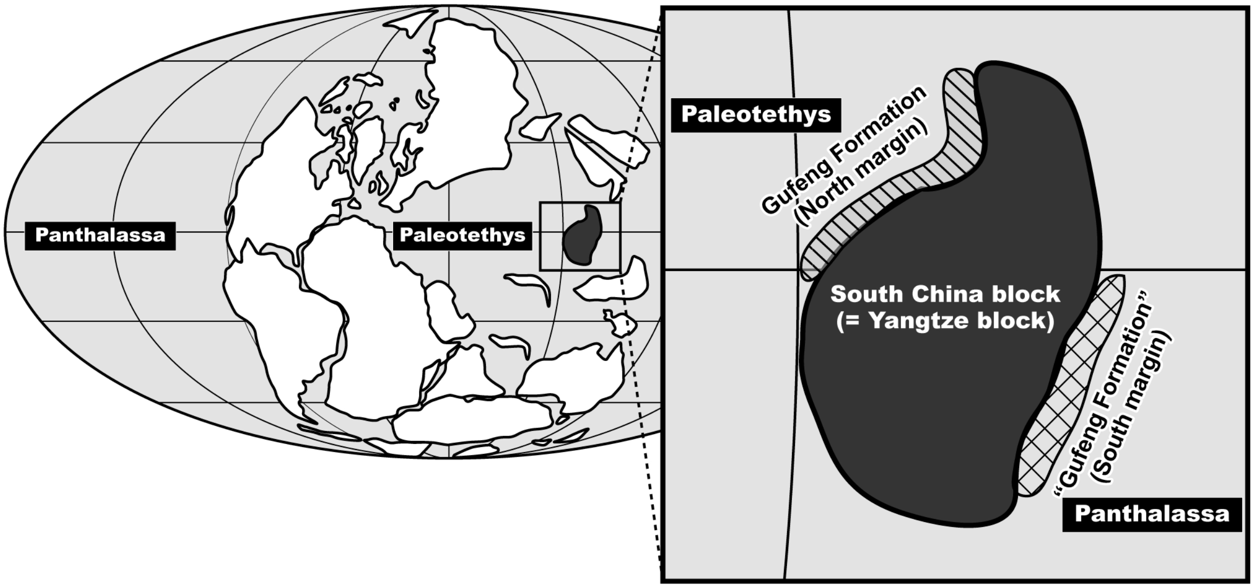

Figure 1. Guadalupian paleogeographic map, modified from Ziegler *et al.* (1997).

and Jones, 1992) or the Permian Chert Event (Beauchamp and Baud, 2002).

The Gufeng (Kuhfeng) Formation in South China has yielded Guadalupian (middle Permian) fossils of several kinds (e.g. ammonoids, brachiopods, and conodonts). In particular, the Gufeng Formation is known to have abundant radiolarian-bearing strata. This fossiliferous formation has attracted attention in recent years (e.g. Zhang *et al.*, 2019) because the formation may record paleobiological responses to environmental changes through the Permian. Yao *et al.* (2015) studied the fluctuation of chert bed thickness in the Gufeng Formation in relation to cyclic astronomical forcing of climate change, which in turn affected radiolarian productivity.

In addition, the Gufeng Formation is important from both paleogeographic and paleobiogeographic points of view. The Gufeng Formation consists of sediments on the South China block (Yangtze block). This block had been situated at the east end of the Paleotethys near the boundary between the superoceans Panthalassa and Paleotethys in the middle Permian (e.g. Ziegler *et al.*, 1997; Golonka and Ford, 2000) (Figure 1). Because the South China block acted as a wall between the both superoceans, a paleobiogeographic boundary has been recognized around the South China block for several groups such as fusulinids (e.g. Kobayashi, 1997), brachiopods (e.g. Shen *et al.*, 2009), and radiolarians (Ito *et al.*, 2016b).

Furthermore, the Gufeng Formation is known to have oil-rich strata; therefore, petrochemical studies have been performed (e.g. Xia *et al.*, 1995; Zeng *et al.*, 2004; Yang and Yao, 2008). Previous studies have focused on the porosity of the rocks in the Gufeng Formation as a reservoir rock (Wu *et al.*, 2012; Liang *et al.*, 2014). In recent years, its potential as an origin and reservoir of shale gas has also been a focus of study (Du *et al.*, 2015).

In short, the strata of the Gufeng Formation are extremely significant in terms of paleontology, sedimentology, paleogeography, paleobiogeography, and petroleum geology. Meanwhile, the formation has regional differences in several characteristics, such as lithostratigraphy and biostratigraphy. Due to these regional differences, even the definition and distributions of the formation have been debated (e.g. Hu, 2000; Kuwahara *et al.*, 2004; Yao *et al.*, 2007). On the basis of previous studies combined with ours, here we compile the lithostratigraphy, radiolarian occurrences with biostratigraphy, and geochemical characteristics of the Gufeng Formation in each region. This article aims to provide a general review of these aspects for future reference.

Lithostratigraphy

Definition and distribution

The Gufeng Formation was originally called the Gufeng Zhen Limestone at Hujia Village of Gufeng Town, Anhui Province by Ye and Li (1924) (Figure 2). The Bureau of Geology and Mineral Resources of Anhui Province (1997) re-defined the Gufeng Formation as follows (translated from the Chinese): It is characterized by black or gray-yellow thin-bedded siliceous rocks, siliceous shales, siltstones, carbonaceous shales, and manganese shales. The Gufeng Formation overlies the Qixia

	Author	Name	Definition
Original definition	叶良辅・李捷（1924）	孤峰镇石灰岩	为黑色灰质頁岩及硅质甚富之灰岩等，间干栖霞灰岩及龙潭煤系间，底部之灰质黑色页岩含化石极丰，其最著者为菊石及腕足类。
	Ye and Li (1924)	Gufeng Zheng Limestone	It is characterized by black carbonate shales and silica-rich carbonates, which are lithostratigraphically located between the Qixia and Longtan formations. Basal black shales include abundant fossils represented by ammonoids and brachiopods.
Emended definition	安徽省地质矿产局（1997）	孤峰組	指栖霞組与龙潭組之间的薄层状硅质岩、硅质页岩、粉砂质泥岩、碳质页岩、锰质页岩地层，下部页岩含锰及磷結核。 产菊石、腕足类、双壳类及放射虫等多门类化石。 底与栖霞組平行不整合接触，以厚层灰岩消失、含锰页岩出現为界； 頂与龙潭組整合接触，以薄层硅质岩消失、页岩出現为界。
	Bureau of Geology and Mineral Resources of Anhui Province (1997)	Gufeng Formation	It is characterized by black or gray-yellow thin-bedded siliceous rocks, siliceous shales, siltstones, carbonaceous shales, and manganese shales. The Gufeng Formation overlies Qixia Formation and underlies Longtan Formation. Basal shales include manganese and phosphate nodules. Several fossils (e.g. ammonoids, brachiopods, bivalves, and radiolarians) occur from it. The boundary with the underlying Qixia Formation is disconformity. The thick layered limestone disappears, and the manganese-bearing shale appears as the boundary. The boundary with the overlying Longtan Formation is conformity. The thin layer of siliceous rocks disappears, and the shale appears as the boundary.

Figure 2. Original and emended definitions of the Gufeng Formation. Note that the information by Ye and Li (1924) is re-quoted from Bureau of Geology and Mineral Resources of Anhui Province (1997). The English translations of the definitions have been made by the authors.

Formation and underlies the Longtan Formation. Basal shales include manganese and phosphate nodules. Several taxa of fossils (e.g. ammonoids, brachiopods, bivalves, and radiolarians) occur from it.

The respective bureaus of geology and mineral resources in each province of China have compiled regional geologies for their provinces. The columnar sections of the stratotype and hypostratotype sections established by the bureaus with some notable sections are summarized in Figures 3 and 4. The Bureau of Geology and Mineral Resources of Anhui Province (1997) established the Hujia section (30°50′N, 118°24′E) in Gufeng as the stratotype section of the Gufeng Formation. In other provinces, the respective bureaus of geology and mineral resources established hypostratotype sections of the Gufeng Formation: the Lengwu section (29°55′N, 119°32′E) in Tonglu (Bureau of Geology and Mineral Resources of Zhejiang Province, 1996), the Hechong section (32°09′N, 119°06′E) in Jurong (Bureau of Geology and Mineral Resources of Jiangsu Province, 1997), the Bijiashan section (30°12′N, 114°47′E) in Daye (Bureau of Geology and Mineral Resources of Hubei Province, 1996), and the Lengshuixi section in Shizhu (Bureau of Geology and Mineral Resources of Sichuan Province, 1997).

The Gufeng Formation is distributed over the north margin of the South China block (Figure 3). Its distributional area is subdivided into three regions: the Lower Yangtze region (northern Zhejiang, southern Jiangsu, and south Anhui), the Middle Yangtze region (Hubei), and the Upper Yangtze region (Shaanxi and northern Sichuan). Previous studies have also considered siliceous rocks on the south margin of the South China block (southern Hunan, northwestern Guangdong, and eastern Guangxi) to be part of the Gufeng Formation. However, the so-called "Gufeng Formation" in the block's south margin differs from the typical Gufeng Formation in the north margin in its lithostratigraphy, as will be described in detail. We therefore regard the Gufeng Formation as being distributed only over the north margin.

Lithology and its correlations

North margin.—The Hujia section in Gufeng, the stratotype section of the Gufeng Formation, is divided into the following subsections in ascending order (Bureau of Geology and Mineral Resources of Anhui Province, 1997): subsection 1: brownish-black manganese mudstone; subsection 2: yellow mudstone, interbedding gray siliceous mudstone and thin-bedded chert; subsection 3: yellow mudstone including gray phosphate muddy nodules; subsection 4: gray siliceous mudstone; subsection 5: black thin-bedded chert interbedding black thin-bedded

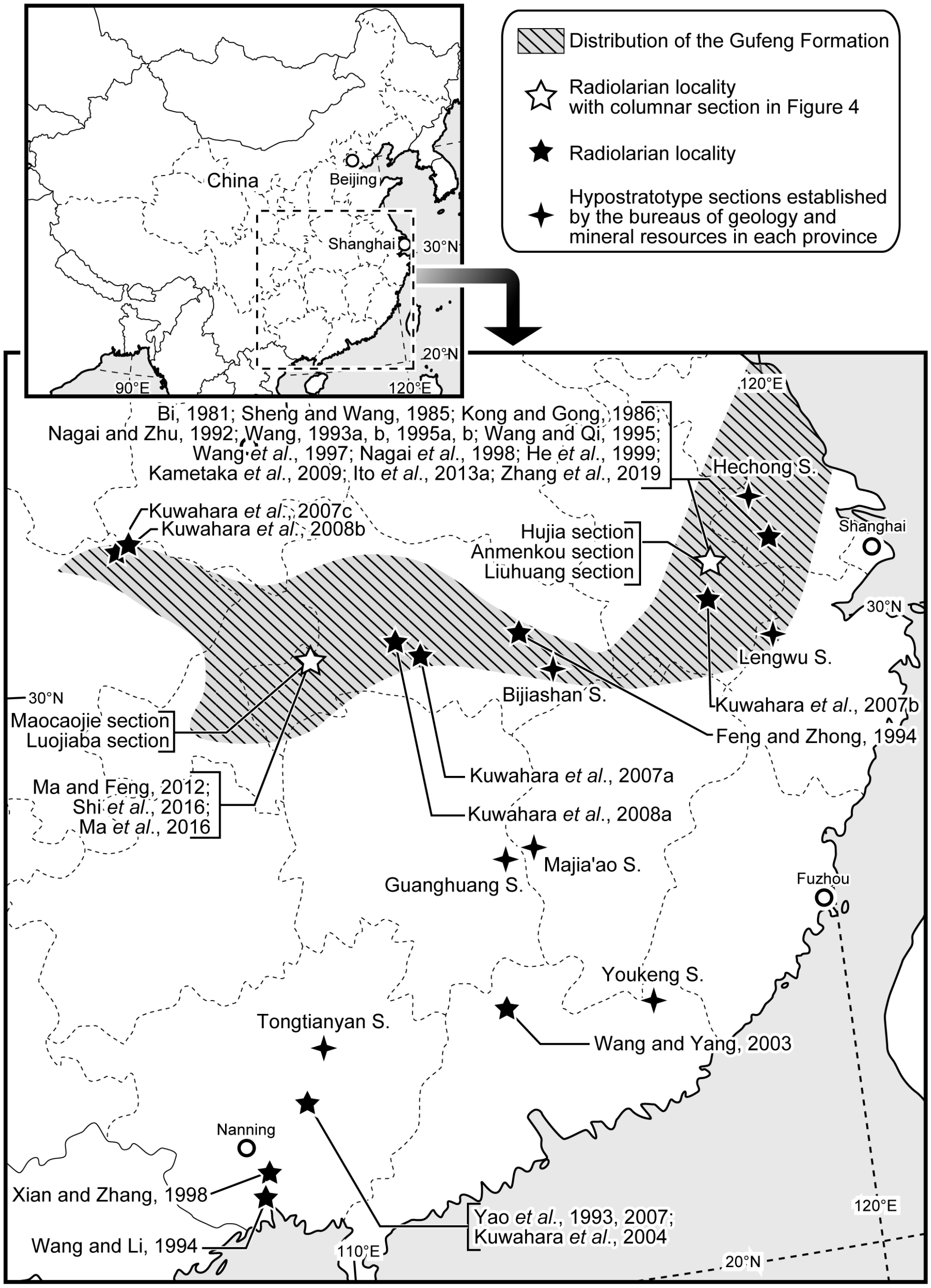

Figure 3. Distributions of the Gufeng Formation with the major localities of sections and the radiolarian localities from previous studies. The distributions are based on Wu *et al.* (2015). Detailed location of the Lengshuixi section in Shizhu was not shown by Bureau of Geology and Mineral Resources of Sichuan Province (1997); therefore, the location is not presented.

siliceous mudstone; and subsection 6: black thin-bedded siliceous mudstone interbedding carbonaceous mudstone. The Gufeng Formation of the section conformably contacts with the underlying Qixia and overlying Longtan formations.

The Gufeng Formation at Chaohu in Anhui has been studied in detail mainly by a research group of Nagoya University and Nanjing University (Nagai and Zhu, 1992;

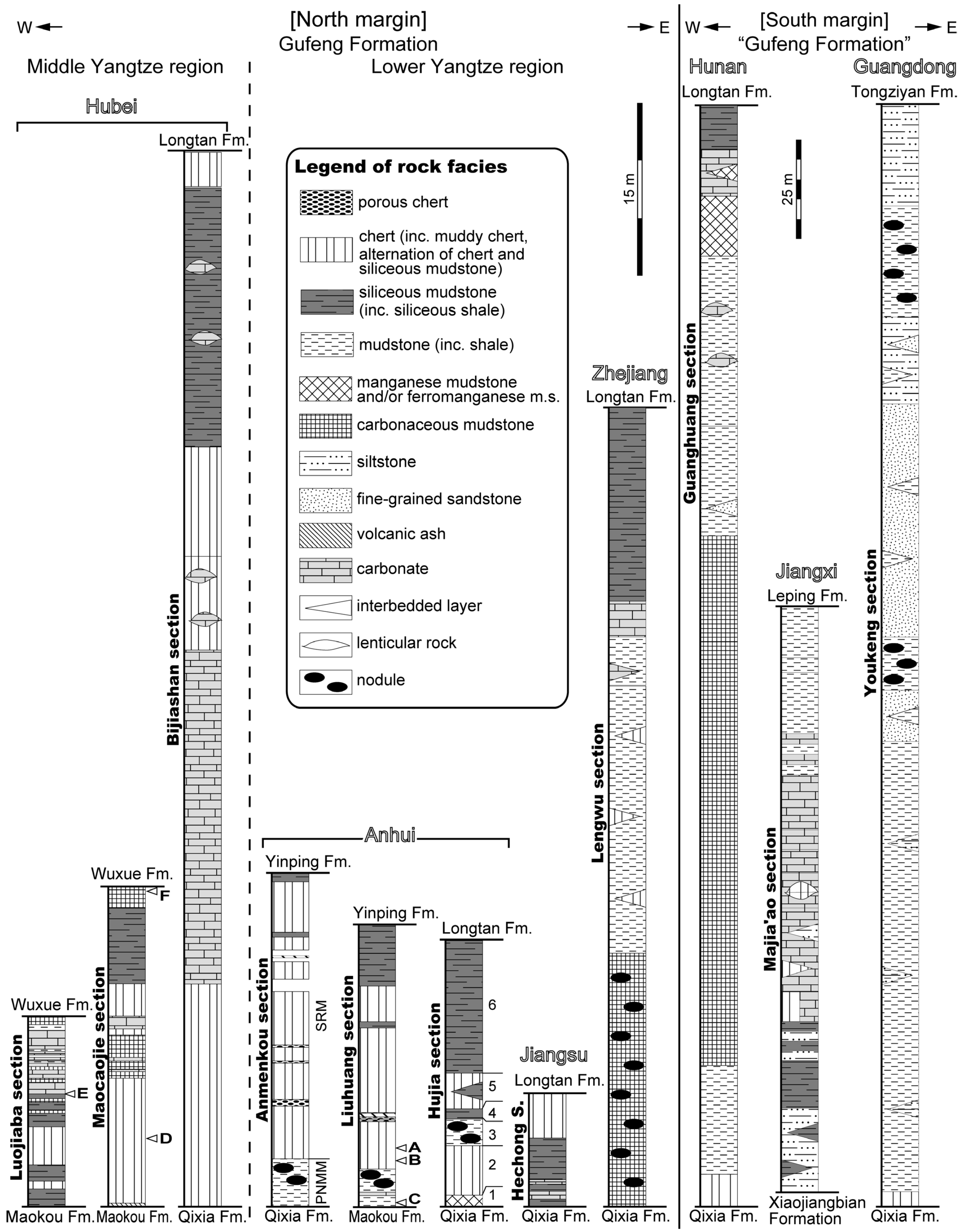

Figure 4. Lithostratigraphy of the stratotype section of the Gufeng Formation in Anhui Province and the hypostratotype sections in the Hubei, Jiangsu, Zhejiang, Hunan, and Guangdong provinces with major sections. White triangles with capital letters indicate occurrence horizons of each photograph of Figure 5.

Nagai *et al.*, 1998; Zhu *et al.*, 1999; Kametaka *et al.*, 2002, 2005, 2009; Takebe *et al.*, 2007). Kametaka *et al.* (2002) and Kametaka *et al.* (2005) divided the Gufeng Formation of the Anmenkou section at Chaohu into two members: the Phosphate Nodule-bearing Mudstone Member (PNMM) and the Siliceous Rock Member (SRM) in ascending order. The former (*ca.* 4 m in total thickness) consists of mudstone including abundant phosphate nodules; the latter (*ca.* 25 m) is composed primarily of alternations of black chert, mudstone, and siliceous mudstone, with minor tuffaceous mudstone and porous chert beds. Ito *et al.* (2013a) investigated the Liuhuang section near the Anmenkou section and detected a lithologic similarity between the Liuhuang and Anmenkou sections. In the Liuhuang section, the siliceous rock is dark-colored (black to dark-gray) and well bedded (Figure 5A, B). The Gufeng Formation disconformably contacts with the limestone of the underlying Maokou Formation in the Liuhuang section (Figure 5C). Zhang *et al.* (2019) investigated the Hexian core drilled at Hexian 50 km northeast of Chaohu and subdivided the Gufeng Formation in the core into three members, the Lower Phosphate Nodule-bearing Mudstone Member (LPMM), the Lower Chert-Mudstone Member (LCMM), and the Upper Mudstone Member (UMM), with the Lower Shale Member (LSM) of the Yinping Formation. The LPMM and LCMM can be lithostratigraphically correlated to the PNMM and SRM, respectively.

Porous chert (Kametaka *et al.*, 2005; nectic chert in Zhu *et al.*, 1999 and Kametaka *et al.*, 2002) is a remarkable rock in the Gufeng Formation in the Lower Yangtze region. As its name suggests, the porous chert has abundant small cavities and shows a spongy structure compared to commonly known normal chert, which is characterized by being dense and nonporous. The bulk specific gravity of the porous chert is only 1.1–1.2 (Kametaka *et al.*, 2005). The porous chert is interbedded in the normal chert beds and is generally thicker than the normal chert beds.

Ma *et al.* (2016) and Shi *et al.* (2016) studied the lithostratigraphy of the Luojiaba and Macaojie sections near Jianshi, western Hubei, respectively. The Gufeng Formation in both sections consists primarily of siliceous and muddy rocks. The lower parts of the Gufeng Formation in both sections are characterized by the dominance of dark-colored well bedded chert (Figure 5D), whereas the upper parts are characterized by muddy rock with carbonate (Figure 5E). The Gufeng Formation in both sections is conformably covered by the limestone of the Wuxue Formation (Figure 5F). In these sections, the Gufeng Formation conformably overlies the Maokou Formation. Meanwhile, Chen *et al.* (2000) observed clastic rocks in the basal part of the Gufeng Formation at Huangyan in Jianshi and concluded that the Gufeng Formation unconformably overlies the Maokou Formation there. The Bijiashan section contains thick carbonate rocks and is much thicker than the Luojiaba and Macaojie sections. This may indicate that the Bijiashan section represents a shallower facies.

In short, the Gufeng Formation in the north margin is characterized by siliceous and muddy rocks. Lithostratigraphy of the Gufeng Formation in the Lower Yangtze region comprises muddy rock, chert, and muddy rock with nodules in descending order whereas that in the Middle Yangtze region consists of chert, muddy rock with carbonate, and muddy rock in ascending order.

South margin.—The bureaus of geology and mineral resources in Hunan, Jiangxi, Guangxi, and Guangdong established hypostratotype section of the Gufeng Formation in each province: the Guanghuang section (27°17′N, 113°41′E) in You (Bureau of Geology and Mineral Resources of Hunan Province, 1997), the Majia'ao section (27°16′N, 113°53′E) in Lianhua (Bureau of Geology and Mineral Resources of Jiangxi Province, 1997), the Tongtianyan section in Liuzhou (Bureau of Geology and Mineral Resources of Guangxi Zhuang Autonomous Region, 1997), and the Youkeng section (24°32′N, 116°09′E) in Jianling (Bureau of Geology and Mineral Resources of Guangdong Province, 1996).

These sections are characterized by a great quantity of clastic rocks, such as carbonaceous mudstone, mudstone, and sandstone, with little chert (Figure 4). The typical Gufeng Formation in the north margin, however, is characterized by siliceous and muddy rocks as mentioned previously. We therefore believe that the "Gufeng Formation" in the south margin should be isolated from the Gufeng Formation and given another formation name.

Hu (2000) argued that the Gufeng Formation is also distributed over the south margin of the South China block based on discussions including fossil data. However, the Gufeng Formation is a lithostratigraphic unit. According to the International Stratigraphic Guide (Murphy and Salvador, 1999), "Lithostratigraphic units are defined and recognized by observable physical features and not by their inferred age, the time span they represent, inferred geologic history, or manner of formation."

Radiolarian occurrences

The Gufeng Formation contains several kinds of macrofossils and microfossils, such as conodonts (e.g. Ching, 1960; Wang, 1995a; Kuwahara *et al.*, 2008a; Ma *et al.*, 2016), foraminifers (e.g. Wang, 1993c), brachiopods (e.g. Jing and Hu, 1978; Xu *et al.*, 2004), sponge spicules (e.g. Kuwahara *et al.*, 2007b; Ito *et al.*, 2016e), mollusks (e.g. Xi, 1982; Kametaka *et al.*, 2009), and fish microremains

Figure 5. Field occurrences of the Gufeng Formation. **A, B,** black bedded chert in the Liuhuang section in Chaohu, Anhui; **C,** overturned basal mudstone and stratigraphically overlying limestone of the Maokou Formation in the Liuhuang section; **D,** black bedded chert of the Maocaojie section in Jianshi, Hubei; **E,** mudstone including lenticular limestone in the Luojiaba section in Jianshi; **F,** carbonaceous mudstone and stratigraphically overlying limestone of the Wuxue Formation in the Maocaojie section. The occurrence horizons of each correspond to the white triangles in Figure 4.

<table>
<tr><th colspan="2" rowspan="3">Age</th><th rowspan="3">Southwest Japan (Ishiga, 1986, 1990; Kuwahara et al., 1998)</th><th rowspan="3">South China (Wang and Yang, 2007, 2011)</th><th colspan="3">North margin</th><th colspan="2">South margin</th></tr>
<tr><th colspan="3">Gufeng Formation</th><th colspan="2">“Gufeng Formation”</th></tr>
<tr><th>Upper Yangtze Region (Shichuan) (Kuwahara et al., 2007c, 2008b)</th><th>Middle Yangtze Region (Hubei) (Feng and Zhong, 1994; Kuwahara et al., 2007a, 2008a; Ma and Feng, 2012; Ma et al., 2016; Shi et al., 2016)</th><th>Lower Yangtze Region (Anhui and Jiansu) (e.g. Sheng and Wang, 1985; Wang and Qi, 1995; Wang et al., 1997; He et al., 1999; Kuwahara et al., 2007b; Kametaka et al., 2009; Ito et al., 2013a)</th><th>Guangxi (Yao et al., 1993; Wang and Li, 1994; Xian and Zhang, 1998; Kuwahara et al., 2004)</th><th>Guangdong (Wang and Yang, 2003)</th></tr>
<tr><td rowspan="7">Permian</td><td>Lopingian (part)</td><td>Follicucullus charveti-Albaillella yamakitai Assemblage Zone</td><td>F. bipartitus-F. charveti-F. orthogonus Assemblage Zone</td><td></td><td></td><td></td><td>F. charveti-A. yamakitai Assemblage Zone</td><td rowspan="3"></td></tr>
<tr><td rowspan="3">Guadalupian</td><td>F. ventricosus-F. scholasticus Assemblage Zone</td><td>F. scholasticus-F. ventricosus Assemblage Zone</td><td>F. scholasticus-R. uralicus Assemblage Zone</td><td>F. scholasticus Assemblage Zone</td><td>F. scholasticus-R. uralicus Assemblage Zone</td><td>F. ventricosus-F. scholasticus Assemblage Zone</td></tr>
<tr><td>Ps. monacantha Range Zone</td><td>Ps. monacantha Range Zone</td><td></td><td>Ps. monacantha Assemblage Zone</td><td>Ps. monacantha Assemblage Zone</td><td rowspan="2"></td></tr>
<tr><td>Ps. globosa Assemblage Zone</td><td>Ps. globosa Range Zone</td><td>Ps. longtanensis-Ps. fusiformis Assemblage Zone</td><td>Ps. globosa- Assemblage Zone</td><td>Ps. longtanensis-P. fusiformis Assemblage Zone</td><td>Ps. fusiformis-Ps. globosa Assemblage Zone</td></tr>
<tr><td rowspan="3">Cisuralian (part)</td><td>Ps. longtanensis Assemblage Zone</td><td>Ps. Ishigai Abundance zone</td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td><td>P. banchengensis Assemblage Zone</td><td rowspan="3"></td></tr>
<tr><td>A. sinuata Range Zone</td><td>A. sinuata Abundance Zone
A. xiaodongensis Range Zone</td><td>Albaillella sinuata Assemblage Zone</td></tr>
<tr><td>Ps. scalprata m. rhombothoracata Assemblage Zone</td><td>Ps. rhombothoracata Assemblage Zone</td><td>P. scalprata Assemblage Zone</td></tr>
</table>

Figure 6. Summarized radiolarian zones of the Gufeng Formation in each province in previous studies. Note that the *Follicucullus monacanthus* Zone is changed to the *Pseudoalbaillella monacantha* Zone according to the taxonomic reconsideration by Ito *et al.* (2015). *F.*, *Follicucullus*; *R.*, *Ruzhencevispongus*; *Ps.*, *Pseudoalbaillella*; *A.*, *Albaillella*.

(e.g. Kuwahara *et al.*, 2007b; Mao *et al.*, 2013).

Since the 1980s, radiolarian occurrences have been reported in the Gufeng Formation in several areas. On that basis, radiolarian zones have been constructed. Meanwhile, an integrated radiolarian biostratigraphy has been compiled in Southwest Japan (Ishiga, 1986, 1990; Kuwahara *et al.*, 1998) and South China (Wang and Yang, 2007, 2011). The radiolarian zones of Southwest Japan, South China, the Gufeng Formation in the north margin, and the “Gufeng Formation” in the south margin are summarized in Figure 6.

Radiolarian biostratigraphy of the north margin

Bi (1981) found spherical radiolarians in thin sections from the Tianbaoshan section in southeast Nanjing, Jiangsu, which was probably the first report of radiolarians from the Gufeng Formation. Sheng and Wang (1985) derived radiolarian fossils from siliceous rocks in the Longtan area in Nanjing using the hydrofluoric acid method and revealed radiolarian microphotographs via scanning electron microscopy (SEM) for the first time. Since these studies, several researchers have reported radiolarian occurrences in the Gufeng Formation in the Lower Yangtze region (Kong and Gong, 1986; Nagai and Zhu, 1992; Wang, 1993a, b, d, 1995b, c; Jiang *et al.*, 1994; Wang and Qi, 1995; Wang *et al.*, 1997; Nagai *et al.*, 1998; He *et al.*, 1999; Kuwahara *et al.*, 2007b; Kametaka *et al.*, 2009; Ito *et al.*, 2013a; Zhang *et al.*, 2019). Sheng and Wang (1985) constructed the *Pseudoalbaillella scalprata-Ps. nanjingensis* and *Phanicosphaera mammilla* assemblage zones, in ascending order. Wang (1995c) found the first occurrence of *Follicucullus monacanthus* Ishiga and Imoto in the Gufeng Formation. Wang (1995b) discussed the age assignment of *F. monacanthus* and concluded that the *F. monacanthus* assemblage from the Gufeng Formation corresponds to that of the *F. monacanthus* Zone of Japan and the USA. (Ishiga, 1986, 1990; Blome and Reed, 1992). Wang and Qi (1995) constructed the following assemblage zones: *Ps. fusiformis-Ps. longtanensis*, *F. monacanthus*, and *Ruzhencevispongus uralicus-F. scholasticus* in ascending order. Since the study by Wang and Qi (1995), the Gufeng Formation in the Lower Yangtze region has been divided into three radiolarian assemblage zones (e.g. He *et al.*, 1999; Kametaka *et al.*, 2009; Ito *et al.*, 2013a).

Feng (1992) discovered radiolarians in the Wuchan area, which was the first radiolarian report from the Gufeng Formation in the Middle Yangtze region. Since this study, several researchers have reported radiolarian occurrences in this region (Feng and Zhong, 1994; Kuwahara *et al.*, 2007a, 2008a; Ma and Feng, 2012; Ma *et al.*, 2016; Shi *et al.*, 2016). Ma and Feng (2012) constructed the *Pseudoalbaillella globosa*, *Follicucullus monacanthus*, and *F. scholasticus* assemblage zones in ascending order.

The radiolarian zonation of the Lower Yangtze and Middle Yangtze regions are well correlated based on the lineage from *Pseudoalbaillella* Holdsworth and Jones to *Follicucullus* Ormiston and Babcock in the Guadalupian (e.g. Ishiga *et al.*, 1982; Wang and Yang, 2011; Zhang *et al.*, 2014; Ito *et al.*, 2015, 2016a).

In the Upper Yangtze region, fewer radiolarian studies have been performed compared to the Lower and Middle Yangtze regions. Kuwahara *et al.* (2007c) found *Copicyntra*? sp. and *Copiellintra*? sp. in the Gufeng Formation of the Mingyuexia 1 section in northern Sichuan. They also found *Pseudoalbaillella* cf. *longtanensis* Sheng and Wang and *Ps. fusiformis* (Holdsworth and Jones) from the uppermost part of the Maokou Formation just below the Gufeng Formation in that section. Kuwahara *et al.* (2008b) found *Ps. fusiformis* and *Follicucullus* cf. *scholasticus* Ormiston and Babcock in the Chejiaba section in Chaotian, northern Sichuan.

Radiolarian biostratigraphy of the south margin

The first occurrence of a radiolarian fossil from the "Gufeng Formation" in the south margin of the South China block was reported by Yao *et al.* (1993). They surveyed Late Paleozoic strata in Guizhou and Guangxi and obtained *Follicucullus scholasticus*, *Latentifistula* sp., and *Pseudoalbaillella* sp. from the "Gufeng Formation" in the Tongtianyan section in Guangxi. Wang and Li (1994) found *F. charveti* Caridroit and De Wever, *F. bipartitus* Caridroit and De Wever, and *Albaillella triangularis* Ishiga, Kito, and Imoto, corresponding to radiolarians of the *F. bipartitus-F. charveti* Assemblage Zone in Southwest Japan (Ishiga, 1986, 1990). Xian and Zhang (1998) researched the Bancheng area in Guangxi and constructed the following ascending radiolarian zones: *Ps. scalprata*, *A. sinuata*, *Ps. banchengensis*, *Ps. globosa-Ps. fusiformis*, *F. monacanthus*, and *F. scholasticus*. According to Xian and Zhang (1998), these zones correspond to radiolarian zones in Southwest Japan found by Ishiga (1986, 1990). However, judging from the text and figures of Xian and Zhang (1998), some of the radiolarian zones they constructed do not correspond directly to the radiolarian zones of Ishiga (1986, 1990). For example, *F. scholasticus*, which is a characteristic species of the *F. scholasticus* Assemblage Zone of Ishiga (1986, 1990), occurred in the *Ps. globosa-Ps. fusiformis* and *F. monacanthus* zones of Xian and Zhang (1998). The *A. sinuata* Zone of Ishiga (1986, 1990) is a range zone defined by the occurrence of *A. sinuata*. However, Xian and Zhang (1998) divided the *A. sinuata*-bearing strata of their section into the *A. sinuata* and *Ps. banchengensis* assemblage zones. Comparing the radiolarian zonation of Ishiga (1986, 1990) with that of Xian and Zhang (1998), the *Ps. longtanensis* Assemblage Zone, the *Ps. globosa* Assemblage Zone, and the *F. monacanthus* Range Zone of Ishiga (1986, 1990) are absent in the section of Xian and Zhang (1998). The Qinfang area, including the Bancheng area, is known as an orogenic belt in the late Paleozoic (e.g. He *et al*., 2014; Ke *et al*., 2018), and orogeny might cause the absence of some biozones.

Kuwahara *et al.* (2004) found *Albaillella yamakitai* from the Tongtianyan section, Guangxi, which is a characteristic species of the *Follicucullus charveti-A. yamakitai* Assemblage Zone. It has been proposed that the base of the Lopingian of the radiolarian biostratigraphy is defined by the first occurrence of *A. yamakitai* or just below it (e.g. Mitsumura and Kamata, 2009; Nishikane *et al.*, 2011). This indicates that the top of the "Gufeng Formation" in Guangxi should reach the uppermost Guadalupian.

Wang and Yang (2003) found *Pseudoalbaillella fusiformis* and *Ps. globosa* in the Renhua area in Shaoguan, Guangdong. They constructed the *Ps. fusiformis-Ps. globosa* Zone corresponding to the *Ps. fusiformis-Ps. longtanensis* Zone in the Lower Yangtze region.

Stratigraphic change of radiolarian fauna

Stratigraphic change of radiolarian fauna has been clearly recognized in the Gufeng Formation in the north margin. Sheng and Wang (1985) divided radiolarians from the Longtan area into two faunas in ascending order: *Pseudoalbaillella* and *Phanicosphaera*. Kametaka *et al.* (2009) showed that Albaillellaria decrease but Latentifistularia increase upward in the Anmenkou section. Ito *et al.* (2013a) also recognized a similar pattern in the Liuhuang section. In the Middle Yangtze regions, Albaillellaria occur in the lower parts of the Gufeng Formation, but rarely occur in the upper part (Shi *et al.*, 2016).

The radiolarian componential ratio at the order level (Albaillellaria, Latentifistularia, Entactinaria, and Spumellaria) has been used as an indicator of water depth (e.g. Kozur, 1993; Kuwahara, 1999). Kametaka *et al.* (2009) referred to these studies; however, they pointed out that the chief cause of the radiolarian faunal change in the Gufeng Formation in the Anmenkou section is not change in the water depth. This is because there are no remarkable lithological changes in the Anmenkou section. In other words, the depth of deposition of the Anmenkou section would have had to change by several hundreds of meters in order to be a critical factor for the faunal change.

Recently, Xiao *et al.* (2017) studied the latest Permian radiolarian vertical distribution based on a correspondence analysis. Their result suggests that radiolarians

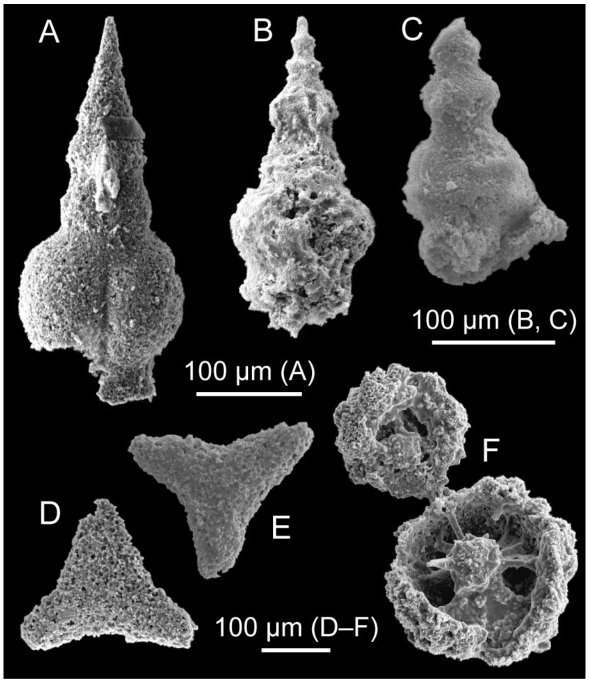

Figure 7. SEM images of major remarkable radiolarians from the Gufeng Formation (reprinted from Ito *et al.*, 2013a, reproduced with permission). **A, B,** *Longtanella* cf. *zhengpanshanensis* Sheng and Wang; **C,** *Longtanella* sp.; **D, E,** *Ruzhencevispongus uralicus* Kozur; **F,** *Hegleria* cf. *mammilla* (Sheng and Wang).

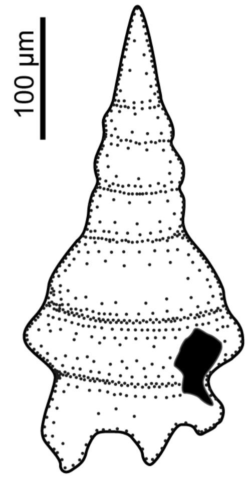

Figure 8. Sketch of a holotype specimen of *Longtanella zhengpanshanensis* Sheng and Wang, type species of the genus *Longtanella* Sheng and Wang (drawn from Sheng and Wang, 1985).

characterized different water depths at the species level even in the same order. Likewise, further studies on radiolarian vertical distributions in the middle Permian are necessary to understand the faunal change in the Gufeng Formation.

Remarkable radiolarian occurrences

In this section, we focus on remarkable radiolarian taxa and forms from primarily taxonomic and paleobiogeographic points of view, combined with our previous studies in other areas.

Longtanella *Sheng and Wang*.—*Longtanella* is likely an endemic genus of the Gufeng Formation (Figure 7A–C). *Longtanella* generally occurs in the chert of the Gufeng Formation of the Lower Yangtze (Wang, 1993a; Kametaka *et al.*, 2009; Ito *et al.*, 2013a) and Middle Yangtze (Feng, 1992; Shi *et al.*, 2016) regions. This genus also occurs in the chert of the "Gufeng Formation" in the south margin (Xian and Zhang, 1998). Probable *Longtanella* occurs in the Sa Kaeo Formation in the Sra Kaeo suture zone in eastern Thailand (Saesaengseerung *et al.*, 2009) and the Kamiaso Unit in central Japan (Ito *et al.*, 2016d).

The taxonomy of *Longtanella*, however, is currently debatable. Since Sheng and Wang (1985) described the genus, subsequent studies mainly in China have used this taxonomic name (e.g. Kozur and Mostler, 1989; Feng, 1992; Wang, 1993a; Kametaka *et al.*, 2009; Ito *et al.*, 2013a; Shi *et al.*, 2016; Xiao *et al.*, 2018). Meanwhile, several previous studies have synonymized this genus with *Pseudoalbaillella* (e.g. De Wever *et al.*, 2001; Nestell and Nestell, 2010) or *Parafollicucullus* Holdsworth and Jones (Noble *et al.*, 2017). *Longtanella* was diagnosed as "Shell smooth, straight, bilaterally symmetrical turriformis. The shell wall divided into the spire, the turri-body and the turri-bottom composed of ring-like swollen segments. Last segment constrictive, with 4 flaps vertically extending downward" (Sheng and Wang, 1985, p. 179). According to the diagnosis, description, and holotype (Figure 8) of *Longtanella*, the genus seems to differ from *Pseudoalbaillella* and *Parafollicucullus* in lacking a winged pseudothorax and having four flaps. Further detailed observations are needed to solve this taxonomic problem.

Ruzhencevispongus uralicus *Kozur*.—*Ruzhencevispongus uralicus* is a characteristic species of the upper part of the Gufeng Formation (e.g. Wang, 1993a, b, 1995c; Wang and Qi, 1995; Kametaka *et al.*, 2009; Ito *et al.*, 2013a). This species possesses a triangular platy spongy shell (Kozur, 1980) (Figures 7D, 7E). Wang (1993d) examined the morphology of *R. uralicus* with samples from Chaohu and Hushan. He divided this species into three morphotypes, namely *triadiatus*, *subtriadiatus*, and *uralicus*. Even though *Ruzhencevispongus* commonly occurs in South China including in the Gufeng Formation, only a few such occurrences have been reported in Southwest

Japan (e.g. Ishiga, 1990).

Hegleria *Nazarov and Ormiston*.—Occurrences of this genus have been reported worldwide, and this genus is seemingly a cosmopolitan taxon. However, there are similar outer-shaped radiolarians in the Permian. Ito *et al.* (2017c) stated these radiolarians as "*Hegleria*-shaped" radiolarians. The inner structure is important to identify "*Hegleria*-shaped" radiolarians. *Hegleria* has multiple internal rays that connect a central sphere to the outer shell (e.g. Noble and Jin, 2010) (Figure 7F). Several previous studies in the Gufeng Formation have shown radiolarians having this structure (e.g. Wang, 1993a, b, 1995c; Wang and Qi, 1995; Kametaka *et al.*, 2009; Ito *et al.*, 2013a), indicating that *Hegleria* surely occurred in the Gufeng Formation.

Meanwhile, "*Hegleria*-shaped" radiolarians having a concentric shell, probably *Paracopicyntra* spp., have also been discovered in the Gufeng Formation (e.g. Wang, 1993a, 1995b; Kametaka *et al.*, 2009). Further, Kametaka *et al.* (2009) reported "*Hegleria*-shaped" radiolarians having a discoidal form as *Hegleria* sp. aff. *H. mammilla*, which might be *Guiuva sashidai* Ito and Feng.

Pseudotormentus *De Wever and Caridroit.—Pseudotormentus* commonly occurs in deposits from the Panthalassa (e.g. De Wever and Caridroit, 1984; Blome and Reed, 1992, 1995; Mitsumura and Kamata, 2009; Nakae, 2011; Ito *et al.*, 2013b; Ito and Matsuoka, 2015a, b, 2016, 2018) but rarely occurs in deposits from the Paleotethys. The Gufeng Formation, comprised of deposits from the Paleotethys, has rarely yielded *Pseudotormentus*. Ito *et al.* (2016b) examined this uneven distribution of *Pseudotormentus* and pointed out the possibility that it is a facies-dependent genus of a Panthalassan equatorial warm current.

Kametaka *et al.* (2009), however, reported the common occurrence of *Pseudotormentus* in the Gufeng Formation in the Anmenkou section. On the basis of the hypothesis of Ito *et al.* (2016b), the Gufeng Formation of the Anmenkou section might have been locally affected by the Panthalassan equatorial warm current. Alternatively, other factors such as lithology might control the uneven distribution of *Pseudotormentus*.

Corythoecidae Nazarov.—No radiolarian fossils of the family Corythoecidae, characterized by a bilaterally symmetrical shell with a lateral foramen, have been discovered in the Gufeng Formation. Even though the occurrence of this family is very rare worldwide (De Wever *et al.*, 2001), Ito *et al.* (2017a) speculated that most species of the Corythoecidae occurred in phosphate-rich facies on the basis of a compilation of the previous occurrences and implied that this family preferred nutrient-rich conditions.

In the Lower Yangtze region, abundant phosphate nodules are contained in the lowermost part of the Gufeng Formation (e.g. Huang *et al.*, 1994; Kametaka *et al.*, 2009; Ito *et al.*, 2013a). Although no radiolarians have been obtained in this part of the Gufeng Formation, it might have the potential to yield species of the Corythoecidae if the hypothesis of Ito *et al.* (2017a) is correct.

Swollen type.—Dimorphic pairs, comprised of normal and swollen types, are known in some taxa of the Order Albaillellaria (e.g. Ishiga, 1991; Ito and Matsuoka, 2015b, 2017; Ito, 2017; Ito *et al.*, 2018). The swollen type is characterized by having a swollen apical portion. Ishiga (1991) suggested the possibility that the dimorphic pairs reflect alternating generations.

Previously, no occurrences of the swollen type have been reported from the Gufeng Formation; however, Xian and Zhang (1998) have reported the swollen type of *Albaillella sinuata* Ishiga and Watase and *Pseudoalbaillella globosa* Ishiga and Imoto in the "Gufeng Formation" in the Bancheng area.

Conjoined or malformed radiolarians.—Conjoined or malformed radiolarians are known in both living and fossil specimens (e.g. De Wever, 1985; Anderson and Gupta, 1998; Itaki and Bjørklund, 2007; Dumitrica, 2013; Afanasieva and Amon, 2016; Ito *et al.*, 2017b). Afanasieva and Amon (2016) classified the conjoined or malformed radiolarians as two types: conjoined radiolarians in which two or more individuals are joined together were named as a multiplicative type; radiolarians having double or branching structure (e.g. spine, arm) were named as a supplemental type.

Certain radiolarian specimens of the multiplicative type have never discovered from the Gufeng Formation so far. Meanwhile, a specimen from the Gufeng Formation in the Anmenkou section shown by Kametaka *et al.* (2009, p. 117, fig. 7.18, identified as *Ishigaum* sp.) possesses a branching arm. The specimen can be classified as one of the supplemental type of Afanasieva and Amon (2016).

Age assignments

The age of the Gufeng Formation has been calibrated primarily based on fossil data. Ching (1960) discovered the conodont *Jinogondolella nankingensis* (Ching) in the basal mudstones of the Gufeng Formation in the Longtan area, Jiangsu. Subsequent studies have found this species in the basal mudstones of the Gufeng Formation in the Lower Yangtze region (e.g. Wang, 1995a; Kametaka *et al.*, 2009). *Jinogondolella nankingensis* is an index species of the Roadian (Ogg *et al.*, 2016). Meanwhile, Kametaka *et al.* (2009) also found ammonoids *Shouchangoceras* sp. and *Erinoceras* sp. from mudstones of the lower PNMM in the Anmenkou section, Anhui. The ranges of *Shouchangoceras* and *Erinoceras* are contained in the Wordian and the Roadian–Wordian, respectively (Zhao and Zheng, 1977); therefore, Kametaka *et al.* (2009) concluded that the age of the lower PNMM is Wordian and that of the SRM is Wordian or younger.

Ma *et al.* (2016) correlated conodont and radiolarian biozones in the Luojiaba section in western Hubei. They concluded that the *Pseudoalbaillella globosa*, *Follicucullus monacanthus*, and *F. scholasticus* radiolarian zones could be directly correlated with the *Jinogondolella nankingensis gracilis*, *J. aserrata*, and *J. postserrata* conodont zones.

In addition to the fossil data, Zhu *et al.* (2013) reported zircon U–Pb ages of 272.0±5.5 Ma (MSWD = 2.6) and 271.5±3.3 Ma (MSWD = 1.7) separated from volcanic ash beds within the basal shale strata of the Gufeng Formation in the Chaohu area, Anhui. The age of the boundary between the Kungurian (Cisuralian) and Roadian (Guadalupian) is 272.3 Ma according to the 2016 geologic time scale (Ogg *et al.*, 2016), so that the zircon U–Pb ages can be correlated to the lowermost part of the Roadian. Zhang *et al.* (2010) correlated the conodont and radiolarian biozones across the Cisuralian-Guadalupian boundary and concluded that the base of the Roadian coincides with the first occurrence of *Ps. globosa*. Consequently, the zircon U–Pb ages are consistent with the fossil data, even though the taxonomy of *Pseudoalbaillella globosa* is debatable (Ito *et al.*, 2016c).

In short, the Gufeng Formation is nearly consistent with the Guadalupian based on conodonts and the zircon U–Pb ages. In particular, the base of the Gufeng Formation should be near the boundary between the Cisuralian and Guadalupian. However, the top of the Gufeng Formation is uncertain because of fewer fossil occurrences and lack of numerical age dating.

Geochemical characteristics

Geochemical studies on the Gufeng Formation have increased since the 1990s (e.g. Lu and Qu, 1990; Xia *et al.*, 1995; Yang and Feng, 1997). Siliceous rocks within the Maokou Formation, which is a heterotopic facies of the Gufeng Formation, have also been geochemically investigated (e.g. Zhou *et al.*, 2009).

Origin of siliceous rock

Most previous studies have concluded that the siliceous rocks of the Gufeng Formation on the north margin are biogenic. The Al–Fe–Mn diagram defined by Adachi *et al.* (1986) and Yamamoto (1987) has generally been used in speculations about the origin of chert in the Paleozoic and Mesozoic (e.g. Du *et al.*, 2007; Ito *et al.*, 2016f). Most researchers have applied this diagram to the chert of the Gufeng Formation. Most previous studies date the analyzed samples in the biogenesis field, or near it, in the Al–Fe–Mn diagram but not near the hydrothermal field (e.g. Kametaka *et al.*, 2005; Wang *et al.*, 2008; Yang and Yao, 2008; Han *et al.*, 2014). Meanwhile, a few studies have indicated the influence of hydrothermal activities in the Lower Yangtze region (Xia *et al.*, 1995; Xie *et al.*, 2013). Consequently, in general, a hydrothermal component barely contributed little to the composition of the rocks in the Gufeng Formation except in a few areas.

In contrast to the Yangtze region, a scattering of studies on the "Gufeng Formation" in the south margin indicate that the chert is likely hydrothermal. Fu *et al.* (2004) investigated the "Gufeng Formation" in Shaoyang in Hunan and showed that the chert plots in the hydrothermal field on the Al–Fe–Mn diagram. Shi *et al.* (2016) pointed out the differences in the chert formation processes between the north and south margins. Further research is necessary to interpret the origin of the siliceous rocks of the "Gufeng Formation" on the south margin because there are fewer studies pertaining to it compared to those on the Gufeng Formation in the north margin.

Origin of organic matter

In contrast to the studies on the origin of the siliceous rocks, a few studies have dealt with the origin of organic matter within the Gufeng Formation. Takebe *et al.* (2007) investigated organic matter in the black chert of the Anmenkou section using the van Krevelen diagram (atomic H/C ratio versus atomic O/C ratio). This diagram shows four types of kerogen according to the origin of the organic matter (van Krevelen, 1961). The analyzed data of Takebe *et al.* (2007) plotted in the field of type IV indicating reworked and highly oxidized organic material. Oxic weathering can cause an increase in the atomic O/C ratio of kerogen (e.g. Petsch *et al.*, 2000). However, due to several geochemical results, such as the small variation of the atomic O/C ratio, S enrichment, and the inclusion of pyrites, Takebe *et al.* (2007) concluded that the black chert was not affected by oxic weathering and originated from terrestrial or reworked organic matter.

However, considering the high degree of maturity estimated in a subsequent study, the analyzed data by Takebe *et al.* (2007) were likely not primary. In general, kerogens subjected to increasing thermal stress move toward the lower left corner of the van Krevelen diagram (Hunt, 1995). This tendency has been reported by laboratory experiments (e.g. Kotarba and Lewan, 2004; Lewan and Kotarba, 2014; Takahashi and Suzuki, 2017). According to the geochemical works by Du *et al.* (2015), the vitrinite reflectance (VR %) and Rock-Eval T_{max} of siliceous and muddy rocks in the Gufeng Formation have a range of 1.2–2.0% and 460–560°C, respectively. These values indicate a high degree of maturity. Under such a high degree of maturity, the van Krevelen diagram is not applicable to estimation of the origin of the organic matter.

The supply of terrestrial material to the Gufeng Formation is irrefutable due to several observed facts as mentioned in the previous section, such as the presence of intercalated clastics within the Gufeng Formation. The origin of the organic matter in the Gufeng Formation is debatable; therefore, further data such as the stable carbon isotopic composition of the organic matter are needed to discuss its origin.

Sedimentary environment

There had been speculations as to the sedimentary environment of the Gufeng Formation based on lithology and radiolarian faunal comparison. Kong and Gong (1987) postulated that the siliceous rocks of the Gufeng Formation were formed in a deep-sea environment resulting from rift faulting because the radiolarian fauna is similar to the Japanese assemblage. Zhu (1989) concluded that the Gufeng Formation was deposited in an intraplatformal environment. Since the 1990s, a geochemical approach to speculations about the sedimentary environment of the Gufeng Formation has been adopted. Such studies have generally concluded that the Gufeng Formation formed in a continental shelf environment (e.g. Kametaka *et al.*, 2005).

Murray (1994) placed the pelagic and continental margin fields in the Fe_2O_3/TiO_2 versus $Al_2O_3/(Al_2O_3+Fe_2O_3)$ diagram on the basis of chert from continental margin, pelagic, and ridge-proximal environments, ranging from the Early Paleozoic to the Neogene. To speculate about the sedimentary environment, the Murray diagram has been used (e.g. Hara *et al.*, 2010; Ito *et al.*, 2016f; Kemkin *et al.*, 2017). Most of the analyzed samples from the Gufeng Formation plot in the continental margin field in the diagram (e.g. Kametaka *et al.*, 2005; Wang *et al.*, 2008; Yang and Yao, 2008; Han *et al.*, 2014).

Redox conditions and changes

Redox conditions and changes during the deposition of the Gufeng Formation have been studied in detail, especially in the Lower Yangtze (Kametaka *et al.*, 2005) and the Middle Yangtze (Shi *et al.*, 2016) regions. In short, the redox condition of the Gufeng Formation in the Lower Yangtze region changed from aerobic to suboxic to anoxic, whereas that in the Middle Yangtze region changed from oxic to anoxic to suboxic. In this section, we focus on the Lower and Middle Yangtze regions based on the discussions and speculations of the previous studies.

The Anmenkou section in the Lower Yangtze region is divided into the PNMM and SRM in ascending order (Kametaka *et al.*, 2005). The lowermost mudstone of the PNMM contains glauconite pellets. Glauconites are generally formed under aerobic shallow water (e.g. Tucker, 1991; Prothero and Schwab, 1996). Consequently, the lower PNMM was formed under such conditions.

The upper PNMM contains abundant phosphate nodules. Phosphate nodules are generally formed under oxygen-minimum zones during low clastic supply on the outer shelf and upper slope (e.g. Tucker, 1991; Prothero and Schwab, 1996; Trappe, 1998). Kametaka *et al.* (2005) therefore concluded that the upper PNMM is formed under suboxic conditions.

Kametaka *et al.* (2005) concluded that the SRM of the Anmenkou section was formed in a continental margin under anoxic conditions on the basis of several features of the chert, such as high Mo, Ni, Cu, and V and extremely low Mn contents. These elements are used as an indicator of the redox condition of the sediments. For example, Mo is scavenged by Mn-oxides under oxic conditions (Shimmield and Price, 1986); Mo is dissolved and remobilized under suboxic conditions (Shimmield and Price, 1986; Chaillou *et al.*, 2002; McManus *et al.*, 2002); and Mo forms strong associations with sulfide, concentrating in deposits (Vorlicek *et al.*, 2004). Nickel and Cu also concentrate in sediments under reducing conditions (Calvert and Pedersen, 1993). Vanadium in deposits primarily originates from continental flux or inclusion in seawater. The V and U originating from continental flux decrease in proportion to the Al concentration. Conversely, the seawater-derived V in sediments depends on the redox condition of the deposits (Hori *et al.*, 2000). Manganese generally deposits as Mn-oxide (MnO_2) under oxidizing conditions, whereas it becomes Mn^{2+} and readily secedes from deposits under reducing conditions (Calvert and Pedersen, 1993).

In the Middle Yangtze region, Shi *et al.* (2016) subdivided the Maocaojie section into three units. The lower unit consists primarily of siliceous rocks; the middle unit is composed of limestone, carbonaceous mudstone, and muddy chert; and the upper part consists of muddy chert, siliceous mudstone, and calcareous mudstone. The geochemical results by Shi *et al.* (2016) indicated that the lower, middle, and upper units were formed under oxic, suboxic, and anoxic conditions, respectively. On the basis of comparison to the stratigraphic change of the radiolarian component, Shi *et al.* (2016) concluded that the widespread anoxia was promoted by the elevated primary productivity.

Concluding remarks

In this article, we reviewed the lithostratigraphy, radiolarian occurrences with biostratigraphy, and geochemical characteristics of the Gufeng Formation. Here we summarize the lithostratigraphy and redox conditions of the Gufeng Formation of the Anmenkou and Maocaojie sec-

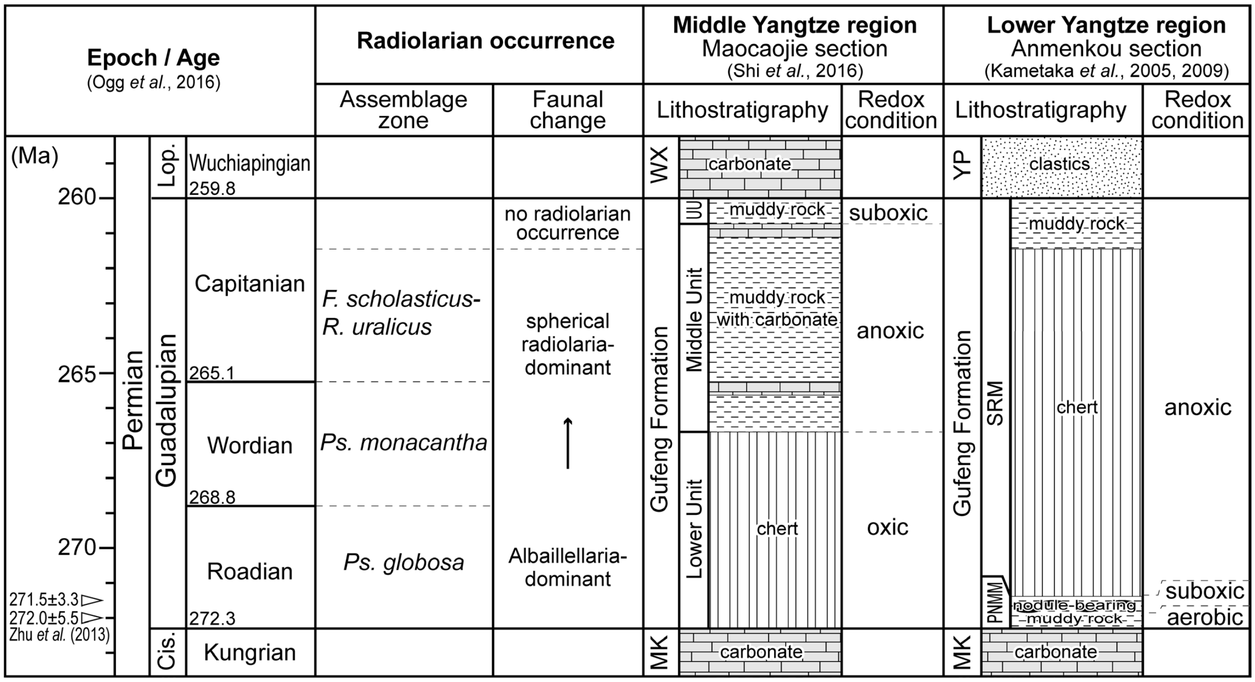

Figure 9. Schematic model showing vertical changes of lithology, radiolarian fauna, and redox condition. Numerical ages with white arrows indicate zircon U–Pb ages of 272.0 ± 5.5 Ma (MSWD = 2.6) and 271.5 ± 3.3 Ma (MSWD = 1.7) separated from volcanic ash beds within the basal shale strata of the Gufeng Formation in Chaohu area, Anhui by Zhu *et al.* (2013). Lop., Lopingian; Cis., Cisuralian; *F.*, *Follicucullus*; *R.*, *Ruzhencevispongus*; *Ps.*, *Pseudoalbaillella*; MK, Maokou Formation; WX, Wuxue Formation; YP, Yinpin Formation; UU, Upper Unit.

tions as representative examples of the Lower and Middle Yangtze regions, respectively (Figure 9).

In the Anmenkou section of the Lower Yangtze region, the dominant rock facies of the Gufeng Formation are nodule-bearing muddy rock, chert, and muddy rock in ascending order. The former is called the PNMM; the latter two are called the SRM by Kametaka *et al.* (2002, 2005). Based on the lithology, the lower PNMM formed under aerobic shallow water and the upper PNMM formed under suboxic conditions (Kametaka *et al.*, 2005). The geochemical characteristics of the SRM indicate that it was formed under anoxic conditions (Kametaka *et al.*, 2005).

In the Maocaojie section of the Middle Yangtze region, the dominant rock facies of the Gufeng Formation are chert, muddy rock with carbonate, and muddy rock (Shi *et al.*, 2016). The geochemical results indicate that these parts were formed under oxic, anoxic, and suboxic conditions, respectively (Shi *et al.*, 2016).

In contrast to the Lower and Middle Yangtze regions, fewer studies have focused on the Gufeng Formation in the Upper Yangtze region (e.g. Kuwahara *et al.*, 2007c, 2008a; Zhou *et al.*, 2009). In the recent decade, upper Capitanian carbonates of the Maokou Formation in the Chaotian section in northern Sichuan have been studied in detail (e.g. Lai *et al.*, 2008; Saitoh *et al.*, 2013, 2014; Chen *et al.*, 2011). Further studies on stratigraphic change in the lithostratigraphy, radiolarian biostratigraphy, and geochemical characteristics of the Gufeng Formation and chert beds within the carbonates of the Maokou Formation in the Upper Yangtze region should reveal the paleoenvironmental developments on the north margin of the South China block.

Acknowledgements

We thank Weihong He (China University of Geosciences, Wuhan) and Masao Kametaka (Dia Consultant Co. Ltd.) for critical review on this manuscript and valuable suggestions. Comments given by Associate Editor, Toshiyuki Kurihara (Niigata University), improved greatly this manuscript. We are most grateful to the following students and PhD students of China University of Geosciences, Wuhan, for kind help for fieldwork of the Gufeng Formation in Chaohu (Anhui) and Jianshi (Hubei) and collecting and reading the Chinese articles: Lei Zhang, Yong Lei, Qing Hu, Lei Shi, Jun Shen, Wenchao Cao, Qiangfen Ma, Qi Wu, Hailong Gao, and others. This study has been financially supported by NSFC (40839903 and 40921062) and "111" Project (B08030) of China University of Geosciences, Wuhan and "Niigata University's Scholarship Program for Graduate School Students Conducting Research Abroad".

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Author contributions

T. I. initiated the study and wrote most part of the paper. K. U. T. re-wrote mainly the chapter of the Origin of organic matter. Q. F. and A. M. supervised this study and writing of the paper. All authors contributed to the writing of the paper.