Integrated Radiolarian and Conodont Biostratigraphy of the Middle to Late Permian Linghao Formation in Northwestern Guangxi, South China

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Abstract: The Permian radiolarian zones and their correlations with conodont zones or other chronostratigraphic schemes are still under debate. In this study, four genera, 21 species and two subspecies of radiolarians together with one genus and six species of conodonts were recovered from the Linghao Formation cropping out at the Longwangpo (LWP) section, northwestern Guangxi, South China. Six radiolarian interval zones and one abundance zone are recognized in the section, namely in ascending order, the Follicucullus scholasticus, Albaillella cavitata, A. protolevis, A. levis, A. excelsa, A. triangularis Interval zones and A. yaoi Abundance Zone. They are correlated with the Clarkina dukouensis, C. guangyuanensis and C. orientalis conodont zones recognized at the same section. Based on our data, the F. scholasticus Interval Zone and the lowermost part of A. cavitata Interval Zone are recognized to be upper Capitanian age, whereas the four Albaillella Interval zones are of Lopingian age (Wuchiapingian to the late Changhsingian). Two previously known Changhsingian radiolarian zones, namely the A. triangularis and A. yaoi Interval zones, should be extended down to the uppermost Wuchiapingian in this studied section.

Key words: biostratigraphy, radiolaria, conodont elements, Guadalupian/Capitanian–Lopingian, Linghao Formation, Guangxi


1 Introduction

Conodonts have been used for decades as index fossils for international bio-stratigraphic correlations of the Permian. However, in general, they are absent in Guadalupian and Lopingian deep-water chert sequences, although some rare exceptions exist (e.g., Ma et al., 2016), whereas radiolarians are typically common (e.g., Feng and Algeo, 2014). Amongst radiolarians, albaillellids display the most distinct shapes and shorter stratigraphic ranges, and are therefore a good index group for the biostratigraphy of Upper Palaeozoic pelagic and hemipelagic deposits (Sashida et al., 2000; Wu and Feng, 2008; Zhang et al., 2018).

Permian radiolarian zones were first introduced by Holdsworth and Jones (1980), based mainly on albaillellids. Since then, considerable progress has been achieved in the biostratigraphic research of Permian radiolarians based essentially on studies from Japan (see review in Danelian et al., 2017).

During the late 1980s and 1990s, many well-preserved radiolarian fossils were found in several areas of South China. Because of relatively complete deep-water siliceous sequences, radiolarian biostratigraphy has been further refined and developed in both Japan and South China. Previously, the Middle Permian radiolarian biostratigraphy was represented by the Parafollicucullus (previously called Pseudoalbaillella, according to Noble et al., 2017) and Follicucullus assemblage zones, while the Late Permian biostratigraphy was represented by the
Neoalbaillella assemblage zones. Coming into the 21st century, these assemblage zones have gradually been replaced by the more detailed interval or lineage zones (Ishiga, 1990; Zhang et al., 2014). Besides southern China and southwestern Japan, Permian radiolarian zones have also been widely recognized, in Italy, Japan, Russia, USA, and South East Asia (Blome and Reed, 1992, 1995; Kuwahara, 1997; Sashida et al., 2000; Xia et al., 2004; Wang et al., 2006, 2012; Jin et al., 2007; Wu and Feng, 2008, Feng et al., 2009; Wu et al., 2010; Zhang et al., 2014, 2018; Xiao et al., 2018; Nestell et al., 2019). In recent years, the number of Permian radiolarian zones has gradually increased from the original 9 to 17 zones (Zhang et al., 2018).

In general, Permian radiolarian biostratigraphy is more complete and detailed than that of any other epoch of the Paleozoic era (see Aitchison et al., 2017). However, a series of problems have arisen, which can be summarized as follows: 1) the accuracy of the radiolarian zones, such as Neoalbaillella and Albalillella interval zones, is not always consistent and different authors apply differing definitions to these zones (Yao et al., 2001), resulting in many obstacles to correlate between these zones in their studies (e.g., Zhang et al., 2018, but also see Xiao et al., 2018); 2) the resolution of Permian radiolarian zones is still low compared to conodont zones, and precise age constraints for most radiolarian zones remain undetermined (Feng et al., 2009; Zhang et al., 2018). A high-resolution correlative framework is still needed for sections that contain both radiolarian and conodonts, or other standard fossil groups. However, such sections are scarce for the Middle to Late Permian interval; 3) the current radiolarian zones are still not widely applicable because all of the species of the order Albaillellaria are found mainly in >500 m-deep-water environments (Xiao et al., 2017). Thus, they are relatively rare or even absent in shallower siliciclastic rocks; 4) additionally, radiolarian biostratigraphy in the vicinity of key events, such as extinction periods, has not yet proven to be useful for defining geochronology. Recently, Zhang et al. (2018) reviewed the Permian radiolarian biostratigraphy and their zonal correlation with conodont zones. Some quantitative radiolarian biostratigraphy based on Bayesian inference methods also have been established (Xiao et al., 2018). Inevitably, inconsistencies occur between the traditional and non-traditional methods. These inconsistencies can originate from the choice and analysis of a dataset since the range of some key radiolarian biostratigraphies could have been misinterpreted in some areas of South China and Japan (see discussion in Zhang et al., 2018). In addition, some studies have tried to apply new index taxa (e.g., Latenitistularia) for Middle–Late Permian biostratigraphy (Kuwahara et al., 2017), but examination of their availability and validity is still needed. Anyway, to solve the disputes mentioned above, more complete investigations are still needed.

Many studies on the radiolarian and conodont zones have been carried out on the Longwangpo section in northwestern Guangxi but they were focused on the Changhsingian (Jin et al., 2007; Wu and Feng, 2008, Wu et al., 2010). Wang et al. (2006) reported five Albailllella and three Neoalbaillella species from eight samples in the Longwangpo II section, including Albailllella triangularis, A. excelsa, A. levis, A. proteolis, A. lautus, Neoalbaillella ornithoformis, N. optima and Neoalbaillella sp., all of which belong to the Changhsingian Albailllella proteolis, A. levis-A. excelsa, Neoalbaillella ornithoformis and N. optima zones. Feng et al. (2009) also synthesized the radiolarian biostratigraphy in South China, which included the Longwangpo section but they only presented fossil ranges.

In this study, high-resolution sampling of the Longwangpo section allows us to correlate radiolarian zones with the co-occurring conodont records at the same section. Here, we take the detailed data from Feng et al. (2009, fig. 2) to supplement and review. Moreover, we have additional taxa including Parafollicucullus and Follicucullus from the Guadalupian, and Albailllella and Neoalbaillella as well as the conodonts from the Lopingian. Study of our new materials aims to provide data to refine the albaillellarian biostratigraphy and help establish direct correlation between radiolarian and conodont index species.

2 Geological Setting

The 48 m-thick Longwangpo section is located to the northwest of Nandan city, Guangxi, and is exposed along the north side of the Nandan–Tian’e secondary road, approximately 2 km from the city (Fig. 1). The base of the section is faulted and the Middle to Upper Permian Linghao and Lower Triassic Luolou formations are exposed. The Linghao Formation in this section has also been called the Dalong Formation by Feng et al. (2009). However, since its range and lithology are still distinct from the standard Dalong Formation in South China, we keep its local name, the Linghao Formation herein. The lower part of the Linghao Formation is dominated by green to grey laminated thin-bedded siliceous mudstone, the middle part is characterized by medium- to thick-bedded limestone, and the uppermost part consists of yellow tuffaceous mudstone, locally interbedded with black thin-bedded cherts or limestone concretions. The overlying Luolou Formation is characterized by thin-bedded yellow calcareous mudstone interbedded with fine-grained sandstone and wackestone. No unambiguous Permian/Triassic boundary was recognized here, probably because of soil coverage.

3 Samples and Methods

We obtained 114 samples for radiolarian analysis from the Longwangpo section. Samples were first crushed into 1 cm³-fragments, which were then immersed in 2%-5% HF solution for eight hours at ambient temperature. Residues were sieved through a 63 µm-mesh and dried in preparation for examination under a binocular microscope. Ten samples were collected from carbonate-rich layers for conodont analysis, each sample weighing 10 kg. Samples were first crushed into fragments of 5 cm³, then immersed in 10% acetic acid solution at ambient temperature and rinsed every 24 h for 10 days. For those
samples that could not be disaggregated using acetic acid, 1%–2% HF solution was employed. Residues were sieved between 20- and 160-mesh sieves, then separated using a 2.81 g/mL heavy liquid of bromoform (2.89 g/mL) and acetone (0.79 g/mL). Finally, the residues were dried and then examined using a binocular microscope.

Radiolarian and conodont element specimens were analyzed and photographed using a scanning electron microscope (SEM) at the State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences (CUG), Wuhan. All figured specimens are housed in the collection at School of Earth Sciences, China University of Geosciences (Wuhan), Wuhan, China (X0310/1001–X0310/1103).

4 Results

After processing, 55 samples yielded well-preserved radiolarian and five samples (LWP1-9, 4-2, 4-3, 6, 10-22-2) contained abundant conodont elements. Following detailed taxonomic study, 21 Albaillellaria species are recognized (see Figs. 2–4). Six conodont species are also identified, including Clarkina dukouensis, C. postbitteri postbitteri, C. guangyuanensis, C. liangshanensis, C. longicuspidata and Clarkina sp. (Figs. 5–6). The position of these collected samples, the occurrence of the characteristic radiolarian and conodont species, as well as radiolarian and conodont zones are shown in Fig. 2.

4.1 Biostratigraphy

4.1.1 Radiolarian zones

Six radiolarian zones are reported from this section. Since the type section, definition and modification histories of these zones are discussed in detail by Zhang et al. (2018), we follow their work here and only repeat essential information for this section. The detailed descriptions of each zone are provided below:

**Follicucullus scholasticus Interval Zone**

This zone was initially defined by Ishiga et al. (1982a) from the Capitanian of southwestern Japan. Its base is defined by the first occurrence (FO) of *Follicucullus scholasticus* and its top corresponds to the FO of *F. bipartitus* (Zhang et al., 2014). However, both the underlying (*F. porrectus*) and the two overlying interval zones (*F. bipartitus* and *F. charveti*) were not found in this study. The only sample (LWP 1-4) that yielded a relatively abundant and distinctive fauna associated with a few Parafollicucullus species indicates that this bed belongs to the lower part of the *Follicucullus scholasticus* Zone. Hence, the precise upper and lower boundaries of this zone remain unclear in this section.

**Albaillella cavitata Interval Zone**

This zone was established by Feng et al. (2009). Its base is defined by the first occurrence (FO) of *Follicucullus scholasticus* and its top corresponds to the FO of *F. bipartitus* (Zhang et al., 2018). However, both the underlying (*F. porrectus*) and the two overlying interval zones (*F. bipartitus* and *F. charveti*) were not found in this study. The only sample (LWP 1-4) that yielded a relatively abundant and distinctive fauna associated with a few Parafollicucullus species indicates that this bed belongs to the lower part of the *Follicucullus scholasticus* Zone. Hence, the precise upper and lower boundaries of this zone remain unclear in this section.
characterized by the dominance of *Follicucullus orthogonus* and *F. charveti* in the lower part (beds 1–3); *Albaillella cavitata* and *A. yamakitai* are dominant in the middle part (beds 3–5) of the zone and Albaillellaria are rare except for samples LWP7-1 and LWP7-6 and a few layers of bed 10 (e.g., LWP10-2) in the upper part of the zone. Other common taxa in this zone are *Follicucullus scholasticus*, *F. bipartitus*, *Albaillella protolevis*, and *Albaillella* sp. G of Kuwahara et al. (1998).

**Albaillella levis Interval Zone**

The *Albaillella levis* Zone was established as an abundance zone from the Lopingian of southwest Japan by Yao et al. (2001). It was originally defined as an abundance zone and later revised into an lineage zone in South China by Xia et al. (2004). The base of this zone is defined by the FO of *A. levis* and the top corresponds to the FO of *A. excelsa*.

In the studied section, it has been found in samples LWP7-1 to LWP7-6 and a few layers of bed 10 (e.g., LWP10-2) in the upper part of the zone. Other common taxa in this zone are *Follicucullus scholasticus*, *F. bipartitus*, *Albaillella protolevis*, and *Albaillella* sp. G of Kuwahara et al. (1998).

**Albaillella excelsa Interval Zone**

This zone was established by Yao et al. (2001) as an...
Fig. 3. Middle to Late Permian radiolarians from the Longwangpo section, northwest Guangxi, China.

(A) Parafollicucullus sp. A, LWP(2)1-4/001; (B) Parafollicucullus sp. B, LWP(2)1-4/002; (C) Follicucullus porrectus Rudenko, 1984 in Rudenko and Panasenko, 1990, LWP(2)1-4/005; (D) Follicucullus scholasticus Ormiston and Babcock, 1979, LWP(2)1-4/011; (E–H) Follicucullus bipartitus Caridroit and De Wever, 1984; (E) LWP1-11/021; (F) LWP1-11/022; (G) LWP1-11/024; (H) LWP1-11/028; (I) Follicucullus sp. cf. F. dilatatus Rudenko, 1984 in Rudenko and Panasenko, 1990; LWP2-2/002; (J) Follicucullus charveti Caridroit and De Wever, 1984, LWP1-11/001; (K) Follicucullus orthogonus Caridroit and De Wever, 1984; LWP(2)1-11/011; (L–M) Albaillella yamakitai Kuwahara, 1999; (L) LWP1-11/006; (M) LWP1-11/037; (N–P) Albaillella caviata Kuwahara, 1999; (N) LWP5-9/181; (O) LWP5-9/003; (P) LWP5-9/004; (Q–R) Albaillella protolevis Kuwahara, 1999; (Q) LWP(2)5-5/004; (R) LWP5-11/002; (S–V) Albaillella levis Ishiga et al., 1982b; (S) LWP10-5/002; (T) LWP10-8/003; (U) LWP10-4/002; (V) LWP(2)10-5/005; (W) Albaillella sp., LWP10-19/008; (X–Y) Neoalbaillella ornithoformis Takemura and Nakaseko, 1981; (X) LWP(2)10-14/008; (Y) LWP(2)10-14/009; (Z) Albaillella angusta Kuwahara, 1999; LWP(2)10-17/001; (AA) Albaillella triangularis Ishiga et al., 1982b; LWP(2)10-19/001; (AB) Albaillella sp. cf. A. Angusta Kuwahara, 1999, LWP(2)10-15/010; (AC) Neoalbaillella sp., LWP(2)10-14/007.

Scale bar = 50 μm.
Fig. 4. Middle to Late Permian radiolarians from the Longwangpo section, northwestern Guangxi, China. (A–B) Albaillella lauta Kuwahara in Kuwahara and Sakamoto, 1992; (A) LWP(2)10-16/008; (B) LWP10-16/003; (C) Albaillella flexa Kuwahara in Kuwahara and Sakamoto, 1992, LWP10-13/003; (D–E) Albaillella sp. cf. A. excelsa Ishiga et al., 1982b; (D) LWP10-18/011; (E) LWP10-18/013; (F–J) Albaillella excelsa Ishiga et al., 1982b; (F) LWP10-18/004; (G) LWP10-16/005; (H) LWP10-18/007; (I) LWP10-18/003; (J) LWP(2)10-16/002; (K–L) Albaillella angusta Kuwahara, 1999; (K) LWP(2)10-18/007; (L) LWP10-18/005; (M–P) Albaillella triangularis Ishiga et al., 1982b; (M) LWP10-24/001; (N) LWP10-24/002; (O) LWP(3)10-20/002; (P) LWP(3)10-20/003; (Q–R) Albaillella yaoi longa Jin and Feng in Jin et al., 2007; (Q) LWP10-21/004; (R) LWP10-20/003; (S) Albaillella yaoi yaoi Kuwahara, 1999, LWP10-21/002; (T) Albaillella sp. cf. A. angusta Kuwahara, 1999, LWP10-18/010; (U) Albaillella sp. cf. A. triangularis Ishiga et al., 1982b, LWP10-22/005; (V–W) Neoabaillella optima Ishiga et al., 1982b; (V) LWP10-24/005; (W) LWP10-24/003; (X) Neoabaillella camarata Wu and Feng in Wu et al., 2010; LWP11-10/001; (Y) Neoabaillella sp. cf. N. grypus Ishiga et al., 1982b, LWP10-8/001. Scale bar = 50 μm.
Fig. 5. Late Permian conodont elements from the Longwangpo section, northwestern Guangxi, China. (A, C–F) Clarkina postbitteri postbitteri Mei and Wardlaw in Mei et al., 1994a; (A) LWPC1-9/010; (C) LWPC1-9/008; (D) LWPC1-9/003; (E) LWPC1-9/005; (F) LWPC1-9/004; (B, G) Clarkina dukouensis Mei and Wardlaw in Mei et al., 1994a; (B) LWPC1-9/006; (G) LWPC1-9/033; (H–AC) Clarkina guangyuanensis Dai and Zhang, 1989; (H) LWPC4-2/011; (I) LWPC4-2/063; (J) LWPC4-2/067; (K) LWPC4-2/021; (L) LWPC4-2/048; (M) LWPC4-2/055; (N) LWPC4-2/054; (O) LWPC4-2/001; (P) LWPC4-2/008; (Q) LWPC4-2/045; (R) LWPC4-2/047; (S) LWPC4-2/019; (T) LWPC4-2/027; (U) LWPC4-2/049; (V) LWPC4-2/015; (W) LWPC4-2/079; (X) LWPC4-2/073; (Y) LWPC4-2/012; (Z) LWPC4-2/060; (AA) LWPC4-2/065; (AB) LWPC4-2/004; (AC) LWPC4-2/058; 1, upper views; 2, oblique lateral views. Scale bar = 200 μm.
Fig. 6. Late Permian conodont elements from the Longwangpo section, northwestern Guangxi, China.

(A–E) Clarkina guangyuanensis Dai and Zhang, 1989; (A) LWPC4-3-019; (B) LWPC4-3-002; (C) LWPC4-3-004; (D) LWPC4-3-007; (E) LWPC4-3-011; (F–I) Clarkina liangshanensis (Wang, 1978); (F) LWPC6/001; (G) LWPC6/003; (H) LWPC6/006; (I) LWPC6/011; (J–T) Clarkina longicuspidata Mei and Wardlaw in Mei et al., 1994a; (J) LWPC10-22-2-020; (K) LWPC10-22-2-034; (L) LWPC10-22-2-011; (M) LWPC10-22-2-014; (N) LWPC10-22-2-043; (O) LWPC10-22-2-056; (P) LWPC10-22-2-017; (Q) LWPC10-22-2-057; (R) LWPC10-22-2-058; (S) LWPC10-22-2-003; (T) LWPC10-22-2-005; 1, upper views; 2, oblique lateral views. Scale bar = 200 μm.
abundance zone from the Lopingian of southwestern Japan. Feng et al. (2009) revised it to an interval zone. The base of this zone is defined by the FO of *Albaillella excelsa* and the top by the FO of the *A. triangularis*. This zone is very short in the studied section, ranging from samples LWP10-16 to LWP10-18. *Albaillella excelsa*, *A. longa*, *A. flexa*, *A. angusta* and *Neoalbaillella optima* are the dominant species throughout this zone.

### Albaillella triangularis Interval Zone

This zone was defined in Lopingian strata of southwestern Japan by Yao et al. (2001). It was originally defined as an abundance zone and later revised as an interval zone (Zhang et al., 2018). The base of this zone is defined by the FO of *Albaillella triangularis* and the top by the abundant occurrence of *A. yaoi*. It ranges through a short interval from samples LWP10-19 to LWP10-20 in the studied section. *Albaillella excelsa*, *A. longa* and *A. flexa* are the dominant species of the zone. This zone has also been recognized from the neighboring area, such as the Dongpan, Liuaiqiao and Paibi sections in southern Guangxi (Jin et al., 2007; Wu and Feng, 2008; Feng et al., 2009; Wu et al., 2010).

#### Albaillella yaoi Abundance Zone

The *Albaillella yaoi* Zone was established in Lopingian strata of southwestern Japan by Xia et al. (2004) as a lineage zone. Zhang et al. (2018) redefined it as an abundance zone. The base of this zone is defined by the abundant occurrence of *A. yaoi* (specifically in the studied section, the FO of the subspecies *A. yaoi yaoi* because it occurred earlier than any other) and the top by the disappearance of all Albaillellaria (Feng et al., 2009). It ranges from samples LWP10-20 to LWP13-3-1 in the studied section. However, the range of the index species is quite short at the studied section. *Albaillella yaoi yaoi*, *A. yaoi longa*, *A. excelsa*, *A. triangularis*, and *Neoalbaillella optima* are the common species/subspecies throughout this zone. However, the top of the zone is not yet resolved in the studied section. This zone also has been recognized from the neighboring area in the Dongpan, Liuiqiao and Paibi sections in southern Guangxi (Jin et al., 2007; Wu and Feng, 2008; Feng et al., 2009; Wu et al., 2010).

#### Conodont biostratigraphy

Given that only five beds were productive for conodonts in this section (Figs. 2, 5, 6), an accurate zonation is difficult to establish. Nevertheless, based on the relatively numerous specimens recovered, the conodont succession can be described as follows:

Unit 1, sample LWP1-9. Numerous elements extracted from this bed were identified as *Clarkina postbitteri postbitteri*, but most of them belong to a juvenile form, judging by their small size and more discrete denticles than on adults. Juvenile elements of *Clarkina* species are very similar in the Wuchiapingian, and so it is difficult to identify taxa on such materials. Other specimens with denticles more closely distributed on the platform are identified as *C. dukouensis*. Thus, this sample might belong to the lower part of the *C. dukouensis* Zone (Mei et al., 1994b).

Unit 4, samples LWP4-2 and LWP4-3. These beds are characterized by the presence of *Clarkina guangyuanensis* and therefore can be assigned to the *C. guangyuanensis* Zone (Mei et al., 1994b).

**Unit 6, sample LWP6.** This bed is characterized by the species *Clarkina liangshansensis*. The range of this species extends from the *C. guangyuanensis* Zone to the lower part of the *C. orientalis* Zone (Mei et al., 1994b; Shen and Mei, 2010; Yuan et al., 2019). The sample should belong to the upper part of the Wuchiapingian stage.

#### 5 Discussion

#### 5.1 Important index genus and species ranges in the studied section

Fundamentally, the radiolarian biostratigraphy of Permian is based mainly on four major genera: *Parafollicucullus*, *Follicucullus*, *Albaillella* and *Neoalbaillella* (Wang et al., 2006; Wu and Feng, 2008; Wang and Yang, 2011; Zhang et al., 2018). However, the ranges of these genera are still controversial and details are provided below:

- **Parafollicucullus** appeared in the Late Carboniferous and disappeared in the latest Capitanian; *Follicucullus* is generally considered to have gone extinct during early to middle Lopingian; *Albaillella* and *Neoalbaillella* went extinct at the end of Permian in South China (Zhang et al., 2014). In Japan, Far East Russia, Thailand and New Zealand, species of *Albaillella* and *Neoalbaillella* have been discovered in the Changaishingian (Ishiga et al., 1982a, b, c; Kuwahara and Yao, 1998; Wang et al., 2006), and some *Albaillella*, *Follicucullus* and *Parafollicucullus* species have even been reported from Triassic or Jurassic strata (Bragin, 1991; Sugiyama, 1997; Takemura et al., 1998, 2002; Ishida and Murata, 2006; Sano et al., 2010, 2012; Kamata et al., 2014). Amongst these, some genera (e.g., *Albaillella* and *Follicucullus*) are considered as ‘Lazarus taxa’ that survived in “unknown refuges” (De Wever et al., 2006: p53), and a few have been confirmed as reworked radiolarians that originated from sediments on the flanks of submarine highs, such as seamounts, or related to global-scale tectonic movements and erosion history, or from Permian exotic rocks and clastic grains (Ando et al., 1991; Sugiyama, 1992; Kamata et al., 2000; Ishida and Murata, 2006). Undoubtedly, some reports still need further examination (De Wever et al., 2006).

Here, taking the Longwanggo section as a case study, where the Middle Permian to Earliest Triassic successions are continuous and well-outcropped, we discuss the FO, LO and ranges of the *Parafollicucullus*, *Follicucullus*, *Albaillella* and *Neoalbaillella* in the studied area. The genus *Parafollicucullus* disappeared at the bottom of the Longwanggo section, which is similar to the first occurrence of the *Follicucullus*. Although evidence of conodont zones are still needed, the age of their interval should belong to the Guadalupian, since a remarkable
A black-white layer of clay was discovered at bed LWP1-9. A similar clay layer can be observed in many sections spanning the Guadalupian–Lopingian boundary (G-LB) transition in South China, such as the Maoshan section in Enshi (Zhang et al., 2007; Zhong et al., 2020). The accurate age and the source of the clay are still disputed, although it may be related to the Pre-Lopingian extinction events (Zhong et al., 2020). Combined with associated black mudstone and black shales, this clay layer can be roughly taken as a sign of the G-LB. The first occurrence of *Albaillella yamakitai* (sensu lato) is in the Capitanian *Jinogondolella altudaensis* conodont Zone in North America and southwestern Japan (Maldonada and Noble, 2010; Nestell and Nestell, 2010; Noble and Jin, 2010, Nishikane et al., 2011). In this study, *A. yamakitai* occurred slightly below the clay layer and, thus, it could also be below the G-LB. In the Xiaodong area, the FO of *A. yamakitai* is generally associated with the *A. cavitata* (Zhang et al., 2018). Thus, the *Follicucullus scholasticus* Interval Zone should be limited to the Middle Permian.

In the Longwangpo section, most of the *Follicucullus* species disappear at the top of bed LWP5-11. However, a few specimens of *F. orthogonus* can be found from bed LWP10-5, which is close to the FO of *Albaillella levis*. The FO of *F. orthogonus* specimens are higher than the FO of conodont *Clarkina liangshanensis*, so the *Albaillella levis* Zone should belong to late Wuchiapingian. The FO of *A. triangularis* is in bed LWP10-19, while the FO and abundance of *A. yaoi* start from bed LWP10-20 onwards. Abundant conodont elements of *Clarkina longicuspidata* were found in the basal part of the range of *Albaillella yaoi*, implying that the FO of *A. triangularis* might be located slightly below the Wuchiapingian–Changhsingian boundary. In the Dongpan, Liuqiao and Paibi sections in South Guangxi and sections from southwestern Japan, the FO of *A. triangularis* is considered to be at the Wuchiapingian–Changhsingian boundary and the FO of *A. yaoi* can be correlated with the middle-upper part of the *Clarkina yini* Zone (Yao et al., 2001; Wu and Feng, 2008). Thus, the FOs of *Albaillella triangularis* and *A. yaoi* in the studied section might both be lower than in the other mentioned areas. Since the topmost part of the section is slightly covered and weathered, the LO of these two species are not clear in the studied area.

For enhanced biostratigraphic interpretation, further investigations on the FO, LO and ranges of these species worldwide are still required, especially for those taxa that responded quickly to key geological and biological events.

### 5.2 Worldwide correlation of recognized radiolarian zones in the studied area

Based on our current conodont data, a simple correlation has been established in this study. However, due to the low sample density, a detailed discussion on traditional (e.g., Zhang et al., 2018) and nontraditional (e.g., Xiao et al., 2018) methods is risky and, therefore, is not included herein.

#### Follicucullus scholasticus Interval Zone

The *Follicucullus scholasticus* Interval Zone is generally correlated with the Capitanian (Zhang et al., 2014, 2018). This zone is widespread in South China (Wang and Li, 1994; Wu et al., 1994; Sun and Xia, 2006; Wang and Yang, 2007, 2011), southwestern Japan (Ishiga et al., 1986; Ishiga, 1990), and central Oregon and Texas, USA (Blome and Reed, 1992; Maldonado and Noble, 2010).

#### Albaillella cavitata Interval Zone

In this study, the *Albaillella cavitata* Interval Zone is assigned to the Wuchiapingian (Fig. 7). However, this zone is generally assigned to the uppermost Capitanian–Wuchiapingian because the FO of *A. cavitata* is recognized as below the basal Wuchiapingian (base of Lopingian) in both South China and southwestern Japan.
(Nishikane et al., 2011; Zhang et al., 2014). This zone can be roughly correlated with the *Folliculusculus bipartitus–F. charveti–F. orthogonus* Assemblage Zone and the lower part of *Foremanhelena triangula* Abundance Zone in South China (Wang and Yang, 2007, 2011), the *Folliculusculus scholasticus–F. ventricosus* Assemblage Zone and the lower part of the *F. charveti–A. yamakitaiz* Assemblage Zone in southwestern Japan (Yao et al., 2001; Zhang et al., 2018). This zone has been recognized in SW Japan (Kuwahara et al., 1998; Kuwahara, 1999) and South China (Xia et al., 2005; Sun and Xia, 2006; Wang et al., 2006; Wang and Yang, 2007, 2011; Fig. 7). The zonal species or the associated species can be widely recognized from the Quinn River Formation in USA (Blome and Reed, 1995), Malaysia (Jasin, 1997), northern Turkey (Goncuoglu et al., 2004), Thailand (Sashida et al., 2000; Saesaengseerung et al., 2007) and Palawan, Philippines (Marquez et al., 2006).

**Albaillella levis, Albaillella excelsa and Albaillella triangularis Interval Zones**

These interval zones might be correlated with the middle–upper part of the conodont *Clarkina orientalis* Zone (basically, restrained by the occurrences of *C. longicuspidata* and *C. liangshenensis*) in the studied section. The *Albaillella triangularis* Zone was interpreted as corresponding to the upper part of the *Neogondolella postwangi* and lower part of the *Neogondolella yaoi* Conodont zones in the Liujiao and Dongpan sections, Guangxi (Wu and Feng, 2008). However, based on present data, the range of *Albaillella triangularis* is from the upper Wuchiapingian to the lower–middle Changhsingian. The *A. levis* Interval Zone in the studied section can be roughly correlated with the middle part of the *Formanhelena triangula* Abundance Zone in South China (Wang and Yang, 2007, 2011). It can also be roughly correlated with the middle part of the *Folliculusculus charveti–Albaillella yamakitaiz* Assemblage Zone (Yao et al., 2001) and the *Albaillella levis* Lineage Zone (Xia et al., 2004) in SW Japan (Fig. 7). The *A. excelsa* Interval Zone in the studied section can be roughly correlated with the upper part of the *Foremanhelena triangula* Abundance Zone in South China (Wang and Yang, 2007, 2011), the upper part of the *Folliculusculus charveti–Albaillella yamakitaiz* Assemblage Zone (Yao et al., 2001) and the *Neosalbaillella optima–Albaillella lauta* Lineage Zone (Xia et al., 2004) in SW Japan (Fig. 7). The *A. triangularis* Interval Zone in the studied section can be roughly correlated with the *Albaillella proteolis* Interval Zone and the lower part of the *A. levis–A. excelsa* Abundance Zone in South China (Wang and Yang, 2007, 2011), the uppermost part of the *Folliculusculus charveti–Albaillella yamakitaiz* Assemblage Zone and the *Neosalbaillella ornithoformis* Assemblage Zone (Yao et al., 2001), the *Albaillella angusta–A. flexa* and the *A. triangularis* Lineage zones in SW Japan (Fig. 7; Xia et al., 2004).

It should be noted that the FO of *Neosalbaillella ornithoformis* is roughly equivalent to *Albaillella proteolis* in southwestern Japan (Kuwahara et al., 1998). However, it occurs slightly later than the FO of *A. levis* and even *Neosalbaillella optima* in the studied section. The three zonal species can be widely recognized in South China (Yao and Kuwahara, 2000; Sun and Xia, 2003, 2006; Xia et al., 2005; Wang et al., 2006; Wang and Yang, 2007, 2011; Feng et al., 2009), SW Japan (Kuwahara et al., 1998; Yao et al., 2001; Xia et al., 2004), Thailand (Sashida et al., 2000a, b; Sashida and Salyapongse, 2002) and the Malay Peninsula (Sashida et al., 1995; Jasin et al., 2005; Jasin and Harun, 2011).

**Albaillella yaoi Abundance Zone**

The range of *Albaillella yaoi* can be roughly correlated with the uppermost part of the *Clarkina orientalis* conodont Zone in the studied section (represented by occurrences of *C. longicuspidata*; Yuan et al., 2014). In the Dongpan section of Guangxi, the *Albaillella yaoi* Zone can be correlated with the middle-upper part of the *Neogondolella yaoi* Zone (Wu and Feng, 2008). Thus, the range of *Albaillella yaoi* is relatively long, probably extending from the uppermost Wuchiapingian to the upper Changhsingian. The *A. yaoi* Abundance Zone in the studied section can be roughly correlated with the upper part of the *Albaillella levis–Albaillella excelsa* Abundance Zone, the *Neoalbaillella ornithoformis* Assemblage Zone, the lower part of the *Neoalbaillella optima* Assemblage Zone (Wang and Yang, 2007, 2011) and the *Albaillella yaoi* Range Zone (Feng et al., 2009) in South China. It can also be correlated with the lower to middle part of the *Neosalbaillella optima* Zone (Yao et al., 2001), the *Albaillella yaoi* Lineage Zone and the *Albaillella degradans* Lineage Zone (Xia et al., 2004) in SW Japan (Fig. 7). The zone species is widely recognized in southwestern Japan (Kuwahara et al., 1998; Kuwahara, 1999) and South China (Wang et al., 2006; Wang and Yang, 2007, 2011).

**6 Conclusions**

Abundant radiolarians and a few conodont elements were obtained from the bedded chert succession of the Longwanggo section, northwestern Guangxi.

Twenty-one radiolarian species belonging to four genera were identified. Based on their stratigraphic distribution, six radiolarian zones are recognized in the Guadalupian to Lopingian strata, in ascending order: the *Folliculusculus scholasticus, Albaillella cavitata, A. levis, A. excelsa, A. triangularis* and *A. yaoi* interval zones.

Six conodont species of the genus *Clarkina* were identified. Their occurrences are attributed in ascending order to the *Clarkina dukouensis, Clarkina guangyuanensis* and *Clarkina orientalis* zones.

We consider that the *Folliculusculus scholasticus* Zone is assigned to the upper Capitanian, *Albaillella cavitata* is attributed to the uppermost Capitanian–Wuchiapingian time interval, *Albaillella levis, Albaillella excelsa*, and *Albaillella triangularis* interval zones are attributed to the Wuchiapingian, and the *Albaillella yaoi* Interval Zone is referred to the uppermost Wuchiapingian–Changhsingian.

**Acknowledgements**

This work was supported by the National Natural Science Foundation of China (Grant nos. 41172202, 40839903 and 41372030), the Ministry of Education of

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