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Integrated radiolarian and conodont biostratigraphy of the Middle Permian Gufeng Formation (South China)

Biostratigraphie intégrée de radiolaires et de conodontes issus de la formation de Gufeng du Permien moyen (Chine méridionale)

Qiangfen Ma[a,b], Qinglai Feng[a,*], Martial Caridroit[b], Taniel Danelian[b], Ning Zhang[a]

[a] *State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences, 430074 Wuhan, Hubei, PR China*
[b] *Université de Lille – Sciences et Technologies, CNRS, UMR 8198, Évo-Éco-Paléo, 59655 Villeneuve-d'Ascq cedex, France*

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ABSTRACT

Radiolarians are usually abundant in chert sequences and they have thus been widely used for the biostratigraphy of deep-water sediments. However, there are many difficulties in the correlation of radiolarian biostratigraphic schemes with the standard conodont zones. In this study, 21 radiolarian species were extracted from the Gufeng Formation that crops out in the Luojiaba (LJB) section (western Hubei, China), together with 5 co-occurring conodont species. In this way, it is the first time that the *Pseudoalbaillella globosa*, *Follicucullus monacanthus* and *F. scholasticus* radiolarian zones can be directly correlated with the *Jinogondolella nankingensis gracilis*, *J. aserrata* and *J. postserrata* conodont zones. Accordingly, the 3 radiolarians zones are now firmly correlated with the Roadian to middle Capitanian interval (Middle Permian).

Mots clés :
Permien moyen
Formation de Gufeng
Radiolaires
Conodontes
Chine méridionale

RÉSUMÉ

Les radiolaires sont souvent abondants dans les séries biosiliceuses, et ils sont largement utilisés pour la biostratigraphie des séries pélagiques profondes. Néanmoins, nombreuses sont les difficultés de corrélation des biozonations à radiolaires avec les zones standard à conodontes. Dans cette étude, 21 espèces de radiolares ont été extraites de la formation de Gufeng, qui affleure dans la coupe de Luojiaba (LJB) de la province de Hubei (Chine), ainsi que cinq espèces de conodontes. De cette façon, c'est la première fois que les zones à *Pseudoalbaillella globosa*, *Follicucullus monacanthus* et *F. scholasticus* des radiolaires peuvent être directement corrélées aux zones à *Jinogondolella nankingensis gracilis*, *J. aserrata* et *J. postserrata* des conodontes. Par conséquent, trois zones à radiolaires sont maintenant corrélées avec certitude avec l'intervalle Roadien à Capitanien moyen (Permien moyen).

* Corresponding author.
E-mail address: qinglaifeng@cug.edu.cn (Q. Feng).

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1. Introduction

Radiolarians are usually abundant in chert sequences and consequently they have been used extensively for biostratigraphic investigations of deep-water sediments. However, correlations are in general difficult between radiolarian zones and the standard conodont zones used for Permian strata (Gradstein et al., 2012). Although 16 radiolarian zones exist for the Permian, their correlation with the 36 Permian conodont zones has only been roughly established given the extremely scarce co-occurrence of the two microfossil groups in the same sedimentary sequences. Moreover, nearly all existing studies have focused either on the Early Permian (Ishiga, 1986, 1990) or on the Guadalupian-Lopingian boundary (Xia et al., 2005; Sun and Xia, 2006) or finally the Cisuralian-Guadalupian boundary (Zhang et al., 2010). Accurate age assignments of Middle Permian radiolarian zones are still missing.

Holdsworth and Jones (1980) first introduced Permian radiolarian assemblages mainly based on the presence of albaillellids, but its chronostratigraphic calibration was very coarse due to the lack of other index fossils (e.g. bivalves, foraminifers and ammonoids). A few years later, Ishiga (1986, 1990) established 13 radiolarian assemblages or assemblage zones for the Late Carboniferous to Late Permian interval based on material from Southwest Japan, where some of the radiolarian zones could be correlated with conodont and fusulinacean zones. Later, Permian radiolarian zones established in North America (Blome and Reed, 1992) and South China (Wang et al., 1994) were recognized. The Permian biostratigraphic framework has improved and a high-resolution Permian conodont biostratigraphic sequence was drawn up (Mei and Henderson, 2001). Therefore, in order to ascertain the accurate age calibration of Middle Permian radiolarian zones, comparative studies of radiolarians and other age diagnostic fossils, especially conodonts, have become an important task.

Abundant radiolarians were recovered and radiolarian bioevents and zones were recognized from the Luojiaba section, Jianshi county, western Hubei province; a preliminary report was presented Ma and Feng (2012). Further detailed investigations allowed us to find in some beds abundant conodonts together with radiolarians, allowing thus direct correlations between the radiolarian and conodont record. Moreover, several additional radiolarian species were recently identified, which improved understanding the diversity of the recovered radiolarian assemblages in the studied section.

2. Paleogeographic setting and lithostratigraphy of the studied section

It is likely that following the influence of oceanic upwelling during the Permian (Shang et al., 2008), radiolarian cherts of the Gufeng and Dalong formations (Middle and Upper Permian, respectively) accumulated in basins situated around the Yangtze Block (Feng et al., 1993). During the Permian, the study area was situated at the northern margin of the Yangtze platform (Fig. 1A).

The studied Luojiaba section is 19 m-thick and crops out in a quarry close to the village of Luojiaba, 80 km northeast of the Enshi City, in western Hubei, China (Fig. 1B). It is divided into 8 members and 3 formations (Fig. 2). The Maokou Formation is composed of light gray limestones. The 16 m-thick Gufeng Formation is characterized by intercalations of black cherts and siliceous/carbonaceous mudstone, yielding numerous radiolarians and conodonts. The overlying Wuxue Formation is composed mainly of massive limestones.

3. Materials and methods

Sixty-one samples were collected from the studied section, 5 of them came from the Maokou Formation, 54 from the Gufeng Formation and 2 samples from the Wuxue Formation. Samples were processed for radiolarians and conodonts and etched with 3–4% hydrofluoric acid solution

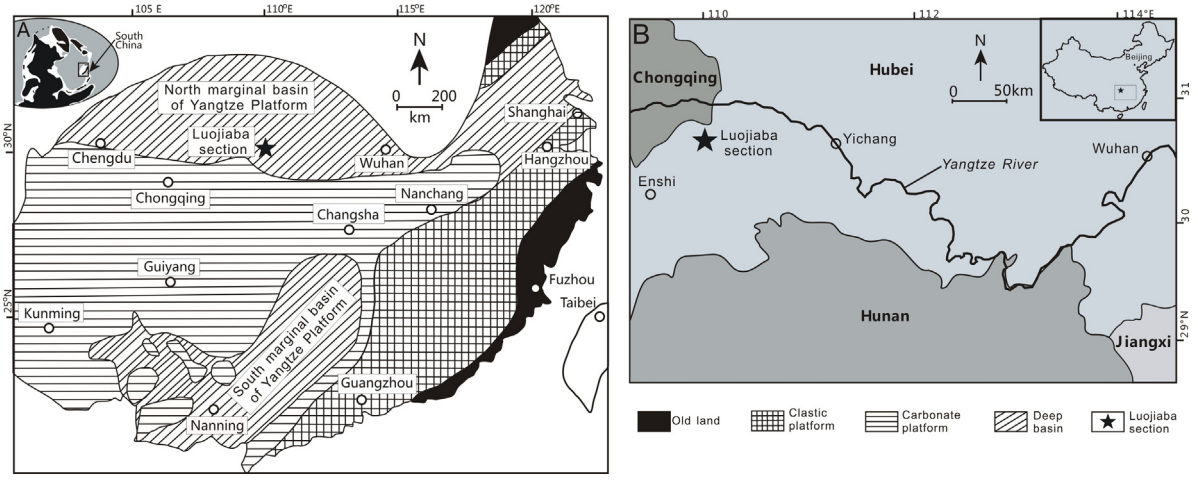

Fig. 1. Middle Permian paleogeographic map of South China and location of the Luojiaba section in Hubei Province (modified from Feng et al., 1993).
Fig. 1. Carte paléogéographique de la Chine du Sud au Permien moyen et localisation de la coupe de Luojiaba dans la province de Hubei (modifiée d'après Feng et al., 1993).

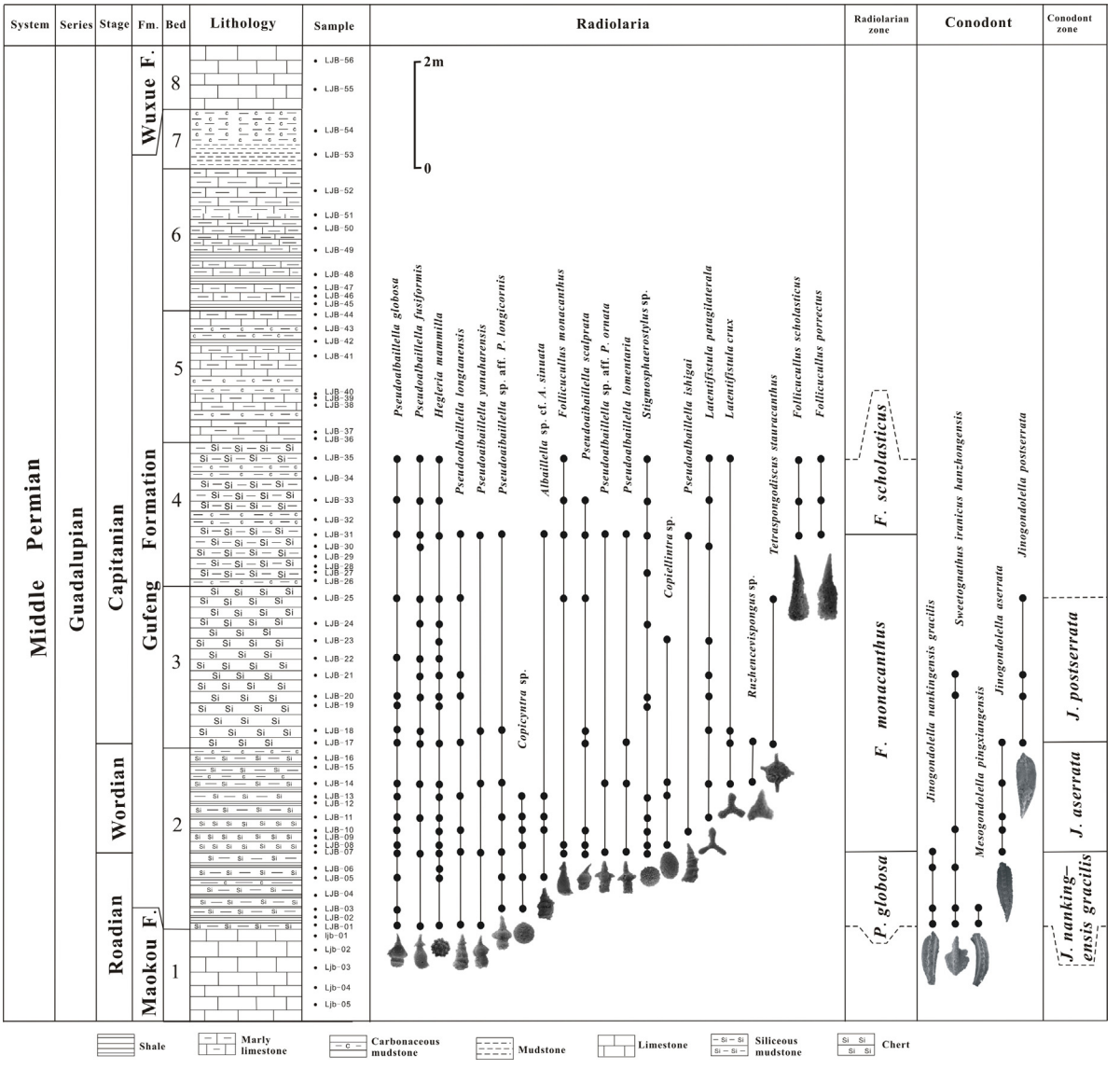

Fig. 2. Occurrence of radiolarian and conodont species identified throughout the Luojiaba section and its biostratigraphic subdivision.
Fig. 2. Distribution des espèces de radiolaires et de conodontes déterminées à travers la coupe de Luojiaba et son découpage biostratigraphique.

at room temperature. After being washed and dried, radiolarians and conodonts were carefully picked up from the residues under a binocular microscope. Finally, the microfossils were photographed with the use of a Quant200 scanning electron microscope.

4. Results

Radiolarians were obtained from twenty-three samples, 150 conodonts were found in eleven of them. Twenty-one radiolarian and 5 conodont species were identified. The position of the studied samples, the occurrence of the identified radiolarian and conodont species, as well as the radiolarian and conodont zones are given in Fig. 2. Details of the recognized biozones and their justification are as follows.

4.1. Radiolarian biozones

Following comparison with the known biozonal schemes available (e.g., De Wever et al., 2001; Ishiga, 1986, 1990; Sun and Xia, 2006; Wang and Yang, 2007, 2011; Wang et al., 1994, 2012; Zhang et al., 2014), three radiolarian zones are recognized in ascending order (Fig. 2).

The ***Pseudoalbaillela globosa* Zone** was defined by Ishiga (1986) and Sun and Xia (2006) as the interval between the first occurrence (FO) of *P. globosa* Ishiga and Imoto (Fig. 3, 16–18) and the FO of *Follicucullus monacanthus* Ishiga and Imoto. At Luojiaba section, the radiolarian fauna preserved within this biozone is abundant and highly diverse. The co-occurring species are mainly Albaillellids, including *P. fusiformis*, *P. longtanensis*, *P. yanaharensis*, *P.* sp. aff. *P. longicornis*, *Albaillella* sp. cf.

Fig. 3. Conodonts and radiolarians from the Luojiaba section. Scale bar = 100 μm for all illustrated specimens. **1–5**, *Jinogondolella nankingensis gracilis* (Clark & Ethington) Mei and Henderson, 2002. **1**, oblique upper view, LJB-01; 2, upper view, LJB-01; 3–4, upper view, LJB-03; 5, oblique upper view, LJB-07. **6–9**, *Jinogondolella aserrata* (Clark & Behnken, 1979). 6–7, upper view, LJB-07; 8, upper view, LJB-10; 9, upper view, LJB-17. **10–11**, *Jinogondolella postserrata* (Behnken, 1975). 10, upper view, LJB-17; 11, upper view, LJB-21. **12–13**, *Sweetognathus iranicus hanzhongensis* (Wang, 1978). 12, upper view, LJB-01; 13, upper view, LJB-21. **14–15**, *Mesogondolella pingxiangensis* Zhang, Hederson and Xia, 2010. 14, oblique upper view, LJB-01; 15, upper view, LJB-03. **16–18**, *Pseudoalbaillella globosa* Ishiga and Imoto, 1982. 16, LJB-7; 17, LJB-11; 18, LJB-25. **19–21**, *Follicucullus monacanthus* Ishiga and Imoto, 1982. 19, LJB-07; 20, LJB-33; 21, LJB-35. **22–23**, *Follicucullus porrectus* Rudenko, 1984. 22, LJB-31; 23, LJB-35. **24–25**, *Follicucullus sholasticus* Ormiston and Babcock, 1979. 24, LJB-31; 25, LJB-33.

Fig. 3. Conodontes et radiolaires extraits de la coupe de Luojiaba. Échelle = 100 μm pour tous les spécimens illustrés.

A. sinuata. Spumellarian polycystines are few, with only *Hegleria mammilla* and *Copicyntra* sp. being present (Fig. 2).

This biozone is widespread in southern China (eg. Sun and Xia, 2006; Wang and Yang, 2007, 2011), Southwest Japan (Ishiga, 1986, 1990), Far East Russia (Kotlyar et al., 2007; Rudenko and Panasenko, 1997), and North America (Blome and Reed, 1992).

The ***Follicucullus monacanthus* Zone** was defined initially by Ishiga (1986) as the interval between the FO of *F. monacanthus* Ishiga and Imoto (Fig. 3, 19–21) and the FO of *F. scholasticus* m. I. It corresponds to the *F. monacanthus* and *F. porrectus* zones recently established by Zhang et al. (2014). At Luojiaba, abundant radiolarians were discovered from this biozone; in addition to the index species a number of other Albaillellids, such as *P. globosa*, *P. fusiformis*, *P. longtanensis*, *P. yanaharensis*, *P. lomentaria*, *P. ishigai*, *P.* sp. aff. *P. longicornis*, *P. scalprata*, *P.* sp. aff. *P. ornata* and *Albaillella* sp. cf. *A. sinuata*, dominate the assemblage and co-occur with some Spumellarian (*Hegleria mammilla*, *Tetraspongodiscus stauracanthus*, *Copicyntra* sp., *Copiellintra* sp.), Entactinarian (*Stigmosphaerostylus* sp.) and Latentifistularian (*Latentifistula crux*, *L. patagilaterala*, *Ruzhencevispongus* sp.) radiolarians.

The *F. monacanthus* radiolarian zone can be correlated to contemporary zones in southwest Japan (Ishiga, 1986, 1990), North America (Blome and Reed, 1992), Qinzhou

and Menglian areas (Guangxi and Yunnan provinces) of China (Wang et al., 1994), Far East Russia (Rudenko and Panasenko, 1997).

The ***Follicucullus scholasticus* Zone** was first introduced by Ormiston and Babcock (1979) (Fig. 3, 24–25). Ishiga (1986) divided it to *F. scholasticus* m. I and *F. scholasticus* m. II. However, *F. scholasticus* m. I is now considered as the typical morphotype for *F. scholasticus*, while *F. scholasticus* m. II is now assigned to *F. porrectus* Rudenko (Wang et al., 2012) (Fig. 3, 22–23). Based on data from the Guangxi province, the *F. scholasticus* zone is more recently defined as the interval between the FO of *F. scholasticus* Ormiston and Babcock (Fig. 3, 24–25) and the FO of *F. charveti* Caridroit and De Wever (Zhang et al., 2014). The base of this biozone at Luojiaba occurs at the level of sample LJB-31 based on the FO of *F. scholasticus*, but its top cannot be determined in the studied section due to the absence of Albaillellids in its uppermost part. The assemblage is characterized by the presence of abundant *F. scholasticus* and other abundant and diverse Albaillellids (*F. porrectus*, *P. globosa*, *P. fusiformis*, *P. scalprata*, *F. monacanthus*), as well as Spumellarians (*Hegleria mammilla*), Entactinarians (*Stigmosphaerostylus* sp.) and Latentifistularians (*Latentifistula crux*, *L. patagilaterala*) (Fig. 2).

This biozone is widespread in South China (e.g., Sun and Xia, 2006; Wang and Yang, 2007, 2011; Wang et al., 1994; Zhang et al., 2014), Southwest Japan (Ishiga, 1986, 1990), Far East Russia (e.g., Kotlyar et al., 2006, 2007; Suzuki et al., 2005), and North America (Blome and Reed, 1992).

4.2. Conodont fauna and biozones

At the Luojiaba section, five conodont species are identified, dominated by representatives of *Jinogondolella* and *Sweetognathus*. Based on the stratigraphic occurrence of the identified species, the following three biozones can be recognised in ascending order (Fig. 2):

***Jinogondolella nankingensis gracilis* Zone**. Its base is defined by the FO of *J. nankingensis gracilis* (Clark & Ethington) and its top by the FO of *J. aserrata* (Clark & Behnken). In this study, the top of this biozone can be clearly identified at the level of sample LJB-07. This conodont zone is characterized by abundant specimens of *J. nankingensis gracilis* (Fig. 3, 1–5), as well as *Sweetognathus iranicus hanzhongensis* and *Mesogondolella pingxiangensis* as associated conodont species. According to Zhang et al. (2010), this zone is correlated partly or entirely with the Roadian (Fig. 4) (Kitao, 1996).

***Jinogondolella aserrata* Zone**. It is defined by the total range of *J. aserrata* (Clark & Behnken) (Fig. 3, 6–9). Co-occurring conodont species are rare, with only *Sweetognathus iranicus hanzhongensis* being identified in the present study. The FO of *J. aserrata* establishes the boundary between the Roadian and the Wordian, as decided by the Subcommission on Permian Stratigraphy (2007). Previous studies (eg. Glenister et al., 1999; Kozur, 1995; Mei and Henderson, 2001, 2002; Mei et al., 1994) assigned the *J. aserrata* zone to the Wordian (Fig. 4).

***Jinogondolella postserrata* Zone**. The base of this zone is defined by the FO of *J. postserrata* (Behnken) (Fig. 3, 10–11); its top cannot be identified in this section. According to the recommendation of the Subcommission on Permian Stratigraphy (2007), the FO of *J. postserrata* pinpoints the Wordian-Capitanian (W-C) boundary.

4.3. Discussion

The discovery of radiolarians with co-occurring conodonts allows precise biostratigraphic and chronostratigraphic correlations and a good estimate of the sedimentation rate for the accumulation of the siliceous mudstone member of the Gufeng Formation.

i) The *Pseudoalbaillella globosa* radiolarian zone can be correlated (at least partly) with the *Jinogondolella nankingensis gracilis* conodont zone (Fig. 4). Consequently, the *P. globosa* zone can be correlated with the Roadian Stage. The result is consistent with biostratigraphic investigations from the southern part of South China (Zhang et al., 2010).

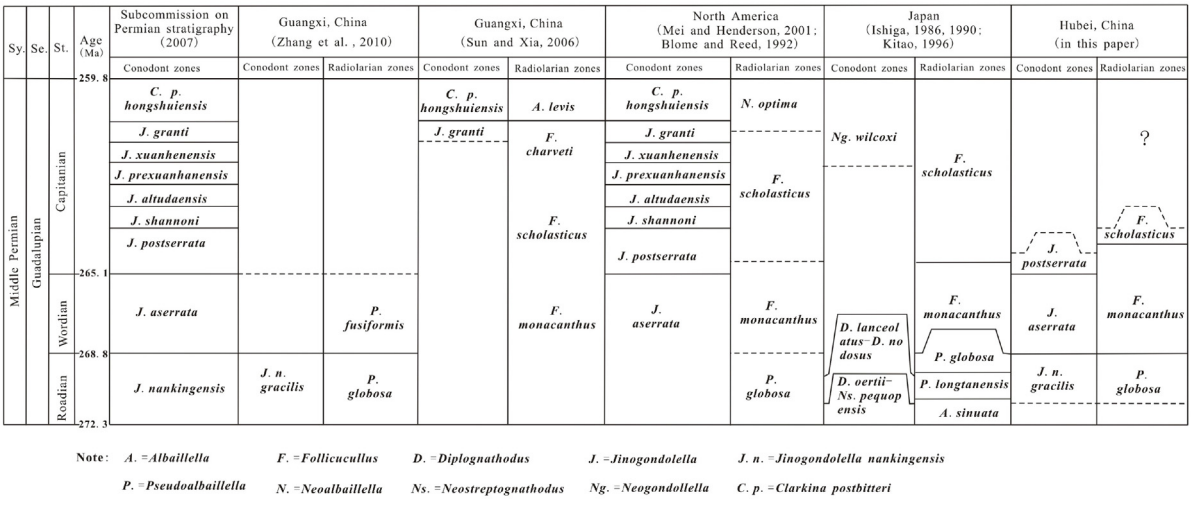

Fig. 4. Correlation chart of Middle Permian conodont and radiolarian biozones (time scale according to Gradstein et al., 2012).

Fig. 4. Tableau de corrélation des biozones de conodontes et de radiolaires du Permien moyen (échelle de temps d'après Gradstein et al., 2012).

ii) The *Follicucullus monacanthus* zone is found in southwest Japan, western North America, South and Southwest China, Malaysia and Thailand (Blome and Reed, 1992; Feng, 1992; Ishiga, 1986; Sashida et al., 1997; Spiller and Metcalfe, 1995; Wang et al., 1994). Previously, it has been roughly correlated with the Late Leonardian or Early Guadalupian (Blome and Reed, 1992; Ishiga, 1986; Wang et al., 1994). According to our data, the zone can be correlated with the *Jinogondolella aserrata* conodont zone, as well as with most of the *J. postserrata* zone. Therefore, the *F. monacanthus* radiolarian zone can be correlated with the Wordian to Early Capitanian interval, Middle Guadalupian (Fig. 4).

iii) Siliceous mudstones are important hydrocarbon source rocks in South China (eg., Niutitang Formation of Lower Cambrian, Tan et al., 2011; Wufeng Formation of Upper Ordovician, Lin et al., 2012; Gufeng Formation of Middle Permian, Wu et al., 2015; Dalong Formation of Upper Permian, Shen et al., 2014), and yield abundant radiolarians (Xiang et al., 2013). In the process of evaluating the potential of hydrocarbon source rocks, it is important to estimate their sedimentation rate. Based on the conodont biostratigraphic results, it has been estabilished that the *J. aserrata* zone in our section is 2.07 m-thick (confined between samples LJB-07 and LJB-17) (Fig. 2). The base and the top of this zone define the base and the top of the Wordian stage, respectively, with a duration of 3.7 Ma (Gradstein et al., 2012). Therefore, it can be suggested that the siliceous mudstone member (SMM, member 2) accumulated with a sedimentation rate (lithified sediments) of 0.559 m/Ma.

5. Conclusions

Abundant radiolarians and fairly numerous conodonts were obtained from the Middle Permian bedded chert sequence that crops out at the Luojiaba section. Direct correlation between the radiolarian and conodont zones establishes that most of the radiolarian *Pseudoalbaillella globosa* zone can be correlated with the Roadian Stage, that the *Follicucullus monacanthus* zone should be assigned to the Wordian-Early Capitanian interval and that the *Follicucullus scholasticus* zone should be correlated with the Middle Capitanian. The obtained conodont biostratigraphic results allow also to suggest that the siliceous mudstone member of the Gufeng Formation accumulated with a sedimentation rate (lithified sediments) of 0.559 m/Ma.

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