New biostratigraphic and chemostratigraphic data from the Ediacaran Doushantuo Formation in intra-shelf and upper slope facies of the Yangtze platform: Implications for biozonation of acanthomorphic acritarchs in South China

Andrew Donald Hawkins, Shuhai Xiao, Gaqing Jiang, Xinqiang Wang, Xiaoying Shi

Keywords: Ediacaran Period, Doushantuo Formation, Acritarch, Silification, Carbon isotopes

ABSTRACT

Carbon isotopic and microfossil records of the Doushantuo Formation in South China provide a valuable window onto major perturbations of the Ediacaran carbon cycle and the evolution of morphologically complex acanthomorphic acritarchs. Both records exhibit significant geographic heterogeneity related to environmental, taphonomic, and diagenetic variations. Absolute δ13C values vary by as much as 10‰ between sections of the Doushantuo Formation. The geographic and stratigraphic distribution of microfossils in the Doushantuo Formation is controlled by the occurrence of early diagenetic cherts and phosphorites that preserve microfossils. Early diagenetic cherts of the Doushantuo Formation have been investigated extensively at intra-shelf sections around the Huangling anticline but have been poorly documented elsewhere in South China. Here we present new petrographic and micropaleontological data from three Doushantuo sections to the south of the Huangling anticline, including the Wangzishi and Huangjiaping sections representing intra-shelf settings, as well as the Siduping section representing an upper slope setting. We also present δ13C data from Wangzishi. Petrographic observations indicate that some chert nodules at Siduping were formed in situ, whereas others were reworked and probably transported from the outer shelf along with olistostromes. Integrated lithostratigraphic and chemostratigraphic correlations suggest that the fossiliferous intervals at the three studied sections belong to the lower Doushantuo Formation. The new micropaleontological data extend the geographic range of Ediacaran acanthomorphs and suggest that elements of the Tanarium conoides–Hocosphaeridium scaberfacium–Hocosphaeridium anomos biozone recognized in the upper Doushantuo Formation around the Huangling anticline, specifically Hocosphaeridium anomos and Urasphaera nupta, are also present in the lower Doushantuo Formation at the Siduping section. The data suggest that the first appearance of Hocosphaeridium anomos may be in the δ13C chemostratigraphic feature EP1 and it is necessary to revise the acritarch biozonation developed in the Yangtze Gorges area. This study highlights the importance of integrating δ13C chemostratigraphic and acritarch biostratigraphic data from multiple facies to develop Ediacaran acanthomorph biozonation in South China and beyond.

1. Introduction

The Doushantuo Formation is exposed in outcrops scattered across hundreds of kilometers in South China and has yielded one of the richest paleobiological and geochemical records for the lower-middle Ediacaran System in the world (Jiang et al., 2011). Two components of the Doushantuo record in particular have received significant attention: carbon isotope data from carbonates and exceptionally preserved microfossils from early diagenetic cherts and phosphorites. The carbon isotope record of the Doushantuo Formation shows three negative δ13C excursions, the most pronounced of which has been suggested to correlate with the globally recognized Shuram excursion (Zhou and Xiao, 2007; McFadden et al., 2008; Zhu et al., 2013), one of the largest δ13C excursions in Earth history (Grotzinger et al., 2011).
Along with early diagenetic phosphorites (Xiao et al., 2014b), early diagenetic cherts are one of two types of Doushantuo lithologies that have yielded exceptionally preserved microfossils (Muscente et al., 2015). Thus, integrated carbon isotopic and micropaleontological data from the Doushantuo Formation and other Ediacaran successions are essential to improve the stratigraphic correlation and subdivision of the Ediacaran System (Xiao et al., 2016).

A notable feature of both the $\delta^{13}$C carb and silicified microfossil records of the Doushantuo Formation is their significant geographic variability. Although $\delta^{13}$C carb chemostratigraphic patterns are similar among different sections of the Doushantuo Formation, their absolute values sometimes vary by as much as 10‰ across the Yangtze Block (Jiang et al., 2007; Wang et al., 2016, 2017a). Similarly, the occurrence of early diagenetic and fossiliferous cherts is also geographically restricted (Muscente et al., 2015) and taphonomically variable (Zhou et al., 2007). Thus, it is critical to explore as many Doushantuo sections as possible in order to document the geographic heterogeneity of the $\delta^{13}$C carb record and the full stratigraphic range of silicified microfossils.

Previous studies of Doushantuo $\delta^{13}$C carb and silicified microfossils have been largely limited to sections in the Yangtze Gorges area around the southern part of the Huangling anticline (Fig. 1). These sections were deposited in an intra-shelf lagoon (Jiang et al., 2011), and while they may be endowed with favorable taphonomic conditions, bio- and chemostratigraphic models developed in the Yangtze Gorges area need to be tested at other sections beyond the Huangling anticline and in outer shelf to slope environments. At present, this task is challenging because $\delta^{13}$C carb and microfossil data from outer shelf and slope sections are limited, and integrated bio- and chemostratigraphic studies in these sections are few. For example, with a few exceptions (e.g., Yin, 1999; Ouyang et al., 2017; Nie et al., in press), fossiliferous chert nodules of the Doushantuo Formation are known almost exclusively in intra-shelf sections around the Huangling anticline (Liu et al., 2013, 2014a), and slope and basal sections have not been thoroughly explored for silicified microfossils. Similarly, investigation of $\delta^{13}$C$_{\text{carb}}$ chemostratigraphy has primarily been focused on intra-shelf sections (McFadden et al., 2008; Ader et al., 2009; Jiang et al., 2011; Zhu et al., 2013; Cui et al., 2015), with several exceptions (Jiang et al., 2007; Wang et al., 2016, 2017a). Importantly, integrated bio- and chemostratigraphic analyses of the Doushantuo Formation have so far been limited to the Yangtze Gorges area (e.g., McFadden et al., 2008; McFadden et al., 2009; Liu et al., 2013, 2014a), severely hampering our capability to develop a fuller understanding of both records and to evaluate chemostratigraphic and biostratigraphic markers for regional and global stratigraphic correlation (Xiao et al., 2016).

Here we present new petrographic, carbon isotopic, and micropaleontological data from three sections outside the Huangling anticline to address some of the geographic gaps in the records of silicified microfossils and $\delta^{13}$C$_{\text{carb}}$ in the Doushantuo Formation. The three
sections include the intra-shelf Wangzishi and Huangjiaping sections to the south of the Huangling anticline, as well as the upper-slope Siduping section (Fig. 1B). Petrographic observations indicate that early diagenetic cherts at these sections are taphonomically similar to those around the Huangling anticline (Xiao et al., 2010), although some cherts at the Siduping section were reworked and probably transported from elsewhere. The occurrence of silicified microfossils at these sections, and particularly the occurrence of acanthomorphic acritarchs in early diagenetic cherts at the Siduping section, extend the silification taphonomic window to the upper slope setting in the Yangtze Block (Ouyang et al., 2017). Integrated with new and previously published δ13C data from the Wangzishi and Siduping sections, we are able to improve our understanding of the δ13C and exceptionally preserved microfossil records within the Doushantuo Formation across the Yangtze platform, thus contributing to Ediacaran stratigraphic correlation in South China and beyond.

2. Background

2.1. Lithostratigraphy and facies variation of the Doushantuo Formation

The Doushantuo Formation was deposited in a passive continental margin setting on the Yangtze Block between 635 and 551 million years ago (Condon et al., 2005). It overlies the uppermost Cryogenian glacial diamictite of the Nantuo Formation, and is overlain by the upper Ediacaran Dengying Formation in the northwestern portion of the Yangtze Block and by the Liuchapo Formation in the southeast (Jiang et al., 2011). In its type area in the Yangtze Gorges, the Doushantuo Formation can be divided into four lithologic members (Zhao et al., 2013). Member I consists of an approximately 4-m-thick cap carbonate. Member II is 80–120 m in thickness and consists of interbedded black shales, dolostones, and muddy dolostones. Chert nodules occur abundantly in this member and contain exceptionally preserved microfossils, including acanthomorphic acritarchs (Xiao, 2004; McFadden et al., 2009; Liu et al., 2013, 2014b). Member III is 40–60 m in thickness and consists of medium bedded dolostone and sometimes interbedded limestone and silty dolostone. This member also contains fossiliferous chert nodules and banded cherts (Zhou et al., 2007; McFadden et al., 2009; Yin et al., 2009). At the well-studied Jialongwan section, Member IV consists of ~10 m of organic-rich black shale with large carbonate concretions. At some sections in the western part of the Huangling anticline, Member III is overlain by two black shales separated by a dolostone; Zhou et al. (2017) correlate these three units with Member IV, whereas An et al. (2015) correlate only the lower black shale with Member IV. These alternative correlations highlight the fact that the Doushantuo Formation exhibits significant lithofacies variation and that detailed lithostratigraphic correlation is not straightforward (Xiao et al., 2012).

To account for the lithofacies variation, Jiang et al. (2011) proposed that mixed carbonate and fine-grained siliciclastic sediments of the Doushantuo Formation around the Huangling anticline were deposited in a restricted intra-shelf lagoon, whereas slump-derived sediments and predominantly fine-grained siliciclastic sediments were deposited in slope and basin environments to the southeast (Fig. 1B). The lowermost Doushantuo Formation, as represented by Member I and the lowermost Member II, shows relatively little lithofacies variation, suggesting deposition from an open shelf during postglacial transgression. Later in the depositional history of the Doushantuo Formation, however, this open shelf configuration evolved into a rimmed platform, with the development of a shelf margin shoal complex (Jiang et al., 2011). The shelf rim runs in an approximately northeast-southwest direction (modern day orientation) from northeastern Hunan to northeastern-central Guizhou. A restricted intra-shelf lagoon was located to the northwest of this rim, with the slope and basin settings to the southeast on the ocean side of the platform margin.

The three sections sampled in this study—the Wangzishi, Huangjiaping, and Siduping sections (Fig. 1B)—represent two lithofacies in the Yangtze Block. The Wangzishi and Huangjiaping sections are located to the south of the Huangling anticline and were deposited in the intra-shelf lagoon. The stratigraphy in this area is broadly similar to other sections on the southern end of the Huangling anticline (e.g., the Jialongwan section) and the four member lithostratigraphic division developed on the southern end of the Huangling anticline can also be applied in this area. Significant portions of the Doushantuo Formation are covered by vegetation at both the Wangzishi and Huangjiaping sections and the exposed Doushantuo Formation is primarily limited to Member II. As a result, our measured sections at both localities are focused on Member II (Figs. 2 and 3). The Siduping section was deposited in an upper slope setting (Wang et al., 2016). The occurrence of olistostromes at multiple horizons (Fig. 4) indicates that Siduping sediments were supplied in part via downslope transport from the carbonate factory near the shelf-slope break. Syndepositional folds and slump blocks in these olistostrome beds demonstrate sediment mobilization and downslope transport before lithification (Vernhet et al., 2006; Wang et al., 2016).

2.2. Acanthomorph biozonation of the Doushantuo Formation

Two acritarch biozones have been recognized in the Doushantuo Formation around the Huangling anticline (McFadden et al., 2009; Liu et al., 2013, 2014a; Xiao et al., 2014a). The lower biozone (i.e., the Tanarhusia sinospina biozone) is dominated by Tanarhusia sinospina and has been recognized in Member II (McFadden et al., 2009; Liu et al., 2013). The base of the upper biozone (i.e., the Tanarrium conideum–Hocosphaeridium scaberfacium–Hocosphaeridium anomos biozone) is defined by the first occurrence of Hocosphaeridium anomos (Xiao et al., 2014a). In the Yangtze Gorges area, these two biozones are separated from each other by a barren interval characterized by the negative δ13C excursion E2 (Liu et al., 2013). It has been argued that the
stratigraphic ranges of Tianzhushania spinosa and Hocosphaeridium anozos do not overlap, with the former only in the lower biozone and the latter only in the upper (Liu et al., 2013). However, early diagenic phosphorites from the Weng’an area contain elements of both the upper and lower biozones including Tianzhushania spinosa and Hocosphaeridium anozos (Xiao et al., 2014a), suggesting that the stratigraphic ranges of these two taxa may overlap and that there may exist a transitional assemblage between the lower and upper biozones recognized in the Yangtze Gorges area. This suggestion is difficult to evaluate in the Yangtze Gorges area where the boundary between these two biozones falls within a barren interval devoid of early diagenetic cherts. Thus, it is imperative to investigate other Ediacaran sections beyond the Yangtze Gorges area to complement biostratigraphic data from the Huangling anticline.

2.3. δ^{13}C_carb chemostratigraphy of the Doushantuo Formation

Three negative δ^{13}C_carb excursions and two intervening positive excursions have been consistently recognized in the Doushantuo Formation around the Huangling anticline (Zhou and Xiao, 2007; Zhu et al., 2007, 2013; McFadden et al., 2008; Jiang et al., 2011; Wang et al., 2017b). The lowermost negative excursion, termed EN1, occurs within the cap carbonate, which contains microfabrics with extremely negative δ^{13}C_carb values characteristic of methane signatures at the Jiulongwan and Wangzishi sections (Jiang et al., 2003; Wang et al., 2008, 2017c). EN1 is followed by a positive excursion termed EP1 in Member II. The second negative excursion, EN2, occurs near the Member II/III boundary in the Yangtze Gorges area. Succeeding EN2 is a positive excursion (EP2) in the lower Member III. The third and largest negative excursion, EN3, occurs within upper Member III and possibly Member IV, and has been suggested as being correlative with the Shuram excursion (McFadden et al., 2008). Although additional excursions have been identified at some sections (Tahata et al., 2013; Zhu et al., 2013), these are not consistent chemostratigraphic features in the Yangtze Gorges area and may represent diageneric noises (Xiao et al., 2012).

3. Methods

The three sections at Wangzishi (30°32′34.00″N, 111°9′16.20″E), Huangjiaping (30°32′13.26″N, 111°10′2.88″E), and Siduping (28°54′48.90″N, 110°27′2.10″E) were measured and sampled for chert nodules during several field trips in 2007, 2008, 2011, and 2013. As the main goal of this study was to obtain biostratigraphic data from the upper slope setting, the Siduping section was targeted for high-resolution sampling, and supplementary samples were collected at the Wangzishi and Huangjiaping sections representing the intra-shelf setting outside the Huangling anticline. Chert nodules were collected for micropaleontological analysis and carbonate samples for δ^{13}C_carb analysis. All samples were cut perpendicular to the bedding surface to prepare thin sections for petrographic and micropaleontological analyses. A total of 243 thin sections were prepared and examined, including 191 from Siduping, 27 from Wangzishi, and 25 from Huangjiaping. Thin sections were examined for microfossils and petrographic features using an Olympus BX51 microscope. Microfossils were identified, photographed, and positioned using both Olympus BX51 and England Finder coordinates (Supplementary Table S1). Size measurements were made on photographs using imageJ.

Powders of carbonate samples from the Wangzishi section were prepared for δ^{13}C_carb and δ^{18}O_carb analysis. Approximately 100 µg of powder was allowed to react with orthophosphoric acid for 150–200 s at 72 °C in a Kiel IV carbonate device connected to a MAT 253 mass spectrometer. The analytical precision was better than ± 0.05% for δ^{13}C and ± 0.1‰ for δ^{18}O. Results are reported as per mil deviation from Vienna Pee Dee Belemnite (VPDB) (Supplementary Table S2). δ^{13}C_carb, δ^{18}O_carb, and δ^{13}C_organic data of the Siduping section were previously reported in Wang et al. (2016). Because the chemostratigraphic and biostratigraphic data from the Siduping sections were collected on the same field trip in 2007 (although additional biostratigraphic samples were taken in 2011 and 2013), we are able to tie the acanthomorphic data with the δ^{13}C_carb data (Fig. 4).

4. Results

4.1. Petrographic observations of chert nodules

Chert nodules from the Wangzishi and Huangjiaping sections are petrographically similar to those from the Doushantuo Formation in the Yangtze Gorges area (Xiao et al., 2010; Shen et al., 2011; Wen et al.,
By inference, they are genetically similar, having been formed in-situ within the sediments during early diagenesis. However, early diagenetic cherts from the Siduping section, ranging in size from ∼1 mm to centimeters, consist of round or oval nodules that were formed in-situ (Fig. 5A–E) as well as angular, subangular, and subrounded clasts that were reworked (Fig. 5F–K). In-situ chert nodules exhibit the same distinctive features as observed in early diagenetic chert nodules of the Doushantuo Formation around the Huangling anticline (Xiao et al., 2010). They are composed of a silica cortex surrounded by a pyrite rim (Fig. 5C–E) and in some cases a rind of secondary calcite. They are often oblate in shape, with the long axis following sedimentary laminae (Fig. 5D). Laminae within the silica cortex are concordant and often laterally connected with sedimentary laminae in the surrounding sediment matrix (Fig. 5D). Additionally, sedimentary laminae warp above and below in-situ chert nodules (Fig. 5D). These petrographic observations indicate that in-situ chert nodules were lithified before sediment compaction and have not been reworked afterwards.

In contrast, reworked chert clasts tend to occur in olistostrome beds (Figs. 4, 5F and G), suggesting that they, like the olistostromes (Vernhet et al., 2006), were also transported via gravity flows from shelf margin and upper slope environments. These chert clasts have laminae that are discordant with sedimentary laminae in surrounding sediments (Fig. 5H and I). They are often angular in shape (Fig. 5H and I), randomly oriented (Fig. 5H and I), abraded (Fig. 5J), and sometimes embedded within reworked carbonate clasts (Fig. 5J and K). These observations suggest that the reworked chert clasts were already lithified at the time of transportation. Thus, the microfossils preserved in reworked chert clasts, and in olistostrome beds in general, must have come from older strata deposited in shelf margin or upper slope environments. However, given that the reworked chert clasts contain characteristic Doushantuo acanthomorphs, they must have reworked from the Doushantuo Formation. Also, because some olistostromes show evidence of syndepositional soft-sediment deformation (Fig. 5G) (Vernhet et al., 2006), the remobilization of the olistostromes and chert clasts may have occurred prior to complete lithification of the matrix sediment. Thus, the reworked chert clasts could have come from penecontemporaneous or slightly older strata.
4.2. Microfossils

Stratigraphic occurrences of microfossils from the Wangzishi, Huangjiaping, and Siduping sections are shown in Figs. 2–4 and Supplementary Table S1. Only a single species of acanthomorphic acritarchs, *Tianzhushania spinosa* (Fig. 6A and B), was recovered from the Wangzishi section, and no acanthomorphs were recovered from the Huangjiaping section. Several species of filamentous and cocoidal microfossils were recovered from the Wangzishi and Huangjiaping sections, including *Siphonophycus robustum*, *S. kestron*, *Myxococcoides* sp., and *Archaeophycus yunnanensis* (Fig. 6C and D).

As shown in Fig. 4, microfossils were found in both in-situ chert nodules (e.g., Fig. 7C, E) and reworked chert clasts (Figs. 8 and 9) at the Siduping section. Acanthomorph species at the Siduping section include *Appendisphaera crebra* (Fig. 9E and F), *Appendisphaera? hemisphaerica* (Fig. 9C and D), *Asterocapsoides sinensis* (Fig. 8F), *Erichia sp.* (Fig. 8A and B), *Hocosphaeridium anaoz* (Fig. 7E and F; in in-situ chert nodules), *Mengeosphaera minima* (Fig. 7C; in in-situ chert nodules), and *Urasphaera nupta* (Fig. 8C and D). Despite the moderate diversity and abundance of acanthomorphs, the Siduping section is dominated by filamentous, cocoidal, and leiospheric microfossils, including *Siphonophycus robustum*, *S. kestron*, *S. typicum*, *Salome hubeiensis*, *Myxococcoides* sp., and *Leiosphaeridia* spp. A few specimens of multicellular algae have also been found, including a possible specimen of *Wengania* sp. (Fig. 7D). There are also a number of taxonomically unidentified specimens. Worth mentioning is an unidentified acritarch (Fig. 7A) characterized by an exceptionally large vesicle (~1100 μm in diameter) surrounded by a thick multilaminate layer, which is reminiscent of *Tianzhushania spinosa* except for the lack of discernable processes.

Overall, the Siduping microfossils are more strongly carbonized than those in the Yangtze Gorges area, probably due to greater burial depth and higher maturity of carbonaceous material. As such, delicate...
structures such as extremely thin processes are poorly preserved or completely obliterated (e.g., Fig. 9B, F), making it extremely difficult to document such delicate structures in light microscopy. All Siduping microfossils were recovered from a stratigraphic interval 40–90 m above the Nantuo-Doushantuo boundary, an interval characterized by exclusively positive δ¹³C₉ values and correlated with Member II and chemostratigraphic feature EP1 in the Yangtze Gorges area (Wang et al., 2016).

4.3. δ¹³C₉ data from the Wangzishi section

New δ¹³C₉ data from the Doushantuo Formation at the Wangzishi section are presented in Fig. 2. Although the δ¹³C₉ data from the Wangzishi section are limited to an approximately 40 m carbonate interval in the lower Doushantuo Formation, they are useful in chemostratigraphic correlation. The δ¹³C₉ values are exclusively positive, mostly between 4‰ and 8‰. Considering this carbonate unit is in the lower Doushantuo Formation and Tianzhushania spinosa occurs about 15 m above, the most parsimonious correlation is that the positive δ¹³C₉ values at Wangzishi represent EP1 seen at Siduping (Wang et al., 2016) and in the Yangtze Gorges area (Zhou and Xiao, 2007).

5. Discussion

5.1. Distribution of early diagenetic cherts in the Doushantuo Formation

Xiao et al. (2010) proposed that microbial sulfate reduction and the availability of reactive iron played an important role in the formation of a pyrite rim in fossiliferous chert nodules in the Doushantuo Formation. Muscente et al. (2015) further suggested that ferruginous conditions may have been conducive in chert nodule formation in the Doushantuo Formation. If correct, this model would predict that early diagenetic chert nodules were preferentially formed in sediments bathed in ferruginous waters and in stratigraphic intervals recording ferruginous conditions, but are largely absent in lithofacies recording oxic and euxinic redox conditions.

Paleo-redox analyses indicate that oceanic redox conditions during the deposition of the Doushantuo Formation were characterized by temporal fluctuations (Sahoo et al., 2016; Wang et al., 2017a) and spatial heterogeneities (Li et al., 2015, 2017). However, the overall redox architecture is that the open ocean in South China were redox-stratified during the early Ediacaran Period, with surface oxic waters overlying ferruginous waters that enveloped a euxinic wedge (Li et al., 2010). Based on a careful analysis of pyrite in the Doushantuo Formation, Wang et al. (2012) proposed that this euxinic wedge was located in the lower slope and that the upper slope was characterized by ferruginous conditions (perhaps with brief euxinic excursions related to the fluctuation of the chemocline). This hypothesis is supported by Sahoo et al. (2012), who presented Fe speciation data from the lower Doushantuo Formation, showing that the upper slope section at Taoying) is dominated by ferruginous shales whereas the lower slope Wuhe section is dominated by euxinic shales. Thus, the model of Muscente et al. (2015) would predict the presence of early diagenetic and fossiliferous chert nodules in upper slope facies such as the Siduping section and their absence in lower slope facies that intersected the euxinic wedge. This prediction is met by the discovery of early diagenetic and fossiliferous chert nodules at Siduping (Nie et al., in press) and at other upper slope sections (Ouyang et al., 2017). Obviously, as in most Doushantuo sections, fossiliferous chert nodules at the Siduping section occur in discreet horizons, indicating that even in the most favorable settings for early diagenetic chert formation, sufficient conditions were met only episodically. Either redox conditions fluctuated episodically (Wang et al., 2012), or in addition to ferruginous redox conditions, other factors (such as low sedimentation rates and local supply of organic matter needed for the initial nucleation of chert nodules) may have controlled the formation of early diagenetic chert nodules (Xiao et al., 2010).

The Siduping section is distinct from many other Doushantuo
sections in the occurrence of reworked chert nodules that are themselves fossiliferous and early diagenetic in origin. Our study shows that these reworked chert nodules at Siduping were likely formed in shallower facies during early diagenesis and then transported with olistostromes to Siduping. Obviously, such reworked chert nodules do not follow the Muscente et al. (2015) model about the distribution of early diagenetic chert nodules in the Doushantuo Formation, and they complicate our efforts to establish early-middle Ediacaran acanthomorph biozones in South China.

5.2. Acanthomorph biozones of the Doushantuo Formation

The interpretation of the microfossil record of the Doushantuo Formation at the Siduping section is somewhat complicated by the fact that a significant proportion of fossiliferous chert nodules at this section were reworked and probably transported from elsewhere. The prospect of time averaging due to downslope transport is most likely to obscure the acanthomorph biostratigraphic record at Siduping. However, petrographic observation suggests that the reworked chert clasts were likely derived from penecontemporaneous or slightly older strata. This inference is also supported by $\delta^{13}$C_carb, $\delta^{18}$O_carb, and $\delta^{13}$C_organic data, which show virtually no differences between carbonate clasts and matrix in olistostome beds, or between olistostome beds and adjacent beds (Wang et al., 2016). Thus, although there must be some degrees of time averaging, the biostratigraphic sequence should not have been altered beyond recognition. Furthermore, because reworking can only move clasts from older to younger strata, the observed fossil occurrences at Siduping cannot be older than their true (or pre-reworking) stratigraphic occurrences.

The small number of acanthomorphic acritarchs recovered from the
Siduping section precludes a rigorous quantitative description of the character of the acritarch assemblage. However, we can draw several conclusions from the data available. Acanthomorphic acritarchs recovered from the Siduping section include Doushantuo taxa from the Yangtze Gorges and Weng’an areas (Liu et al., 2014a; Xiao et al., 2014a). Importantly, the presence of *Hocosphaeridium anozos* in in-situ chert nodules in the lower Doushantuo Formation at Siduping is significant, because this species is one of the eponymous taxa of the *Tanarium conoideum–Hocosphaeridium scaberfacium–Hocosphaeridium anozos* biozone recognized in Member III and EP2 in the Yangtze Gorges area (Liu et al., 2013). Indeed, the first appearance of this species has been proposed to define the base of the *Tanarium conoideum–Hocosphaeridium scaberfacium–Hocosphaeridium anozos* biozone in the Yangtze Gorges area (Liu et al., 2014a; Xiao et al., 2014a). However, this species has also been found in the upper Doushantuo Formation at Weng’an, where it overlaps with *Tianzhushania spinosa* (Xiao et al., 2014a). Together, these biostratigraphic data suggest that the stratigraphic ranges of *Tianzhushania spinosa* and *Hocosphaeridium anozos* do overlap, although the first appearance datum of the former likely predates that of the latter. Furthermore, because at Siduping *Hocosphaeridium anozos* is present in strata correlated to Member II and EP1 (Wang et al., 2016), the traditional view that the *Tianzhushania spinosa* biozone is restricted to Member II and the *Tanarium conoideum–Hocosphaeridium scaberfacium–Hocosphaeridium anozos* biozone to Member III needs to be revised. This view was based on data from the Yangtze Gorges area where there is a barren interval around the Member II/III boundary and the exact boundary between the two biozones cannot be clarified (McFadden et al., 2009; Yin et al., 2009; Liu et al., 2013, 2014a). The new data from Siduping suggests that the *Tanarium conoideum–Hocosphaeridium scaberfacium–Hocosphaeridium anozos* biozone...
may start somewhere in Member II. Alternatively, if it is desirable to keep this acanthomorph biozone in Member III, then it should be redefined and a transitional biozone should be formally established to accommodate strata where *Tianzhushania spinosa* and *Hocosphaeridium anozos* co-exist, as proposed by Xiao et al. (2012) and Xiao et al. (2014a) based on Doushantuo acanthomorph data from Weng’an.

The inference that elements in the *Tanarium conoideum–Hocosphaeridium scaberfacium–Hocosphaeridium anozos* biozone may range stratigraphically downward relative to their occurrences in the Yangtze Gorges area (Liu et al., 2013, 2014a) is further supported by the discovery of *Urasphaera nupta*, *Appendisphaera? hemispherica*, *Appendisphaera crebra*, and *Mengeosphaera minima* in the lower Doushantuo Formation at Siduping. Of these species, *Urasphaera nupta* is morphological distinct and easily recognizable. All these species have been previously known from the *Tanarium conoideum–Hocosphaeridium scaberfacium–Hocosphaeridium anozos* biozone in the Yangtze Gorges area (Liu et al., 2013, 2014a), but the new data from Siduping show that they may extended to Member II.

The absence of *Tianzhushania spinosa* from the Siduping assemblage is probably a matter of taphonomic or sampling failure. Because of the poor preservation due to strong carbonization, delicate structures such as the extremely thin cylindrical processes of *Tianzhushania spinosa* may have been degraded. Indeed, the taxonomically unidentified acritarch illustrated in Fig. 7A and B may be such a degraded specimen of *Tianzhushania spinosa*, given its large vesicle surrounded by a thick multilaminate layer that is characteristic of *Tianzhushania spinosa*. In addition, the sampling intensity is rather low compared with the Yangtze Gorges sections, which have been studied for decades by many research groups.

We thus predict that, unless *Tianzhushania spinosa* was ecologically...
restricted to the intra-shelf, it should be present in the lower Doushantuo Formation at Siduping. This prediction is based on the lithostratigraphic and δ13C_carb chemostatigraphic correlation of the Siduping and Jiulongwan section (Wang et al., 2016), and is also supported by new δ13C_carb data and stratigraphic occurrence of Tianzhusan_iiia_ana_2a at the Wangzishi section (Figs. 2, 6A). Collectively, these data strongly suggest that the fossiliferous interval at Siduping is equivalent to Member II and chemostatigraphically correlated to EP1 in intra-shelf sections. Thus, Tianzhusan_iiia_ana_2a is expected to be present in the lower Doushantuo Formation at Siduping, a prediction that needs to be verified with better preserved specimens in future investigation.

Microfossil and δ13C_carb records from the Wangzishi section suggest that the sampled interval of the section correlates with the EP1 interval of the lower Doushantuo Formation in the Yangtze Gorges area. The range of δ13C_carb values, between 4‰ and 8‰, is consistent with δ13C_carb values observed within this interval elsewhere. The lack of biostatigraphically informative acritarchs in samples from the Huapingjia section precludes a confident correlation for this section; however, based on lithostratigraphy it is likely that the sampled portion of this section also correlates with Member II in the lower Doushantuo Formation in the Yangtze Gorges area. This inference is confirmed by Yin (1999), who has recovered Tianzhusan_iiia_ana_2a from the lower Doushantuo Formation at the Changyang section, which is only ~2 km to the south of Huapingjia.

6. Conclusion

Micropaleontological and petrographic data from the Wangzishi, Huapingjia, and Siduping sections combined with new δ13C_carb data from the Wangzishi section and previously published δ13C_carb data from the Siduping section provide new insights into the chemostatigraphic and biostatigraphic correlation of the Ediacaran Doushantuo Formation beyond the Huangling anticline in South China. Fossiliferous chert nodules at the Wangzishi and Huapingjia sections that were deposited in intra-shelf settings were formed in situ and are petrographically similar to those in other intra-shelf sections around the Huangling anticline. At the upper-slope Siduping section, both early diagenetic chert nodules formed in situ and reworked chert clasts transported via gravity flows are present, although the latter were likely remobilized from penecontemporaneous or slightly older strata. Acanthomorphic acritarchs were found in chert nodules at both Wangzishi and Huapingjia sections. Tianzhusan_iiia_ana_2a from the Wangzishi section occurs in the lower Doushantuo Formation (equivalent to Member II) above a carbonate unit characterized by δ13C_carb values that are correlated with the δ13C_carb feature EP1. Hocospheithrium_iiia_ana_2a, which currently defines the base of the Tanarrium_conoides–Hocospheithrium_scutiferum–Hocospheithrium_iiia_ana_2a biozone in Member III in the Yangtze Gorges area, occurs in strata equivalent to Member II and EP1 at the Siduping section. The new occurrence of Hocospheithrium_iiia_ana_2a at Siduping suggests that the Tanarrium_conoides–Hocospheithrium_scutiferum–Hocospheithrium_iiia_ana_2a biozone may not be restricted to Member III as previously thought. Instead, this biozone may extend to Member II. Alternatively, if it is desirable to keep this acanthomorph biozone in Member III, it should be redefined and a transitional biozone should be established to accommodate strata where the stratigraphic ranges of Tianzhusan_iiia_ana_2a and Hocospheithrium_iiia_ana_2a overlap.

Acknowledgements

The research was supported by the National Science Foundation (EAR-1528853), NASA Exobiology and Evolutionary Biology Program (NNX15AL27G), and National Natural Science Foundation of China (41272011). We thank Dr. Brian Romans and Dr. Benjamin Gill for useful discussion, Xiaoming Chen and Ke Pang for carbon isotope analysis, and Swapan Sahoo and an anonymous reviewer for constructive comments.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.precedm.2017.08.004.

References


Vernhet, E., Heubeck, C., Zhu, M.-Y., Zhang, J.-M., 2006. Large-scale slope instability at the southern margin of the Ediacaran Yangtze platform (Hunan province, central


