Towards an Ediacaran Time Scale: Problems, Protocols, and Prospects

The Ediacaran Period follows the Cryogenian Period in the wake of a snowball Earth glaciation and precedes the Cambrian Period with its rising tide of animal radiation. It is also the longest among all stratigraphically defined geological periods, lasting 94 million years (635–541 Ma). Hence, a good Ediacaran time scale is essential, not only to elucidate geological time, but also to provide a temporal context for extreme climatic events and transformative evolutionary transitions. Ediacaran fossils are known from many sections and boreholes around the world, permitting ready age recognition and stratigraphic correlation of Ediacaran strata. However, the Ediacaran fossil record is colored by taphonomic biases that variously affect the preservation of the soft-bodied organisms that dominated Ediacaran marine ecosystems, and the Phanerozoic approach of defining stratigraphic boundaries using the first appearance datum (FAD) of widely distributed, rapidly evolving, easily recognizable, and readily preservable species would have limited success in the Ediacaran System. The subdivision of the Ediacaran System must therefore be founded on a holistic approach integrating biostratigraphic, chemostratigraphic, and geochronometric data for correlation. Series-level subdivision of the Ediacaran System is a challenging task, and alternative models subdividing the Ediacaran System into two or three series can be recognized. Resolving these alternatives critically depends on obtaining further data to constrain the age, duration, and global extent of the Shuram negative $\delta^{13}$C excursion, to calibrate and correlate Ediacaran acanthomorph biozones, and to determine the temporal relationship among the Shuram excursion, the Gaskiers glaciation, and Ediacaran acanthomorph biozones. Stage-level subdivisions at the bottom and top of the Ediacaran System, however, are realistic goals in the near future, and we propose that the subdivision of the Ediacaran System should initially aim at the second Ediacaran stage (SES) and the terminal Ediacaran stage (TES) where stratigraphic information is relatively rich and consensus for stratigraphic correlation is emerging. Potential stratigraphic markers for the definition of the SES include the post-glacial radiation of eukaryotes as represented by the first appearance of acanthomorph acritarchs, the termination of the cap carbonate series, or the end of the negative $\delta^{13}$C excursion (EN1 = Ediacaran negative excursion 1) associated with the cap carbonate. Terminal Ediacaran strata are well dated and host several taxa of skeletal and tubular fossils that postdate the Shuram negative $\delta^{13}$C excursion (or its probable equivalent, EN3 = Ediacaran negative excursion 3) where their stratigraphic relationship can be determined; these biostratigraphic markers may be used to define the TES in a Phanerozoic fashion. Additional Ediacaran stages between the SES and TES can be envisioned. Through collaborative efforts in the Ediacaran
community, we hope that the first Precambrian stage will be established in the near future to facilitate a better understanding of the geological aftermath of snowball Earth, the redox history of global oceans, the early evolution of multicellular life, and the evolutionary fuse of the Cambrian explosion.

Introduction

The Ediacaran System was ratified in 2004 (Knoll et al., 2004; Knoll et al., 2006), with its basal boundary defined by a horizon near the base of the Nuccaleena Formation overlying the Cryogenian diamictite of the Elatina Formation at the Enorama Creek section in South Australia (Fig. 1). In 2004, the Subcommission on Ediacaran Stratigraphy (later renamed the Subcommission on Neoproterozoic Stratigraphy) was established to facilitate the correlation and subdivision of the Cryogenian and Ediacaran periods. The Subcommission on Neoproterozoic Stratigraphy conducted a survey in 2009 to gauge the community’s opinion on how to proceed with the subdivision and correlation of the Ediacaran System. Responses came from 20 voting members and 12 corresponding members. The results are summarized in Fig. 2. Briefly, the survey suggested that the Ediacaran System should be first divided into two series, with the lower series characterized by acanthomorphic acritarchs and the upper series by Ediacara-type macrofossils. It was further suggested that, ideally, the base of the upper Ediacaran series should be placed within an outcrop section that has good radiometric age constraints and has the potential for carbon isotope chemostratigraphic and acanthomorphic acritarch biostratigraphic correlation. At that time, it was felt that (1) the subdivision of the Ediacaran System should start with the establishment of two series before the definition of stages, (2) the most useful correlation tools included chemostratigraphy such as $\delta^{13}$C and $^{87}$Sr/$^{86}$Sr excursions, acanthomorphic acritarchs, and Ediacara-type macrofossils, and (3) good GSSPs should be fossiliferous, geochronometrically dated, and have mixed lithologies and the potential for chemostratigraphic and biostratigraphic correlations.

In 2012, the Subcommission on Neoproterozoic Stratigraphy was split into the Subcommission on Cryogenian Stratigraphy and the Subcommission on Ediacaran Stratigraphy. The stated goal of the Subcommission on Ediacaran Stratigraphy is to facilitate international communication and scientific cooperation in Ediacaran stratigraphy, with the ultimate goal to define, by means of GSSPs, a hierarchy of chronostratigraphic units that provide the framework for global correlation. In the past decade, the Subcommission on Ediacaran Stratigraphy and its predecessor organized and sponsored several field workshops to examine potential criteria for Ediacaran subdivision and correlation (Moczydlowska-Vidal et al., 2008; Kumar and Sharma, 2010; Xiao et al., 2011; Gehling and Droser, 2012; Gehling et al., 2012; Kumar and Sharma, 2012; Narbonne et al., 2012a; Kaufman et al., 2014; Pandey and Dimri, 2014; Singh and Ansari, 2014; Xiao and Sharma, 2014; Xiao et al., 2014b). As part of the efforts toward the establishment of intra-Ediacaran GSSPs, we have encouraged—at various scientific meetings and workshops, notably the 2014 Ediacaran Workshop in Wuhan, China, and the STRATI 2015 meeting in Graz, Austria—community-wide discussions about the subdivision and correlation of Ediacaran strata. The purpose of this paper is to summarize the key issues emerging from these discussions and to offer a view on strategies to move forward.

Problems and Challenges

The biostratigraphic and chemostratigraphic basis for the

Figure 1. Ediacaran GSSP (arrow) at Enorama Creek, South Australia.

Figure 2. Responses to the 2009 survey questions: (A) to rate the practicality of criteria for Ediacaran stratigraphic correlations, using a scale of 1 (least practical criterion) to 10 (most practical criterion); and (B) to evaluate the importance of factors that need to be considered in the process of selecting GSSPs for the subdivision of the Ediacaran System, using a scale of 1 (least important) to 10 (most important).
subdivision and correlation of Ediacaran strata has been summarized in Narbonne et al. (2012b), who acknowledged the unique challenges in Ediacaran biostatigraphy due to the dearth of skeletal fossils but also recognized potential opportunities of using climatic and chemostratigraphic events (e.g., Gaskiers glaciation and Shuram $\delta^{13}C$ excursion) as tools to correlate Ediacaran strata. The predominance of non-skeletal fossils in the Ediacaran System means that the documented stratigraphic range of key Ediacaran fossils is more prone to taphonomic limitations than their Phanerozoic counterparts. Hence, the index fossil approach using the first appearance datum (FAD) to define and correlate stratigraphic boundaries—so successfully employed in the establishment of Phanerozoic GSSPs—must be carefully scrutinized and tested against other independent approaches.

Because of this, the subdivision and correlation of the Ediacaran System needs to emphasize the characteristic stratigraphic content within the subdivision, as much as the stratigraphic marker at the subdivision boundary. Similarly, because of taphonomic biases in the preservation of soft-bodied organisms, correlation of Ediacaran strata is forced to be routinely based on non-biostatigraphic markers such as $\delta^{13}C$ chemostratigraphic excursions. However, correlation based on non-directional physical and chemical changes such as glaciation events and chemostratigraphic excursions requires independent calibrations using radiometric dates and biostratigraphic data. Recognizing these challenges, Narbonne et al. (2012) saw the benefits of examining alternative models to divide the Ediacaran System into two or three series (Fig. 3), although the initial survey of the Subcommission on Neoproterozoic Stratigraphy in 2009 recommended a two-series approach.

In the two-series model, the Ediacaran System would include a lower series characterized by acanthomorphic acritarchs and an upper series by Ediacara-type macrofossils. The two series would be separated from each other by the Gaskiers glaciation that is hypothetically correlated with a negative $\delta^{13}C$ excursion named EN2 or Ediacaran negative excursion 2 (Zhou and Xiao, 2007). The excursion EN2 occurs in the middle Doushantuo Formation in South China and is later recognized as BAINCE, or the Baiguoyuan negative excursion 3 (Zhu and Xiao, 2007). The other widely recognized negative $\delta^{13}C$ excursions in the Doushantuo Formation include EN1 (Ediacaran negative excursion 1) in the basal Doushantuo cap dolostone and EN3 (Ediacaran negative excursion 3) in the uppermost Doushantuo Formation (Jiang et al., 2007; Zhou and Xiao, 2007). In the two-series model, the most prominent negative $\delta^{13}C$ excursion in the Doushantuo Formation — namely EN3, which is widely regarded as a correlate of the Shuram negative $\delta^{13}C$ excursion (Grotzinger et al., 2011) — would be in the upper series and would be younger that the Gaskiers glaciation.

In the three-series model, the Ediacaran System would be divided into (1) a lower series characterized by the initial post-glacial radiation of eukaryotes as represented by the early acanthomorph assemblage of Tianzhushania spinosa (Fig. 4A) that primarily occurs in the lower Doushantuo Formation of South China (McFadden et al., 2009; Liu et al., 2013b; Xiao et al., 2014a), (2) a middle series characterized by more diverse acanthomorph assemblages (Fig. 4B–C) as represented by acritarch assemblages in Australia, Siberia, and the East European Platform, as well as the upper Doushantuo Formation in South China (Moczydłowska et al., 1993; Grey, 2005; Willman et al., 2006; Willman, 2007; Willman and Moczydłowska, 2008; Vorob’eva et al., 2009; Sergeev et al., 2011; Willman and Moczydłowska, 2011; Moczydłowska and Nagovitsin, 2012; Xiao et al., 2012; Liu et al., 2014d; Shukla and Tiwari, 2014; Joshi and Tiwari, 2016), and (3) an upper series branded by Ediacara-type macrofossils (Fig. 4D–F) and tubular and ribbon-shaped fossils (Fig. 4G–K) (Grazhdankin, 2014; Narbonne et al., 2014). In this model, it is implied that the Gaskiers glaciation is correlated with EN3 rather than EN2. As such, the lower and middle series would be separated by EN2, and the middle and upper series by Shuram/EN3 and by the Gaskiers glaciation.

As is clear from the two alternative models presented in Narbonne et al. (2012b), one of the most difficult tasks in Ediacaran stratigraphy is the correlation of biostatigraphic, chemostratigraphic, and climatic markers, and the difficulty stems from the fact that these markers tend to be preserved in different lithofacies and in different basins. For example, it is uncertain whether the negative $\delta^{13}C$ excursion associated with the Gaskiers diamicite in Newfoundland (Myrow and Kaufman, 1999) is of global extent, and how it is correlated with the multiple negative $\delta^{13}C$ excursions present in carbonate-dominated successions (e.g., in South China where no Gaskiers-age glacial diamicite was deposited). It is also a matter of debate whether Ediacaran negative $\delta^{13}C$ excursions—such as EN1 in the cap carbonate, EN2 in the middle Doushantuo Formation, and Shuram/EN3 in the Shuram Formation, upper Doushantuo Formation, Wonoka Formation, and other potentially correlate strata—represent disturbances of the global carbon cycle and thus have chemostratigraphic significance. If they do, then the temporal relationships between these negative $\delta^{13}C$ excursions and climatic and evolutionary events (e.g., the Gaskiers glaciation, Doushantu-Pertatataka-type acanthomorphs, and Ediacara-type macrofossils) need to be determined. Below, we offer a brief review of paleoclimatic, biostatigraphic, chemostratigraphic, and geochronometric data of the Ediacaran Period in order to illustrate some of these correlation problems.

**Paleoclimatic data**

Glacial diamicites of the Gaskiers Formation in Newfoundland are constrained between 583.7 Ma and 582.1 Ma (Fig. 5) (Hoffman and Li, 2009; Schmitz, 2012). Possible equivalents of the Gaskiers diamicite include the Squamuit Tillite in the Boston Basin (Thompson and Bowring, 2000), the Croles Hill diamicite in Tasmania (Calver et al., 2004), the Moelv diamicite in southern Norway (Bingen et al., 2005), the Hankalchough diamicite in Tarim (Xiao et al., 2004), and other diamicites in Western Australia, Baltica, Cadomia, Laurentia, and North China (Hoffman and Li, 2009; Li et al., 2013). However, Ediacaran successions in these areas are typically dominated by siliciclastics (Hoffman and Li, 2009), which render a spotty $\delta^{13}C$ chemostratigraphic record. Thus, direct correlation of the Gaskiers glaciation with $\delta^{13}C$ chemostratigraphic excursions is not straightforward, and indirect correlation must be dependent on acanthomorph biostatigraphy as a bridge. In this regard, the Biskopás Formation in southern Norway, which is older than the Moelv Formation and contains Doushantu-Pertatataka-type acanthomorphs (Vidal, 1990; Adamson and Butterfield, 2014), would provide insights into the temporal relationship between biostatigraphic zonations and climatic events. Biostatigraphic data from the Biskopás Formation suggest that at least some members of Doushantu-Pertatataka-type acanthomorphs appeared before the Gaskiers glaciation. Traditionally, Doushantu-Pertatataka-type acanthomorphs are believed to be restricted to the lower Ediacaran System, predating the Gaskiers glaciation.
Figure 3. Two models for Ediacaran subdivision and correlation, modified from Narbonne et al. (2012b). The key difference between these two models relates to how the Shuram excursion is correlated with the Gaskiers glaciation. Radiometric ages shown in red are from Schmitz (2012) and those shown in blue are from Noble et al. (2015). For clarity, all radiometric ages are rounded to the nearest integers. FES: first Ediacaran stage; SES: second Ediacaran stage; TES: terminal Ediacaran stage.
Figure 4. Representative Ediacaran fossils, including acanthomorphs from the early-middle Ediacaran (A–C), Ediacara-type macrofossils from the middle-upper Ediacaran (D–E), and Ediacara-type macrofossil (F) and tubular or ribbon-shaped fossils (G–K) from the terminal Ediacaran. (A) *Tianzhushania spinosa* from lower Member II of the Doushantuo Formation in the Yangtze Gorges area, South China. WD-71-5 (156×34.5), 7.35 m above top of cap dolostone (Zhou et al., 2007). (B) *Tanarium digitiformum* (PN8/4-17/7-2) and (C) *Tanarium tuberosum* (PN8/4-17/6-3) from the Ura Formation of eastern Siberia (Moczydlowska and Nagovitsin, 2012). (D) Rangeomorph *Beothukis mistakensis* (NFM F-758) in the Avalon assemblage, Trepassy Formation, Spaniard’s Bay, Newfoundland (Narbonne et al., 2009). (E) *Tribrachidium heraldicum* (lower) and *Solza margarita* (upper) in the White Sea assemblage, Yorga Formation, Zimnie Gory, White Sea, Russia. (F) *Swartpuntia germisi* in the Nama assemblage, Spitzkopf Member, Urusis Formation, Nama Group, Farm Swartpunt, southern Namibia. (G–H) Phosphatized *Cloudina riemkeae* (LJG-174048), (I) *Sinotubulites baimatuoensis* (courtesy of Zhe Chen), and (J) *Conotubus hemiannulatus* (20040128, courtesy of Yaoping Cai), Dengying Formation, southern Shaanxi Province, South China. (H) is longitudinal cross section of (G), showing nested funnels (Hua et al., 2005). (K) *Shaanxilithes ningqiangensis*, Taozichong Formation, Guizhou Province, South China (Hua et al., 2004).
glaciation and the Shuram excursion (Zhou et al., 2007). However, elements of Doushantuo-Pertatataka-type acanthomorphs have recently been reported from presumably terminal Ediacaran strata (Golubkova et al., 2015); these occurrences need to be critically evaluated in order to test the two alternative models of correlation (Fig. 3).

**Biostratigraphic data**

Doushantuo-Pertatataka-type acanthomorphs have been recovered from a number of Ediacaran successions in South China (Liu et al., 2014d; Xiao et al., 2014a), Australia (Grey, 2005; Willman et al., 2006; Willman, 2007; Willman and Moczydlowska, 2008, 2011), Siberia (Moczydlowska et al., 1993; Sergeev et al., 2011; Moczydlowska and Nagovitsin, 2012), India (Shukla and Tiwari, 2014; Joshi and Tiwari, 2016), Svalbard (Knoll, 1992), and the East European Platform (Vorob’eva et al., 2009; Golubkova et al., 2015). Doushantuo-Pertatataka-type acanthomorphs as a whole seem to be restricted to the lower Ediacaran System, below the Gaskiers-age Moev diamicite in southern Norway and below negative δ13C excursions in South China, South Australia, and Siberia that are interpreted as equivalent to the Shuram excursion (Fig. 5). However, as mentioned above, recent reports of elements of Doushantuo-Pertatataka-type acanthomorphs in terminal Ediacaran rocks (Golubkova et al., 2015) need to be assessed critically.

Acanthomorph biozonation has been applied with variable success in different basins. Four acanthomorph assemblage zones have been recognized in Australia (Grey, 2005), but their application in biostratigraphic correlation outside Australia has met with limited success. For example, although many of the Australian species have been recognized in Ediacaran successions in South China, Siberia, and the East European Platform, a succession of the four Australian assemblage zones have not been documented in these areas. In South China, two acanthomorph assemblage zones are recognized instead—the *Tianzhushania spinosa* assemblage zone in the lower Doushantuo Formation and the *Hocosphaeridium anozos* assemblage zone in the middle-upper Doushantuo Formation (Liu et al., 2014d; Xiao et al., 2014a). The *Tianzhushania spinosa* assemblage zone begins shortly after the basal Ediacaran cap carbonate (McFadden et al., 2009), in close proximity to the 632.48±1.02 Ma age. It has been proposed that the *Tianzhushania spinosa* assemblage zone may have been missing—for taphonomic, paleoecological, or paleobiogeographic reasons—from early Ediacaran successions in most other continents, and that the *Hocosphaeridium anozos* assemblage zone may be correlated with the four acanthomorph assemblage zones recognized in Australia (Liu et al., 2014d; Xiao et al., 2014a), but this correlation needs to be further investigated.

Ediacaran acanthomorph biostratigraphy is complicated by taphonomic vagaries in the preservation, environmental control on the distribution, and inconsistencies in the taxonomy of Ediacaran acanthomorphs. Acanthomorphs preserved in chert nodules and phosphorites, in particular, are subject to taphonomic biases associated with authigenic mineralization (Zhou et al., 2007; Muscente et al., 2015). This is best illustrated by the significant variation in acanthomorph abundance and diversity among different Doushantuo sections in the Yangtze Gorges area (Zhou et al., 2007; McFadden et al., 2009; Muscente et al., 2015). Taphonomic degradation also introduces morphological alterations that could compromise taxonomic identification (Grey and Willman, 2009). In addition, preliminary data show that the distribution of Ediacaran acanthomorphs may be facies dependent, and paleoenvironments may be a factor that controls the presence or absence of acanthomorph taxa (Zhou et al., 2007; Nagovitsin and Kochnev, 2015). Furthermore, acanthomorphs preserved in cherts, phosphorites, and shales are analyzed using different techniques (e.g., thin sectioning, acetic acid maceration, and hydrofluoric acid maceration, respectively). These different methods can also introduce inconsistencies in acanthomorph taxonomy (Xiao et al., 2014a). Due to these taphonomic and methodological factors, it is possible that the taxonomic diversity of Ediacaran acanthomorphs has been greatly inflated and major efforts to standardize acanthomorph taxonomy are needed in order to enable biostratigraphic subdivision and correlation.

Certain taxa or assemblages of Ediacara-type macrofossils may also have biostratigraphic significance. Ediacara-type fossils consist of macroscopic, soft-bodied, morphologically complex, and phylogenetically diverse eukaryotes including animals (Narbonne, 2005; Xiao and Laflamme, 2009; Laflamme et al., 2013; Liu et al., 2014a). These organisms have a global distribution with species reported from every continent except Antarctica. Three assemblages of Ediacara-type macrofossils have been recognized, including the Avalon, White Sea, and Nama assemblages (Waggoner, 1999, 2003; Shen et al., 2008). Although paleoecology and paleoenvironments may have exerted some control on the spatial and temporal distribution of these three assemblages (Grazhdankin, 2004; Gehling and Droser, 2013), evolutionary succession seems to be a major factor (Grazhdankin, 2014; Grazhdankin and Maslov, 2015). As such, these three assemblages may have biostratigraphic significance.

However, the greatest difficulty in using Ediacara macrofossils *sensu stricto* (i.e., soft-bodied Ediacara macrofossils excluding skeletal fossils such as *Cloudina, Namacalathus*, and *Sinitubaliites*) for biostratigraphic purposes lies in their mode of preservation. The overwhelming majority of Ediacara-type macrofossils are preserved as impressions on the tops and bottoms of fine- to medium-grained sandstone beds, and in rare instances as casts/molds or carbonaceous compressions in carbonates or mudstones (Sun, 1986; Grazhdankin et al., 2008; Zhu et al., 2008; Xiao et al., 2013; Chen et al., 2014). Their preservation requires a series of exceptional circumstances, the origins of which are still not fully understood (Gehling, 1999; Narbonne, 2005; Laflamme et al., 2011; Darroch et al., 2012; Kenting and Wilby, 2014). Unique taphonomic settings linked to the vast expanses of microbial mats in Ediacaran oceans may have played a constructive role to improve the preservational fidelity of Ediacara macrofossils (Callow and Brasier, 2009), but how they may have biased the preservation of soft-bodied Ediacara-type macrofossils is unknown. These taphonomic biases must be analyzed and considered when using the PAD of Ediacara-type macrofossils for biostratigraphic correlation. In addition, because the majority of Ediacara-type macrofossils are preserved in siliciclastic successions, which are inappropriate for chemostratigraphic analysis, their correlation with δ13C excursions is not an easy task. In this regard, the search of Ediacara-type macrofossils in carbonate successions (Sun, 1986; Grazhdankin et al., 2008; Chen et al., 2014) and δ13C chemostratigraphic analysis of carbonate interbeds in predominantly siliciclastic successions that bear Ediacara-type macrofossils (Macdonald et al., 2013; Wood et al., 2015) would alleviate some of the problems hampering the correlation between Ediacara-type fossils and δ13C excursions.

Several macrofossils from terminal Ediacaran strata stand out for their preservation potential and potential biostratigraphic correlation. In particular, *Tianzhushania spinosa* and *Hocosphaeridium anozos* may be useful for biostratigraphic correlation, as they are preserved in a variety of sedimentary environments and have been reported from a number of Ediacaran successions in different continents. However, further research is needed to fully understand their distribution and correlation potential.
Figure 5. Representative δ¹³C profiles with approximate horizons of fossil occurrences in Ediacaran successions. Oman: δ¹³C data shown in blue from Fike et al. (2006); δ¹³C data shown in red from Amthor et al. (2003). Siberia: δ¹³C data shown in blue from Ura Uplift section and δ¹³C data shown in red from Zhuya River section (Pokrovskii et al., 2006); biostratigraphic data from Sergeev et al. (2011) and Moczydowska and Nagovitsin (2012). South Australia: δ¹³C data of the Wonoka Formation from canyon shoulder section 1 in the Flinders Ranges (Husson et al., 2015) and δ¹³C data of the Nuccaleena Formation from Calver (2000); biostratigraphic data from Jenkins (1995), Gehling (2000), and (Gey, 2005). South China: δ¹³C data of the Doushantuo Formation from McFadden et al. (2008) and Li et al. (2010), δ¹³C data of the Dengying Formation from Wang et al. (2014), δ¹³C data of the Yanjiahe Formation from Ishikawa et al. (2008), Jiang et al. (2012), and Ishikawa et al. (2013); biostratigraphic data from Liu et al. (2014d), Cai et al. (2010, 2015), Meyer et al. (2012), Chen et al. (2013, 2014) and Cortijo et al. (2015a). Weiscke and Mackenzie Mountains, Northwestern Canada: δ¹³C data from Macdonald et al. (2013); radiometric date from Rooney et al. (2015); biostratigraphic data from Macdonald et al. (2013), Narbonne et al. (2014), and Carbone and Narbonne (2014). Southern Namibia: δ¹³C data shown in blue from Brak section and δ¹³C data shown in red from Zebra River section, both in Zaris Sub-basin (Wood et al., 2015); biostratigraphic data from Germs (1995), Grotzinger et al. (1995), Jensen et al. (2000), Jensen and Runnegar (2005), and Wood et al. (2015). Northern Namibia: δ¹³C data from Halverson et al. (2005). Newfoundland: biostratigraphic data from Narbonne and Gehling (2003), Liu et al. (2010), and Liu et al. (2014b). All radiometric dates are cited from Schmitz (2012) unless otherwise noted. NK: Nikol’skoe Formation; DK: Dzhemkukan Formation; TN: Tinnaya Formation; ABC: ABC Range Quartzite; UT: Uratanna Formation; BF: Blueflower Formation; GT: Gametrail Formation; JB: June beds; YJH: Yanjiahe Formation.
their potential as biostратigraphic markers in the Phanerozoic sense (i.e., their FAD may be useful in the definition and correlation of Ediacaran subdivisions). These include the biomineralizing animals Cloudina (Fig. 4G–H), Sinotubulites (Fig. 4I), and Namacalathus (Grant, 1990; Cai et al., 2015; Zhuravlev et al., 2015; Boag et al., in review). Among these, the tubular fossil Cloudina is the most widespread (Fig. 5), occurring in terminal Ediacaran successions in Namibia (Grant, 1990; Oman (Conway Morris et al., 1990), South China (Hua et al., 2005; Cai et al., 2013; Cortijo et al., 2015a), Spain (Cortijo et al., 2010; Cortijo et al., 2015b), Siberia (Kontorovich et al., 2008; Zhuravlev et al., 2012; Grazhdankin et al., 2015), Canada (Hofmann and Mountjoy, 2001), Mexico (Sour-Tovar et al., 2007), Brazil and Uruguay (Gaucher et al., 2003), and eastern California and Nevada where it was described as Nevada tubulatus dunfee by Signor et al. (1987) but considered as Cloudina by Grant (1990) and Zhuravlev et al. (2012). Another biomineralized tubular fossil, Sinotubulites, also has a wide geographic distribution and has been recovered from terminal Ediacaran strata in South China (Cai et al., 2015), Mexico (McMenamin, 1985), eastern California and Nevada (Signor et al., 1987), and Spain (Cortijo et al., 2015b). The colonial stalked cups of the Ediacaran shelly fossil Namacalathus was first described from Namibia (Grotzinger et al., 2000; Zhuravlev et al., 2015) and also occurs in terminal Ediacaran strata in western Canada (Hofmann and Mountjoy, 2001), Oman (Amthor et al., 2003), and Siberia (Kontorovich et al., 2008; Grazhdankin et al., 2015). Additionally, the problematic ribbon-shaped or tubular fossil Shaaxxlithes have been found in terminal Ediacaran rocks in South China (Meyer et al., 2012), North China and Chaidam blocks (Shen et al., 2007), India (Tarhan et al., 2014), and Siberia (Zhuravlev et al., 2009; Cai and Hua, 2011). Finally, the organic tubular fossil Sabellidites cambriensis first appears in terminal Ediacaran rocks in the East European Platform (Moczydłowska et al., 2014), although it does extend into the basin Cambrian (Narbonne et al., 1987; Landing, 1994). These tubular fossils have the potential to improve the precision of bioclastic biostatigraphic correlation of terminal Ediacaran strata. However, in order to realize their full potential as biostatigraphic markers, taxonomic issues surrounding these taxa need to be resolved. For example, the species-level taxonomy of Cloudina and Sinotubulites needs to be agreed upon (Grant, 1990; Hua et al., 2003; Cai et al., 2015), and the taxonomic relationship between Shaaxxlithes and other problematic terminal Ediacaran fossils such as Xenoxites needs to be resolved (Rogov et al., 2012; Brasier et al., 2013). Additionally, high-resolution biostatigraphic study of these fossils and integration with chemostratigraphic data are required in order to project their correlation potential to areas where they are absent.

Bilaterian trace fossils are moderately abundant in many upper Ediacaran successions (Fig. 5), including the Ediacara Member of South Australia (Jenkins, 1995), the Dengying Formation in South China (Chen et al., 2013; Meyer et al., 2014b), Ediacaran rocks in the East European Platform (Paczesny, 1986; Fedonkin, 1990; Paczesny, 1996; Grazhdankin, 2014; Paczesny, 2014), the Blueflower Formation in the Mackenzie Mountains (Carbonine and Narbonne, 2014), and the Nama Group in Namibia (Jensen et al., 2000; Jensen and Runnegar, 2005; Macdonald et al., 2014). In Newfoundland, structures interpreted as cnidarian traces have been found in ~565 Ma Mistaken Point Formation, representing some of the earliest known evidence for locomotive animals (Liu et al., 2010; Liu et al., 2014b). Overall, all convincing bilaterian trace fossils are restricted to upper Ediacaran rocks, but more work needs to be done in order to determine whether it is possible to select a particular ichnotaxon that has a wide geographical distribution for Ediacaran subdivision and correlation.

Macroalgal fossils have been reported from several Ediacaran successions (Xiao and Dong, 2006; Ye et al., 2015), but their stratigraphic and geographic distribution is limited by the narrow taphonomic window in which these fossils are preserved. The most diverse macroalgal assemblages come from the Lantian, Doushantu, and Liuchapo formations in South China (Steiner, 1994; Xiao et al., 2002; Yuan et al., 2011), as well as the Khatsypt Formation in Siberia (Grazhdankin et al., 2008) and the Pervelok Formation in the Central Urals (Grazhdankin et al., 2007; Marusin et al., 2011). Ribbon-shaped vendotaenid macrofossils are abundant in many late Ediacaran successions, including Vendian strata in the East European Platform (Gnilovskaya et al., 1988), the Dengying Formation in South China (Zhao et al., 1988), and the Feldschuhhorn Member of the Urusis Formation in southern Namibia (Cohen et al., 2009). However, these vendotaenid fossils are morphologically simple, and similar morphotypes may be present in much older rocks (Ye et al., 2015). Overall, Ediacaran macroalgal fossils are of limited biostratigraphic significance because of their restricted distribution and simple morphologies.

**Chemostratigraphic data**

Chemostratigraphy has been commonly used in Ediacaran stratigraphic correlation. The rapid growth of δ13C data, in part driven by the investigation of Ediacaran redox history and climate changes, allows us to test the global extent and stratigraphic consistency of δ13C variations (Fig. 5). Several authors have compiled composite δ13C curves for the Ediacaran Period (Halverson et al., 2005; Halverson et al., 2010; Macdonald et al., 2013). These compilations consistently show a large negative δ13C excursion—first identified in the Shuram Formation in Oman (Burns and Matter, 1993)—that may be useful in global chemostratigraphic correlation of Ediacaran carbonate rocks. Possible equivalents of the Shuram excursion include the EN3 excursion in the upper Doushantu Formation in South China, the Zhuya (=Nikol’skoe + Chena) excursion in Siberia, the Wonoka excursion in South Australia, the Gametrail excursion in northwestern Canada, and the Kanies/Mara excursion in southern Namibia (Fig. 5 and references cited in figure caption). Additional correlatives include the Raintorm Member in Death Valley (Kaufman et al., 2007; Bergmann et al., 2011; Verdel et al., 2011), the Member E of the Nyborg Formation in eastern Norway (Halverson et al., 2005; Rice et al., 2011), and possibly the Shuqian excursion in the Tarim block (Xiao et al., 2004), but these successions are dominated by siliciclastics and, as a result, their δ13C records are stratigraphically sporadic and more susceptible to isotopic mixing with authigenic carbonates (Macdonald et al., 2013; Schrag et al., 2013). Current controversies surrounding the Shuram excursion and its potential correlates include (1) its origin: whether the Shuram excursion represents a disturbance of the global ocean DIC reservoir due to oxidation of organic carbon or methane (Rothman et al., 2003; Fike et al., 2006; Kaufman et al., 2007; McFadden et al., 2008; Bjerrum and Canfield, 2011), reflects conditions conducive to authigenic carbonate precipitation (Grotzinger et al., 2011; Macdonald et al., 2013; Schrag et al., 2013), or results from burial or meteoric diagenesis (Knauth and Kennedy, 2009; Derry,
2010); (2) its complexity: whether the Shuram excursion consists of a simple negative anomaly (Fike et al., 2006; Le Guerroué et al., 2006; An et al., 2015) or a complex negative anomaly punctuated with one or more small-scale positive anomalies (Condon et al., 2005; Verdel et al., 2011; Lu et al., 2013; Zhou et al., in press); and (3) its age and duration: whether it is roughly concurrent with or postdates the 582 Ma Gaskiers glaciation (Fig. 3), and whether it lasted a few million years or up to 50 million years (Le Guerroué et al., 2006). These uncertainties hinder the application of the Shuram excursion in chemostratigraphic correlation of Ediacaran strata, and they are the main reasons behind the two different versions of Ediacaran subdivision (Fig. 3) (Narbonne et al., 2012b).

Strontium isotope chemostratigraphy can also be very useful in the correlation of Ediacaran carbonate strata (Fig. 6, assuming correlation model 2 in Fig. 3). Basal Ediacaran cap carbonates overlying Cryogenian diamicrites tend to have highly variable and sometimes highly elevated 87Sr/86Sr ratios (Sawaki et al., 2010), probably due to variable diagenetic alteration or mixing with glacial meltwaters carrying radiogenic signals derived from continental weathering (Liu et al., 2013a; Liu et al., 2014c). Assuming that the lowest 87Sr/86Sr ratios of the cap carbonates represent seawater signals, Ediacaran carbonates appear to record stepwise increase in 87Sr/86Sr ratios, first from ~0.7073 in the cap carbonates to a plateau of 0.7080 that characterizes the lower Ediacaran System, then rising to a peak of ~0.7090 roughly concurrent with the Shuram excursion, and finally falling back to 0.7085 in terminal Ediacaran (Fig. 6). Because the Sr system is sensitive to diagenetic alteration (e.g., dolomitization) and contamination from detrital components, reliable 87Sr/86Sr measurements only come from pristine limestones. This again raises the issue of cross correlation with successions dominated by dolostones and siliciclastic rocks.

**Geochronometric data**

Ultimately, the integration of biostratigraphy (e.g., acanthomorphs, Ediacara-type macrofossils, tubular fossils, and trace fossils) and chemostratigraphy (e.g., Δ 13C and 87Sr/86Sr) requires radiometric dates to anchor key stratigraphic markers. Currently, high-precision radiometric dates are concentrated in the upper Ediacaran (560–541 Ma). With the exception of clustered radiometric dates in the basal Ediacaran and in the middle Ediacaran (in association with the Gaskiers glaciation), the lower-middle Ediacaran System is poorly dated globally (Fig. 3). Importantly, the Shuram/EN3 excursion and the diversification of acanthomorphs in Australia, Siberia, and the East European Platform have not been constrained with precise radiometric dates; EN3 in the uppermost Doushantuo Formation is constrained to be >551.09±1.02 Ma (Fig. 5), however Re-Os ages (Zhu et al., 2013a) and a radical revision of Ediacaran stratigraphic correlation in the Yangtze Gorges area (An et al., 2015) indicate that EN3 may be significantly older than 551 Ma. With these uncertainties, the alternative models of stratigraphic correlation using the Shuram excursion cannot be resolved (Fig. 3). These two models have different implications for the relative timing of biostratigraphic, chemostratigraphic, and climatic events. Most obviously, the temporal relationship between the Shuram excursion and the Gaskiers glaciation has not been resolved (Fig. 3). Critically, the temporal relationship between the Shuram excursion and the first appearance of Ediacara-type macrofossils is also uncertain. For example, assuming that the Gametrail Formation in the Wernecke Mountains (which is characterized by a pronounced negative δ 13C excursion) and the Gametrail Formation in the Mackenzie Mountains (which records only a moderate negative δ 13C excursion) are both equivalent to the Shuram excursion (Macdonald et al., 2013), the occurrence of rangelormorph Ediacara-type fossils in the underlying June beds in the Mackenzie Mountains (Narbonne et al., 2014) suggests the first appearance of rangelormorphs before the Shuram excursion. These rangeormorphs would postdate the Gaskiers glaciation in correlation model 1, but they predate the Gaskiers glaciation in correlation model 2 (Fig. 3). Macdonald et al. (2013) favored correlation model 1, because the June beds rangeormorph taxa are also found in strata overlying the Gaskiers Formation in Newfoundland. This proposition could be tested directly if the Shuram excursion were radiometrically dated.
Protocols and Strategies

Recognizing the existing challenges in defining Ediacaran series, in the 2014 Wuhan workshop the Subcommission proposed that the subdivision of the Ediacaran System should proceed from the definition of stages, first focusing on the second and the terminal Ediacaran stages, where consensus is emerging with regard to stratigraphic markers of global significance. Thus, the Subcommission established the Second Ediacaran Stage Working Group (SES-WG) and the Terminal Ediacaran Stage Working Group (TES-WG) to focus on these boundaries. The establishment of these two working groups has been communicated to the Ediacaran community in the 2015 Subcommission newsletter. These working groups will organize focused symposia, field workshops, and surveys in order to (1) evaluate potential criteria for the definition of SES and TES; (2) visit, assess, and select GSSP candidates; and (3) formalize the stratigraphic names for the SES and TES, as well as the first Ediacaran stage (FES). Following the successful examples of the Subcommission on Cambrian Stratigraphy, we recommend that the informal stage names SES, TES, and FES be used in scientific communication (Fig. 3) before GSSPs and formal stage names are ratified.

The SES and TES will remain the priorities of the Subcommission in the next few years. We hope that, with the collective efforts of the community, we will be able to achieve our goal of defining the SES and TES in the near future, and then move to the next phase of defining the Ediacaran series and further subdivision of these series.

Prospects

Formulating the Terminal Ediacaran Stage (TES)

Potential criteria for recognizing the terminal Ediacaran stage (TES) are summarized above and in Fig. 3. The oldest skeletal animals in Earth history are represented by Cloudina, Sinotubulites, Namacalathus, and other terminal Ediacaran taxa. These shelly taxa are abundant and globally distributed in terminal Ediacaran strata (see above) but apparently disappear abruptly at the Ediacaran-Cambrian boundary (Amthor et al., 2003; but see Yang et al., 2016), enhancing their utility as index fossils for a terminal Ediacaran stage. Tubular or ribbon-shaped organic compressions are also especially abundant and diverse in rocks of terminal Ediacaran age. Of particular importance are the widely distributed taxa Vendotaenia (Cohen et al., 2009) and Sabellidites (Moczydlowska et al., 2014), although both of these taxa range into younger and/or older strata. Cambroradula decurvatus and Anabarites trisulcatus have been reported from rocks believed to be terminal Ediacaran in age (Nagovitsin et al., 2015; Rogov et al., 2015), but they also extend into the Cambrian, and their terminal Ediacaran occurrences need to be evaluated in conjunction with the current efforts of the Cambrian Subcommission to examine the Ediacaran-Cambrian boundary (Babcock et al., 2014). In contrast, some less widespread taxa such as Corambella (Babcock et al., 2005), Conotubus (Cai et al., 2011; Strange and Rowland, 2015; Smith et al., 2016), Wutubus (Chen et al., 2014), and Sekwitubulus (Carbone et al., 2015) are presently known only from the terminal Ediacaran. Elucidating the taxonomy, ecology, affinities and distribution of the abundant organic tubes that characterize terminal Ediacaran strata will be critical to understanding the paleobiology of this ultimate stage of Ediacaran life.

Other biostratigraphic indicators can also be used to recognize this stage (Fig. 3). Ediacara-type fossils in the Nama assemblage are much less common and less diverse than in the earlier Avalon and White Sea assemblages, and consist mainly of a low diversity of long-ranging taxa such as Pteridinium and Rangea (Shen et al., 2008; Chen et al., 2014; Meyer et al., 2014a; Darroch et al., 2015; Kolesnikov et al., 2015). However, two iconic erinomorph taxa, Swartpantia and Ernietta, are locally abundant in and potentially restricted to terminal Ediacaran strata, although both taxa are known with certainty only from Namibia and the southwest USA (Narbonne et al., 1997; Hagadorn and Waggoner, 2000; Ivantsov et al., 2015; Elliott et al., 2016); several questionable reports of older and younger specimens require further documentation, description, and verification. Horizontal trace fossils are moderately abundant in most terminal Ediacaran successions (see above), and the oldest treptichnid burrows make their first debut in terminal Ediacaran strata (Jensen et al., 2000). In contrast to the diverse assemblages of ornamented acritarchs that permit zonation of older Ediacaran strata (Fig. 3), terminal Ediacaran strata are typified by low diversity acritarch assemblages consisting mostly of smooth leiospheres.

Chemostratigraphy and radiometric dating will be critical in defining the terminal Ediacaran stage. Carbonates in terminal Ediacaran successions typically exhibit slightly to moderately positive δ13C values (Wood et al., 2015; Cui et al., 2016) that lie above strongly negative C-isotope signals potentially correlatable with the Shuram anomaly (Fig. 5). Several negative δ13C excursions are recorded in the Ediacaran of South China (Fig. 5), emphasizing the need for multiple lines of evidence to test and confirm chemostratigraphic correlations. High-precision U-Pb dates from Namibia and South China imply that the base of the oldest Ediacaran shelly fossils in those sections is <551 Ma (Fig. 5), potentially providing a radiometric date for the base of the terminal Ediacaran stage.

Sections that exhibit many or most of these criteria occur in southern Africa (Namibia), Asia (South China and northeastern Siberia), Europe (Spain and northern Norway), western North America (California/Nevada, southern British Columbia, Yukon/ Northwest Territories), and eastern South America (Brazil, Paraguay). Many of these sections exhibit broad-scale intercalations of siliciclastic and carbonate strata, a feature that significantly increases our ability to integrate the multiple biostratigraphic and chemostratigraphic indicators needed to define and correlate a terminal Ediacaran stage. Site visits to key sections commenced in 2014 and will continue in the next few years. A special issue describing and integrating all major sections and correlation techniques for the terminal Ediacaran is planned for 2018, and balloting to define a GSSP for the terminal Ediacaran stage will commence a few months later.

Formulating the Second Ediacaran Stage (SES)

Fewer stratigraphic markers are available in the lower Ediacaran to define the Second Ediacaran stage. One of the stratigraphic markers of global extent is the termination of the cap dolostone overlying terminal Cryogenian glacigenic deposits. The duration of cap dolostone deposition is no more than 10^6 years (Trindade et al., 2003; Font et al., 2010), which would make the first Ediacaran stage (FES) one of the shortest in the geological time scale. It has been proposed that both the top and bottom boundaries of the cap dolostone may be diachronous (Hoffman et al., 2007); however, if the diachronocity is on the order of less than 10^4 years, then the top boundary of the cap
The cap carbonate series, which includes both the cap dolostone and overlying limestone (Hoffman et al., 1998; James et al., 2001), also has a wide geographic distribution. Its duration is ~3 million years given available zircon U-Pb ages (Schmitz, 2012), including a $635.21\pm0.59$ Ma age from within the terminal Cryogenian glaciogenic deposits (Hoffmann et al., 2004; Prave et al., 2016), a $635.26\pm1.07$ Ma age from within the cap dolostone (Condon et al., 2005), a $632.48\pm1.02$ Ma age from about 5 m above the cap carbonate (Condon et al., 2005), and a $632.3\pm5.9$ Ma age from the basal Sheepbed Formation 0.9 m above the cap carbonate near Shale Lake in the Mackenzie Mountains (Rooney et al., 2015). If the top of the cap carbonate series is used as a marker to define the base of SES, then the FES would be <3 million years in duration, on a par with many Phanerozoic stage-level subdivisions. At this time scale, the kind of diachronity discussed in Hoffman et al. (2007) would be negligible.

The cap carbonate series is typically characterized by negative $\delta^{13}$C values (e.g., EN1 in South China). The cross-over to positive $\delta^{13}$C values occurs near the top of the cap carbonate series (Hoffman et al., 1998), although in South China there are many oscillations perhaps related to diagenetic alteration (McFadden et al., 2008; Tahata et al., 2013). The cap carbonate series is also characterized by a rising trend of $^{87}Sr/^{86}Sr$ ratios from ~0.7073 to 0.7080 (Fig. 6) (Halverson et al., 2007). Additionally, the FAD of *Tianzhushania spinosa*—thus far the earliest known Doushantuo-Pertatataka-type acanthomorph—occurs within a few meters above the cap carbonate and in close proximity to the $632.48\pm1.02$ Ma age (Zhou et al., 2007; McFadden et al., 2009). Thus, there are biostratigraphic, lithostratigraphic, and unique lithostratigraphic markers clustered around a horizon dated at 632 Ma. Individually, these markers would be less useful. For example, the occurrence of *Tianzhushania spinosa* may be controlled by its limited biogeographic, ecological, or taphonomic distributions. This species has been reliably reported only from South China and India (Tiwari and Azmi, 1992; Joshi and Tiwari, 2016). An unnamed acanthomorph (Knoll, 1992) from Svalbard, has been synonymized with *Tianzhushania spinosa* (Zhang et al., 1998). Together, these biostratigraphic, chemostratigraphic, lithostratigraphic, and geochronological data would enable global correlation through their linkages with climatic, geochemical, and evolutionary events. This integrative approach offers the greatest potential to define the SES.

**Conclusions**

The subdivision and correlation of Ediacaran strata face unique challenges because of the dearth of skeletal fossils, taphonomic biases in the preservation of soft-bodied organisms, the limited number of high-precision radiometric dates, and lithofacies dependency of certain chemostratigraphic and biostratigraphic data. As such, there are currently significant challenges in dividing the Ediacaran System into two or three series (Fig. 3). The radiometrically constrained Gaskiers glaciation would be a convenient marker for series-level subdivision, but its temporal relationships with the Shuram excursion and biozones of Doushantuo-Pertatataka-type acanthomorphs are uncertain, limiting its utility as a global stratigraphic marker. Future research should focus on resolving the age, duration, and temporal relationship of key evolutionary,geochemical, and climatic changes in the Ediacaran Period.

However, the multiplication of new biostratigraphic, chemostratigraphic, and geochronometric data suggests the optimism of defining the second and terminal Ediacaran stages in the near future. Terminal Ediacaran strata host a series of more or less evenly spaced and high-precision radiometric ages. There are several potential stratigraphic markers (e.g., first appearance of *Cloudina, Sinotubulites, Shaanxilithes, Namacalathus*, taxa of Ediacara-type macrofossils and trace fossils, and post-Shuram $^{87}$Sr/$^{86}$Sr variations) that can be used to define the terminal Ediacaran stage (TES). It is more challenging to define the second Ediacaran stage (SES) because of the fewer number of reliable stratigraphic markers, but the first appearance of an acanthomorph species, the termination of cap carbonate deposition, or the end of EN1 $^{87}$Sr/$^{86}$Sr excursion and its equivalents should be investigated as potential criteria to demarcate the end of the first Ediacaran stage (FES) and to define the second Ediacaran stage (SES).

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