Gondwana Research 28 (2015) 432–450

Contents lists available at ScienceDirect

Gondwana Research

journal homepage: www.elsevier.com/locate/gr

Mass-occurrence of oncoids at the Cambrian Series 2–Series 3 transition: Implications for microbial resurgence following an Early Cambrian extinction

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ARTICLE INFO

Article history:
Received 22 October 2013
Received in revised form 21 March 2014
Accepted 22 March 2014
Available online 18 April 2014

Handling Editor: G.C. Zhao

Keywords:
Oncoids
Organomineralization
Extinction
Anoxic event
Early Cambrian

ABSTRACT

The traditional Lower–Middle Cambrian transition (Cambrian Series 2–Series 3 transition) is marked by the first major biotic extinction of the Phanerozoic Eon. This biotic crisis has been arguably linked to changes in ocean chemistry and/or marine environments but their casual relationships remain controversial. To better understand the microbial responses to paleoceanographic changes across this critical transition, we have studied the environmental conditions for mass–occurrence of oncoids in the western North China Platform. Oncoids at the Lower–Middle Cambrian transition form 1 to 3-m-thick massive beds, show spherical–subspherical morphology, and contain 8–14 light–dark cortical laminar couplets. The light laminae are thicker and contain densely intertwined filamentous cyanobacteria that have calcified sheaths and a prostrate growth pattern. The dark laminae are thinner and rich in organic matter relics, pyrite framboids, and heterotrophic bacteria. In most oncoids, cortical laminae show the same growth orientation for more than five light–dark laminar couplets, suggesting much less frequent grain overturning than generally thought. Both light and dark laminae contain well-preserved organomineralization fabrics/textures including extracellular polymeric substances (EPSs), nanoglobules, polyhedrons, and micropeloids, suggesting oncoid formation in shallow-marine environments with high alkalinity and active sulfate reduction. The presence of pyrite framboids and heterotrophic bacterial relics implies anoxic/dysoxic bottom-water conditions. Stratigraphic correlation indicates that time-equivalent oncolites and other microbialites are widespread not only in North China, but also in other Early Cambrian successions globally. The mass-occurrence of oncoids coincides with the Kalkarindji large igneous province of Australia, a prominent negative $\delta^{13}C$ excursion (ROECE or Redlichiid–Olenellid Extinction Carbon isotope Excursion), a significant increase in $^{87}Sr/^{86}Sr$, and a large positive shift in $\delta^{34}S$. The coincidence of these events suggests that the Early Cambrian biotic crisis may have been caused by an ocean anoxic event resulting from enhanced volcanic release of CO_2, global warming, and increased continental weathering. Preservation of massive oncolites is likely related to decreased metazoan grazing following an Early Cambrian biotic crisis, during which archaeocyathids and many Early Cambrian trilobite taxa went to extinction. The oncoid mass-occurrence provides evidence for the resurgence of microbial life in anoxic/dysoxic marine shelf environments concomitant with the Early Cambrian extinction event.

1. Introduction

The abundance and distribution of microbialites in geological record provide information on the responses of microbial community to environmental and ecological changes (Riding and Liang, 2005; Wood, 2004; Dupraz et al., 2009; Harwood and Sumner, 2011). Numerous studies have demonstrated that the composition, microfabrics and organomineralization features of microbialites can be used to analyze the environmental conditions of microbial ecosystems, such as water depth, temperature, carbonate saturation and redox state (e.g., Woods and Baud, 2008; Kershaw et al., 2012; Mata and Bottjer, 2012; Tang et al., 2013a, 2013b). Particularly during the Phanerozoic, when the preservation of microbialites has greatly reduced due to metazoan grazing and ecological competition (Grotzinger and Knoll, 1999; Riding and Liang, 2005), the mass-occurrence of microbialites is commonly interpreted as recording rapid colonization and ecological expansion of microbes in highly stressed environments where benthic metazoans were largely depressed (Schubert and Bottjer, 1992; Wood, 2000; Whalen et al., 2002; Wang et al., 2005; Kershaw et al., 2007, 2012; Lee et al., 2012).

Oncoids are coated grains larger than 2 mm in diameter that exhibit irregularly concentric laminae (i.e., coatings or cortex) surrounding a

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http://dx.doi.org/10.1016/j.gr.2014.03.015
1342-937X/

nucleus of detrital origin (Tucker and Wright, 1990; Flügel, 2010). They were once called as “spheroidal stromatolites” or “algal balls” (Riding and Voronova, 1982). In general, the formation of oncoids involves microbial encrusting (e.g., Peryt, 1981; Jones and Renaut, 1997; Hägele et al., 2006). Thus, oncolites are generally regarded as a type of microbialites (Tucker and Wright, 1990; Riding, 2000; Shapiro et al., 2009). Oncoids have been recorded in shallow-marine strata from the Paleoproterozoic to Cenozoic (e.g., Li et al., 2000; Schaefer et al., 2001; Shi and Chen, 2006; Reolid and Nieto, 2010; Lazăr et al., 2013). They are also known in a variety of modern depositional environments, such as peritidal beach (e.g., Peryt, 1981; Alshuaibi et al., 2012), fresh-water lakes and rivers (e.g., Davaud and Girardclos, 2001; Hägele et al., 2006), salt lakes (Jones and Renaut, 1994), soil pockets (Jones, 2011), hot springs (e.g., Renaut et al., 1996; Jones et al., 1999a, 1999b), and deep-marine environments below photic zone (Wang et al., 2012b), where environmental conditions are commonly less favorable for benthic metazoans (e.g., Renaut et al., 1996; Hägele et al., 2006).

It is commonly thought that turbulent hydraulics and frequent grain overturning are required for developing the spherical morphology and syn-axial laminations in the cortex of oncoids (e.g., Tucker and Wright, 1990; Shi and Chen, 2006; Flügel, 2010; Zatoń et al., 2012). Therefore, in facies analyses the presence of oncoids in marine carbonate strata has often been taken as an indicator for shallow and agitated depositional environments (e.g., Lanés and Palma, 1998; Shi and Chen, 2006; Flügel, 2010). Many studies, however, indicated that oncoids can form by in situ microbial accretion, not necessarily requiring turbulent hydraulic condition and grain overturning (e.g., Dahanayake et al., 1985; Leinfelder and Hartkopf-Fröder, 1990; Hägele et al., 2006; Shapiro et al., 2009; Jones, 2011; Zatoń et al., 2012). For example, some polymetallic (Fe, Mn, Co, and Ni) nodules on modern ocean seafloor are considered as a kind of oncoids resulted from biogeochemical processes in deep, quiet environments below the photic zone (e.g., Chen et al., 1997; Préat et al., 2011; Wang et al., 2012b). In Mesozoic marine environments of the western Tethys Ocean, ferromanganese macro-oncoids are known to have formed along hardground surfaces and condensed intervals. Some of them were formed far below fair-weather wave base without frequent bottom-water agitation (e.g., Gradziński et al., 2004; Védrine et al., 2007; Reolid and Nieto, 2010; Préat et al., 2011; Zatoń et al., 2012; Lazăr et al., 2013). The occurrence of oncoids in a wide spectrum of environments, their morphological variability, and diverse mineral compositions likely imply that microbes and chemical conditions in waters may have played more important roles in oncoid formation than previously thought (e.g., Hägele et al., 2006; Préat et al., 2011).

An intriguing phenomenon in the geological record that has not been adequately studied is the global occurrence of massive oncolites and other microbialites at the traditional Lower–Middle Cambrian transition (or Cambrian Series 2–Series 3 transition in the new Geological Time Table) (e.g., Youngs, 1978; Shi et al., 1997, 1999; Álvaro et al., 2000; Elicki et al., 2002; Sundberg, 2005; Powell et al., 2006; Yang et al., 2011, 2013; Perejón et al., 2012). Paleontological evidence has shown that a major biotic extinction occurred at this time interval, during which many trilobite taxa and archaeocyathids disappeared (e.g., Zhuravlev and Wood, 1996; Palmer, 1998; Erwin, 2001; Yuan et al., 2002; Hallam, 2005; Peng et al., 2012). Associated with this extinction are prominent changes in seawater carbon, sulfur isotope compositions and $^{87}Sr/^{86}Sr$ ratios (e.g., Montañez et al., 2000; Hough et al., 2006; Zhu et al., 2006). Although there are persistent debates on the bio- and chemostratigraphic correlations and on the precise position of the Cambrian Series 2–Series 3 boundary (e.g., Gaines et al., 2011; Geyer and Peel, 2011; Peng et al., 2012; Álvaro et al., 2013; Gozalo et al., 2013; Landing et al., 2013), the temporal proximity of biological and geochemical events suggests a major paleoceanographic change. A detailed study of the massive oncolites may provide valuable information on the microbial responses to ecosystem changes and help to elucidate the cause of the Early Cambrian biotic extinction.

In this paper we report a comprehensive micro-texture study of the spectacular oncoids from the marine carbonate succession at the Cambrian Series 2–Series 3 transition of the western North China Platform. We mainly focus on the microfabrics and organominerals recognized in oncoid cortices at micro- to nano-meter scales using petrographic microscope, FESEM, EDS and XRF analyses. Micro-texture variations are used to interpret the organomineralization processes and microbe–environmental interactions during oncoid formation. Through a global correlation, we also discuss the casual link between the mass occurrence of oncoids and a possible anoxic event following the biotic extinction event at the Cambrian Series 2–Series 3 transition, with emphasis on the responses of microbial community to changes in ocean chemistry.

2. Geological background

During the Cambrian, the North China Platform was a flat-topped carbonate platform (Fig. 1A) developed after a long period of weathering since its uplift at ca. 850 Ma (e.g., Meng et al., 1997; Xiang et al., 1999; Wang et al., 2000; Cheng et al., 2009). In paleogeographical reconstruction, the North China Platform belongs to the Sino-Korean plate (Wang and Mo, 1995; Wang et al., 2000) that was located in the northern Gondwana continent, close to Australia (Wotte et al., 2007; Fig. 1B).

Following the breaking-up of the supercontinent Rodinia since the late Neoproterozoic, the North China Platform started to subside and receive sediments during the late Early Cambrian (Shi et al., 1997, 1999; Xiang et al., 1999; Wang et al., 2000). In most areas of the platform, the Cambrian Series 1 (i.e., the Terreneuvian) and parts of the Cambrian Series 2 strata are absent. Lithostratigraphic units for rest of the Cambrian are dominated by shallow-water carbonate rocks and are widespread across the platform (e.g., Xiang et al., 1981, 1999; Wang et al., 2000; Peng, 2009). For a given time interval, the major components of benthic fauna and sequence stratigraphic framework are highly comparable across the platform (Zhang et al., 1980; Wang et al., 2000; Cheng et al., 2009).

The Wuhai area of the Inner Mongolia (Fig. 1A) is located in the western margin of the North China Platform. In this area, the Lower Cambrian to Middle Ordovician strata are dominated by shallow-marine carbonates that show an overall shallowing-upward trend (e.g., Shi et al., 1999; Xiang et al., 1999; Wang et al., 2000). A major facies change happened during the latest Middle Ordovician when extension and subsidence occurred along the platform margin (Wang et al., 2000; Cheng et al., 2009). Late Ordovician strata in this area are characterized by deep-water dark graptolite shale and thick terrigenous slope deposits containing abundant slump blocks and turbidites (Wang et al., 2000; Cheng et al., 2009).

In Wuhai area, the Cambrian strata start with the Maozhuang Formation that unconformably overlies the Mesoproterozoic dolostone with locally abundant chert bands and columnar stromatolites (Wang et al., 2000; Cheng et al., 2009). In this formation, two depositional sequences can be recognized (Fig. 1C). The first sequence starts with limestone and silty shale and ends with fine- to medium-grained, cross-bedded quartz sandstone. The second sequence consists of greenish shale–wackestone in the lower part and wackestone–packstone in the upper part. Thick oncolite beds (about 8 m thick) occur in its uppermost part. The top of the second sequence is marked by a type-I sequence boundary characterized by exposure features and minor karst breccias (Fig. 1C). The Maozhaung Formation is overlain by the Xuzhuang Formation, which is dominated by bioturbated, micritic limestone and yellowish green shale, with some grainstone and flat-pebble conglomerate interbeds. In the Xuzhuang Formation, two depositional sequences are also recognizable (Fig. 1C), and oncolite beds are restricted to the lowermost part, less than 3 m thick. Oncoids from this part are commonly smaller (mean diameter of 13 mm) in size than those (average diameter of 15 mm) from the underlying Maozhuang Formation (Fig. 1C).