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Microbial mats in the terrestrial Lower Triassic of North China and implications for the Permian–Triassic mass extinction

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ABSTRACT

Evidence for microbial mats has been reported repeatedly from marine Lower Triassic rocks, but scarcely mentioned in post-mass extinction terrestrial facies. Here, we report from the terrestrial Lower Triassic Liujiagou Formation in North China the presence of five kinds of microbially induced sedimentary structures (MISS) or sedimentary surface textures, including "old elephant skin" textures, wrinkle structures, palimpsest ripples, "*Manchuriophycus*" structures and sand cracks. Terrestrial microbial communities that produced these MISS adapted not only to periodically desiccated conditions, but also to the storm-dominated palaeoenvironments in the Liujiagou Formation. The Permian–Triassic mass extinction (PTME) in North China is marked by the die-off of plants, disappearance of coal beds, extinction of pareiasaurs among tetrapods, decreased bioturbation levels and a dramatic change of sedimentary systems through the Sunjiagou Formation. The Sunjiagou Formation recorded the turnover from an ever-wet to a progressively drier and hotter climate and it spans the PTME in North China. Following this mass extinction, MISS became much more common and widespread, suggesting that the mass extinction provided favourable biological and environmental conditions for the development of the MISS in terrestrial ecosystems, especially the decreased bioturbation intensity and grazing pressure associated with increased temperature and climatic drying. In the upper part of the Liujiagou Formation and overlying Heshanggou Formation, the disappearance of MISS coupled with increased bioturbation might indicate an improvement of terrestrial ecosystems and the beginning of the Triassic biotic recovery. However, as the investigation of MISS in space and time through the geological record is in its early stages, further geobiologic and geochemical studies, as well as high-precision isotopic dating from Permian–Triassic terrestrial successions, are needed to fully reveal the timing and pattern of the Early Triassic terrestrial ecosystem reconstruction.

1. Introduction

Microbially induced sedimentary structures (MISS) were produced by the interaction between microbial activities and physical sedimentary processes in ancient siliciclastic and carbonate depositional systems (Hagadorn and Bottjer, 1997; Noffke et al., 2001; Noffke, 2009, 2010). These structures are always preserved on the upper surfaces of the substrate, which now form rock bedding planes, but the original microbial mats are hardly observed because of destruction during diagenetic processes that followed MISS formation. Analysis of the formation mode and internal textures of these sedimentary structures, as well as comparison with modern microbial mat structures suggest that the formation and preservation of these structures have a direct relationship with the presence of microbial mats (Hagadorn and Bottjer, 1997). Furthermore, MISS are common sedimentary features in Proterozoic-Cambrian strata extending back to the Early Archean (e.g. Hagadorn and Bottjer, 1997, 1999; Gehling, 1999; Noffke et al., 2002, 2003, 2006; Schieber et al., 2007; Meyer et al., 2014), most probably due to the lack of bioturbation that inhibits the formation and preservation of biomats and associated structures. In addition, the occurrence of MISS provides valuable evidence for the detection of early life and reconstruction of environments in the Precambrian (Noffke et al., 2003). So far, several authors have studied Precambrian MISS in continental facies (Prave, 2002; Callow et al., 2011; Simpson et al., 2013; Wilmeth et al., 2014; Strother and Wellman, 2015), and they have argued that microbial communities were flourishing and inhabited continental settings at that time.

In the Phanerozoic, most studies have suggested that sedimentary structures related to microbial communities became more common as a response to periods of lower benthic biodiversity and reduced bioturbation, including a variety of unusual sedimentary structures

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(Sepkoski et al., 1991; Schubert and Bottjer, 1992; Grotzinger and Knoll, 1995; Wignall and Twitchett, 1999; Whalen et al., 2002; Sheehan and Harris, 2004; Calner, 2005; Pruss et al., 2006; Mata and Bottjer, 2009; Buatois et al., 2013; Chu et al., 2015; Ibarra et al., 2016; Peterffy et al., in press; Rakociński and Racki, 2016). However, Davies et al. (2016) recently demonstrated that MISS have been reported more from Phanerozoic than Precambrian strata, and exhibit a pan-environmental and almost continuous record since the Archean, while the perception that MISS are restricted to exceptional intervals of Earth history could arise from a sampling and publication bias. In addition, abiotic and physicochemical sedimentary processes may also create morphologically similar features to MISS, hindering their accurate identification (e.g. McLoughlin et al., 2008; Davies et al., 2016). Therefore, more original observations of MISS from multiple depositional systems should be collected to re-evaluate the relationship between biotic crises and the flourishing of MISS after these events.

As the greatest crisis of the Phanerozoic, the Permian–Triassic mass extinction (PTME) is of particular interest to geologists. This event wiped out over 90% of marine species, and most terrestrial vertebrate and plant species, and brought about a whole-scale restructuring of ecosystems (Erwin, 1993; Retallack, 1995; Looy et al., 1999, 2001; Song et al., 2013; Benton and Newell, 2014; Benton, 2015). The diversity of marine invertebrates declined dramatically (Alroy et al., 2008), and bioturbation returned to Precambrian levels (Knaust, 2010). The terrestrial PTME is confirmed by the significant turnover and loss of life on land from global-scale data, such as tetrapods, insects and plants (Retallack et al., 1996; Grauvogel-Stamm and Ash, 2005; Hermann et al., 2011; Benton and Newell, 2014; Cascales-Miñana and Cleal, 2014; Cascales-Miñana et al., 2015; Yu et al., 2015), though the position of the terrestrial Permian-Triassic boundary is disputed in different regional basins (e.g. Botha and Smith, 2006; Taylor et al., 2009; Gastaldo et al., 2015). Plant diversity had declined substantially through the PTME followed by the Early Triassic "coal gap" (Veevers et al., 1994; Retallack et al., 1996, 2011; Looy et al., 1999, 2001; Rees, 2002; Retallack, 2013). Furthermore, the significant turnover of the terrestrial sedimentary system and the dramatic collapse of soil systems associated with persistent warming, arid climate and enhanced terrestrial weathering have been documented globally during the PTME (Newell et al., 1999; Ward et al., 2000, 2005; Michaelsen, 2002; Miall and Jones, 2003; Arche and Lopez-Gomez, 2005; Retallack, 2005; Algeo and Twitchett, 2010; Algeo et al., 2011; Smith and Botha-Brink, 2014; Metcalfe et al., 2015; Schneebeli-Hermann et al., 2015; Song et al., 2015). Most studies suggest that the destruction of terrestrial ecosystems happened simultaneously with the decline in marine diversity during the Permian–Triassic transition (Twitchett et al., 2001; Shen et al., 2011; Metcalfe et al., 2015; Zhang et al., 2015; Chu et al., in review). Deposits of this unusual period are characterized by the presence of flat-pebble conglomerates (Wignall and Twitchett, 1999), thin-bedded limestones (Pruss et al., 2005), carbonate seafloor fans (Woods et al., 1999), and siliciclastic microbial-mat related wrinkle structures (Pruss et al., 2004; Chu et al., 2015; Tu et al., 2016). Microbial buildups and mats dominated the seabed after the Permian-Triassic crisis, and these microbe-dominated marine ecosystems lasted for about 5–6 Myr in the Early Triassic, linked to the depression of bioturbation and/or to long-term unusual environmental conditions (Chen and Benton, 2012). Most studies that mentioned these unusual sedimentary structures from the Lower Triassic were restricted to marine carbonate and siliciclastic rocks (e.g. Schubert and Bottjer, 1992; Lehrmann, 1999; Wignall and Twitchett, 1999; Woods et al., 1999; Pruss et al., 2004, 2005, 2006; Pruss and Bottjer, 2004; Abdolmaleki and Tavakoli, 2016; Xu et al., 2016). However, less is known about specific changes in terrestrial microbial ecosystems during the PTME and its aftermath, though specific MISS have been reported in terrestrial Lower Triassic rocks (Wehrmann et al., 2012; Chu et al., 2015; Tu et al., 2016).

Terrestrial Permian-Triassic successions are well exposed and widely distributed in the Shanganning Basin and its surrounding area, such as Shanxi, Shaanxi, Henan, and Ningxia Provinces in North China, characterized by inland fluvial and lacustrine siliciclastic redbeds. Complete terrestrial Permian–Triassic sections in North China have been little studied, and yet these sections contain important clues for a better understanding of terrestrial ecosystems. Following our report of microbial-related wrinkle structures from the Lower Triassic of the Dayulin section, Henan Province, North China (Chu et al., 2015), Tu et al. (2016) described some kinds of MISS from the same section and suggested that microbes also proliferated in terrestrial ecosystems in the aftermath of the PTME. The MISS in terrestrial siliclastic facies seem to coincide with the "unusual sedimentary record" in marine settings, which were associated with the end-Permian mass extinction events (Pruss et al., 2004, 2005, 2006; Baud et al., 2007; Chen et al., 2014). Consequently, MISS would be expected to be observed in more terrestrial facies and might be taken as an indicator of the Permian-Triassic boundary in terrestrial stratigraphical sequences. Here we present some more evidence for microbial-mat related sedimentary structures from the Lower Triassic shallow-shore lacustrine siliciclastic deposits in North China. In addition, this study presents a more detailed analysis of terrestrial extinction on the basis of previous and new biostratigraphical, sedimentological, and lithological data from the studied area to reveal the timing and pattern of the PTME in North China. Furthermore, we discuss the relationship between the PTME and the Early Triassic flourishing of MISS.

2. General lithostratigraphy and study sections

The Upper Permian to Lower Triassic sedimentary sequence in North China is represented by the Shiqianfeng Group, which is composed of the Sunjiagou, Liujiagou and Heshanggou formations, in ascending order (Fig. 1). The Sunjiagou Formation consists of fine-grained sandstones and thinly interbedded siltstones in the lower part and reddish siltstone beds, mudstone laminae and interbedded sandstone and marlstone beds in the upper part (Fig. 2A, B). Intensive bioturbation and the *Ullmannia bronnii-Yuania magnifolia* plant fossil assemblage, which is known as the youngest Palaeozoic flora in North China (Wang and Wang, 1986; Chu et al., 2015), occur in the lower part of the formation. In previous stratigraphic studies, the base of the Sunjiagou Formation was dated variously from middle Wuchiapingian to basal Changhsingian, and the Sunjiagou Formation was considered to cover the entirety of the Changhsingian stage from the evidence of lithostratigraphy, palaeobotany and palynology (Wang and Wang, 1986; Stevens et al., 2011; Zhang et al., 2012; Liu et al., 2015), though no reliable age-diagnostic fossils are found in the upper part of the formation. The overlying Liujiagou Formation comprises reddish and brown-reddish, fine-grained sandstones with siltstones and fine-grained conglomerates, bearing abundant ripple marks and cross bedding (Fig. 2C–F), and characterized by lacustrine wrinkle structures but an absence of bioturbation, and deposited in a lake shore or fluvial environment (Chu et al., 2015; Tu et al., 2016). The typical Early Triassic plant fossil *Pleuromeia* occurs in the upper part of the Liujiagou Formation, and these are more widely distributed in the Lower Triassic strata (Wang and Wang, 1982; Wang, 1996; Retallack, 1997; Grauvogel-Stamm and Ash, 2005). The Heshanggou Formation consists of brown-reddish and purple mudstone laminae and siltstone beds with interbedded sandstone beds with diverse ichnofossils, such as *Planolites*, *Psilonichnus*, *Scoyenia*, *Skolithos*, and *Taenidium*, deposited in a shallow-shore lake palaeoenvironment.

The samples of MISS and other sedimentary surface textures were collected from the Liujiagou Formation of the Dayulin and Liulin sections, which are well exposed in Henan and Shanxi provinces, North China (Fig. 1). The Dayulin section is situated near Yiyang County, Luoyang City, Henan Province (Fig. 1B). It includes successive Late Permian to Early Triassic terrestrial siliciclastic deposits from the Sunjiagou, Liujiagou and Heshanggou formations (Fig. 1C). We collected abundant plant fossils and ichnofossils from the lower part of the Sunjiagou

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