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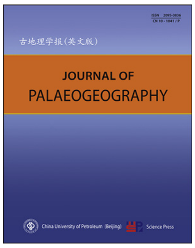

Biopalaeogeography and palaeoecology

Palaeogeographic variation in the Permian—Triassic boundary microbialites: A discussion of microbial and ocean processes after the end-Permian mass extinction

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Abstract Shallow marine carbonate sediments that formed after the end-Permian mass extinction are rich in a thin (maximum *ca.* 15 m) deposit of microbialites. Microbial communities that constructed the microbialites have geographic variability of composition, broadly divisible into two groups: 1) eastern Tethys sites are calcimicrobe-dominated (appearing as thrombolites in the field), with rare occurrence of sediment-constructed microbialites and uncommon cements either within microbial structure or as inorganic precipitates, 2) other Tethys sites are sediment-dominated structures forming stromatolites and thrombolites, composed of micrites and cements, with some inorganic precipitates. These other Tethys locations include western and central Tethys sites but their palaeogeographic positions depend on the accuracy of continental reconstructions, of which there are several opinions. In contrast to geographic variation of microbialites, the conodont *Hindeodus parvus*, which appeared after the extinction and defines the base of the Triassic, is widespread, indicating easy lateral migration throughout Tethys. Conodont animals were active nekton, although being small animals were presumably at least partly carried by water currents, implying active Tethyan surface water circulation after the extinction event. Post-extinction ammonoid taxa, presumed active swimmers, show poor evidence of a wide distribution in the Griesbachian beds immediately after the extinction, but are more cosmopolitan higher up, in the Dienerian strata in Tethys. Other shelly fossils also have poorly defined distributions after the extinction, but ostracods show some wider distribution suggesting migration was possible after the extinction. Therefore there is a contrast between the geographic differences of microbialites and some shelly fossils.

Determining the cause of geographic variation of post-extinction microbialites is problematic and may include one or more of the following possibilities: 1) because calcifying microbial organisms that create calcimicrobes were benthic, they may have lacked planktonic stages that would have allowed migration, 2) eastern Tethyan seas were possibly more saturated with respect to calcium carbonates and microbes, so microbes there were possibly more able to calcify, 3) significant reduction of Tethyan ocean circulation, perhaps by large-scale upwelling disrupting ocean surface circulation, may have limited lateral migration of benthic microbial communities but did not prevent migration of other organisms, and 4) microbes may have been subject to local environmental controls, the mechanisms of which have not yet been recognized in the

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facies. The difficulty of distinguishing between these possibilities (and maybe others not identified) demonstrates that there is a lot still to learn about the post-extinction microbialites and their controls.

Keywords Stromatolite, Thrombolite, Microbialite, Permian—Triassic boundary, Conodonts, Tethys, Mass extinction

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1. Introduction and aim

Permian—Triassic Boundary Microbialites (PTBMs) that formed directly after the end-Permian mass extinction in the latest Permian and earliest Triassic strata occur principally in the low to middle latitudes of Tethys Ocean (Flügel, 2002). Published work by many authors has established a well-developed pattern of microbialite palaeogeographic distribution that has significant geographic variation, principally between western and eastern Tethys, synthesized by Kershaw *et al.* (2012) and outlined later in this paper. However, the key biostratigraphic indicator of the base of the Triassic, the conodont *Hindeodus parvus*, is used as a correlation tool because it was rapidly widespread in a very short time period after the extinction (with possible diachroneity of occurrence, see Zhang *et al.*, 2014). *H. parvus* fossils are the teeth elements of small nektonic chordate-like animals (*e.g.*, Briggs *et al.*, 1983), which although they were mobile, were small and so were presumably also carried by ocean currents. The distribution of *H. parvus* was presumably assisted by active surface ocean circulation. Models indicate a mixed upper ocean across Tethys (*e.g.*, Kidder and Worsley, 2004), with development of gyres in Tethys. Mixed ocean surface waters occur because of wind blow across the ocean surface, which is the principal control on formation of surface ocean circulation. If such circulation patterns really existed then this raises the question of why microbialites are so different between eastern and western Tethys, given that they were most likely composed of bacteria and cyanobacteria. Therefore the aims of this paper are to assess the forces governing these differences and to contribute the knowledge of processes and events in the aftermath of the Earth's largest mass extinction at the end of the Permian period.

This paper is a discussion based on published information. No new data are presented here, and the arguments use the range of current published knowledge of the Permian—Triassic transition facies and biotas. This paper considers key observations of major features of microbia, followed by discussion of the implications for the Permian—Triassic boundary biology and oceanography.

2. Key observations of microbialite construction and distribution

In both eastern and western Tethys, microbialites occur directly after the extinction event and form layered in-place structures that are most appropriately called biostromes. These microbialite biostromes are very thin, maximum *ca.* 15 m thick, and disappear from the rock record as sharply as they appear after the extinction, interpreted by Kershaw *et al.* (2012) to be facies limited, in shallow waters only, and disappeared when water deepened during the post-extinction transgression. Controls on individual microbialite deposits are much debated in the literature, but the palaeogeographic aspects have been given less attention.

The post-extinction microbialite pattern compiled by Kershaw *et al.* (2012) shows that eastern Tethyan PTBMs are most abundant on the South China Block, across the Yangtze Platform, and are largely represented by microbialites which in the field look like thrombolites, commonly with a dendritic macrofabric. However, although these are substantially recrystallized, there is sufficient preservation to demonstrate that the most common well-preserved component is a *Renalcis*-like calcimicrobe (Fig. 1), occurring throughout the Yangtze Platform so that in many places the microbialite can be demonstrated to be a frame-built calcimicrobial biostromal deposit. Sediment-constructed stromatolites occur in some localities (Yang *et al.*, 2011) and a subordinate small shelly fauna, principally of ostracods and gastropods is widespread. In some sites, microbiotas are also proved (Yang *et al.*, 2015). Some of the microbialites are regarded as comprised of clotted fabrics by Zheng *et al.* (2016),