Environmental instability prior to end-Permian mass extinction reflected in biotic and facies changes on shallow carbonate platforms of the Nanpanjiang Basin (South China)

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ABSTRACT

Shallow carbonate platforms exhibit major changes in faunal composition and facies types during the latest Permian and earliest Triassic. Although the microbialites that developed following the latest Permian mass extinction (LPME) have attracted wide attention, temporal variations in shallow-platform facies and faunas prior to the LPME have been less thoroughly studied. Here, we analyze diversity patterns and variation in skeletal composition in three Upper Permian sections from isolated carbonate platforms of the Nanpanjiang Basin. In addition to the well-known transition from fossil-rich Upper Permian limestones to fossil-poor Permian-Triassic boundary (PTB) microbialites, these sections exhibit several distinct changes that predate the mass extinction. First, foram faunas show a shift from non-fusulinid-dominated to fusulinid-dominated communities in the < 1-m interval below the LPME horizon of each section, reflecting a shallowing trend over ~20–30 kyr preceding the mass extinction. Second, a "foram gap" and concurrent "detrital event" are observed below the LPME in all three sections, recording a rapid influx of detrital siliciclastics that predated the mass extinction by < 60 kyr. These features reflect a degree of marine environmental instability prior to the end-Permian mass extinction. The sudden influx of siliciclastics may represent an early perturbation to terrestrial ecosystems linked to incipient Siberian Traps magmatism, resulting in secondary effects in marine environments through increased sediment yields.

1. Introduction

As the largest extinction event of the Phanerozoic, the latest Permian mass extinction (LPME) at 252.2 Ma (Shen et al., 2011; Burgess et al., 2014) eliminated over 90% of species and 79% of genera of marine invertebrates (Raup, 1979; Shen et al., 2011; Payne and Clapham, 2012; Song et al., 2013). This biotic crisis led to the collapse of metazoan reefs, triggered the reappearance of anachronistic carbonate facies such as microbialites, and fundamentally altered the structure of marine ecosystems (Flügel, 2002; Bambach, 2002; Weidlich et al., 2003; Payne et al., 2004; Knoll et al., 2007; Bottjer et al., 2009; Algeo et al., 2011; Kershaw et al., 2012a; Tian et al., 2015a, 2015b). It also initiated a ~5-Myr-long interval of major perturbations to the global carbon and sulfur cycles, as recorded in large (to 10%) excursions in carbonate 813C and sulfate 834S (Payne et al., 2004; Xie et al., 2010; Song et al., 2014a).

Skeletal abundance declined sharply during the end-Permian crisis, reflecting ecological and oceanographic effects (Knoll et al., 1996, 2007; Payne et al., 2006, 2007; Knoll and Fischer, 2011). Knoll et al. (1996) analyzed long-term secular variation in the degree of calcification of marine invertebrate taxa, showing major declines at both the Middle-Late Permian and Permian-Triassic boundaries. Although taxonomic diversity during the Late Permian was lower than in the Middle Permian, skeletal carbonates were still major components of shallow-marine facies, comprising 30–60% of carbonate platform interiors, but following the LPME they were reduced to just < 10% of these facies (Payne et al., 2006; Wang et al., 2009; Tian et al., 2014a).

The end-Permian mass extinction occurred in two stages, as shown...
by studies at Meishan D (the global stratotype section and point, GSSP, of the PTB) and other sections. At Meishan D, the first extinction episode commenced at the top of the latest Permian Clarkina yini conodont Zone and the second episode is in the lower part of the earliest Triassic Isarcicella isarcica Zone (Shen et al., 2011; Song et al., 2013), representing a temporal offset of ~61 (±48) kyr per recent radiometric dating results (Burgess et al., 2014). Each of these extinction episodes was accompanied by major changes in environmental conditions (Xie et al., 2007; Song et al., 2009a, 2013, 2014b). The question of whether marine environmental conditions prior to the first extinction episode were entirely stable or whether there is evidence of “precursor” perturbations has only begun to be addressed in recent studies, some of which have inferred a limited expansion of oceanic euxinia and increased terrestrial inputs (e.g., Li et al., 2016; Dudás et al., 2017; Elrick et al., 2017; Zhang et al., 2018) as well as impacts on deep-water faunas such as radiolarians (Feng and Algeo, 2014) prior to the LPME.

In contrast to slope sections such as Meishan, most shallow-marine shelf and platform sections record only a single extinction event during the Permian-Triassic (P-Tr) transition (e.g., Billa: Farabegoli et al., 2007; Gorjan et al., 2007; Yangou: Tian et al., 2014a). These sections are commonly dominated by microbial facies immediately above the LPME horizon, known as Permian-Triassic boundary microbialites (PTBM), whose depositional conditions and community structure have been well-studied (Ezaki et al., 2003, 2008; Lehrmann et al., 2003, 2007; Baud et al., 2005; Pruss et al., 2006; Wang et al., 2009; Song et al., 2009b; Kershaw et al., 2009, 2011, 2012a; Yang et al., 2011). These sections commonly contain evidence of major environmental changes associated with the LPME (e.g., sea-level fluctuations and ocean acidification) that is not found in deeper settings (Payne et al., 2007; Kershaw et al., 2012a; Yin et al., 2014).

Far less attention has been paid to invertebrate community and carbonate microfacies changes in shallow-marine shelf and platform settings before the LPME. The Nanpanjiang Basin in the southwestern South China Craton contains dozens of continuous carbonate PTB sections that are well exposed, facilitating investigation of biotic and environmental changes prior to the LPME. The Nanpanjiang Basin is at the base of the Upper Permian Wujiapiang Formation and overlying microbialites of the Lower Triassic Daye Formation (Fig. 2; Lehrmann, 1999; Lehrmann et al., 2001; Wang et al., 2005). The PTB, indicated by the first occurrence of Hindeodus parvus, is at the base of the microbialites (Jiang et al., 2014). Placement of the LPME is facilitated by the carbonate δ13C profile, which exhibits a 1% negative shift ~55 cm below the PTB (Song et al., 2014c). Two possible erosion surfaces (Fig. 2A, C) were noted in outcrop: the upper one located at the lithologic contact between Wujiapiang bioclastic limestones and Daye microbialites (called the “basal PTBM diastem” in this study; see below), and the lower one associated with a 2-cm-thick muddy limestone interbed located 40 cm below this contact (called the “uppermost Permian diastem”).

The Taiping section is located 500 m northeast of Taiping Town, Ping guo County, Guangxi Province (23°30′00″N; 107°31′20″E). It was deposited in the interior of the Pingguo Platform at inferred water depths of ~10–30 m (Fig. 1B; water depths may have been greater in the early to middle Late Permian as suggested by chert interbeds in the lower Heshan Formation). It consists of medium-bedded bioclastic limestone of the Upper Permian Heshan Formation, overlain by microbialites of the Lower Triassic Majiaoling Formation (Fig. 3B). The PTB is located at the base of the microbialites based on the first occurrence datum of H. parvus (unpublished data from Kui Wu). Placement of the LPME is facilitated by the carbonate δ13C profile, which exhibits a decline of ~0.6‰ began ~2.4 m below the formation contact (Fig. 4; Luo et al., 2011). Two possible erosion surfaces were noted in outcrop: the lower one located at the lithologic contact between Heshan bioclastic limestones and Majiaoling microbialites (“basal PTBM diastem”; see below), and the upper one located along a stylolite 2 cm above this contact (“lowermost Triassic diastem”; Fig. 3B).

The Lung Cam section is located near Lung Cam village, Ha Giang Province, Vietnam, about 10 km south of the Chinese border (23°14′30″N; 105°13′20″E). It was deposited on the southern part of the Jixi Platform at inferred water depths of ~10–30 m (Fig. 1B). It consists of bioclastic limestones of the Upper Permian Dong Dang Formation overlain by microbialites and micritic limestones of the Lower Triassic Hong Ngai Formation. Although H. parvus has not been reported from Lung Cam or the nearby Nhi Tao section to date (Algeo et al., 2007; Son et al., 2007), the PTB is likely to be located at or close to the base of the microbialite based on analogy with similar sections in South China (such as Wengna and Taiping above). Approximate placement of the LPME is facilitated by the carbonate δ13C profile, which exhibits a gradual decrease beginning ~1.2 m below the formation contact, followed by an abrupt shift at the formation contact (Fig. 4; Song et al., 2007). The presence of erosional surface(s) within the Lung Cam section has not been investigated in the field to date.

The nature of the contact between the PTBM and underlying Upper Permian bioclastic limestones varies among these three sections. At Taiping, the lithologic contact is expressed as dark gray microbialites above a flat surface at the top of light gray bioclastic limestones (red arrow, Fig. 3B), although a stylitized horizon is present two centimeters above this contact (blue arrow, Fig. 3B). A similar arrangement is present in the Laiping section on the Great Bank of Guizhou (Payne et al., 2007). At Wengna, the lithologic contact is expressed as dark-colored microbialites above a gently undulating (~2-cm relief) surface at the top of light gray bioclastic limestones (Fig. 2A, C). The diastem at base of PTBMs shows features that may be consistent with a hiatus (time gap) (Kershaw et al., 2009, 2012a; Yin et al., 2014; Yang et al., 2011). The contact is commonly stylitized, as at Yudongzi and Dongwan (Kershaw et al., 2012a, 2012b), making interpretation of...
original depositional relationships difficult. Yin et al. (2014) employed high-resolution conodont biostratigraphic correlation to calibrate the latest Permian hiatus in South China, although uncertainties remain in areas of microbialite development owing to insecure placement of the P-Tr boundary. Earlier studies reported the first occurrence of *H. parvus* in the middle of the microbialite facies (Wang et al., 2005; Chen et al., 2009), which implied that the lower microbialite was of latest Changhsingian age and, thus, that these sections might be stratigraphically complete (i.e., without a diastem at the lithologic contact at the base of the microbialite). However, recent studies have identified *H. parvus* from close to the base of the microbialites at Dajiang and Cili, implying that the microbialite is mostly or entirely of early Griesbachian age, and, therefore, that a diastem is present at the base of the microbialite ("basal PTBM diastem") (Jiang et al., 2014; Wang et al., 2015). The present study sections (Wengna and Taiping) show the same pattern (see above). Although initiation of PTBM growth may have been diachronous globally (Kershaw et al., 2012a), the available evidence suggests that their bases are approximately correlative across the Nanpanjiang Basin (Fig. 4).

In each study section, samples were collected at regular intervals through the P-Tr transition in order to generate thin sections. A total of 20, 29, and 23 thin sections were made for the Wengna, Taiping, and Lung Cam sections, respectively. Note that the formation contact intervals of the Uppermost Permian bioclastic limestone with the bases of PTBMs had been continuously sampled (< 2 cm) whilst other intervals were sampled with larger spaces (sampling locations are marked along the lithology columns). Although the raw sampling spaces varied, they are comparable temporally as we collected similar numbers of samples...
in equivalent time intervals (Fig. 4). In these thin sections, thousands of individual foraminifers were observed and identified. Microfacies analysis was conducted following the procedures and revised standard microfacies classification of Flügel (2004). In addition, carbonate components were quantified by point-counting, with 100 points counted per thin section using a 10 × 10 grid with nodes 1 mm apart. Fossil frequency was calculated as fossil count / total count × 100%.

3. Results

3.1. Wengna section

A total of 34 species of foraminifers belonging to 27 genera were identified in the Wengna section (Fig. 5), including *Palaeofusulina minima*, *Palaeofusulina sinensis*, *Sphaerulina* sp., *Nankinella* spp., *Para-eichelina* sp., *Palaeotextularia* spp., *Reichelina* spp. (Fig. 6), and eight fusulinid species. This assemblage is dominated by *Palaeofusulina* spp., *Pachyphloia* spp., and *Nodosinelloides* spp. The typical Permian fauna, represented by *Palaeofusulina sinensis*, *Nankinella* spp., and *Pachyphloia robusta*, did not reappear after their disappearance at the LPME, representing the major extinction horizon in the Wengna section (Fig. 5). The only foram taxa that survived into the microbialite interval were *Frondina permica*, *Nodosinelloides aequiampla*, *Geinitzina uralica*, and *Rectocornuspira kalhori*. The muddy limestone bed located 40 cm below the lithologic contact (“late Permian diastem”) contains no forams (“foram gap”; Fig. 5), although most species reappear in the immediately overlying beds, indicating a local facies-controlled disappearance rather than an extinction event.

Four microfacies types were recognized at Wengna: (1) MF1: algal-foraminiferal packstone-grainstone; (2) MF2: dolomitized wackestone; (3) MF3: algal-foraminiferal grainstone; and (4) MF4: dolomitized gastropod wackestone (Fig. 5). MF1 and MF3 are characterized by diverse bioclasts, especially algal and foraminiferal grains. MF1 differs from MF3 by the presence of micrite in the matrix. MF2 and MF4 are characterized by extensive dolomitization. Whereas MF2 is largely non-fossiliferous and contains only a few fossil fragments and ichnofossils, MF4 contains abundant gastropods and ostracods. Irregular sparry mosaics are present in MF4 due to inhomogeneous dolomitization. Additionally, potential cyanobacterial fossils were observed in MF4 (Fig. 5E). These features observed in MF4 (non-fossiliferous micrite
dominated, irregular sparry mosaics associated as well as layers of gastropods and ostracods interbedded) are typical of calcimicrobial-related structures in microbialites (Lehrmann, 1999; Wang et al., 2005). All these observations suggest open to slightly restricted shallow-marine platform environments.

### 3.2. Taiping section

A total of 27 species of foraminifers belonging to 22 genera were identified in the Taiping section (Fig. 7), including 2 genera of fusulinids, Nankinella and Reichelina (Fig. 8). This assemblage is characterized by high abundances of Nankinella sp. and Pachyphloia spp. All species except Tolypammina sp. are found in the Upper Permian, whereas only Rectocornuspira kalhori, Globivalvulina bulloides, Hemi gordius spp., and Tolypammina sp. were found in the Lower Triassic microbialites. Associated with the lithological transition from bioclastic limestone to microbialites, biodiversity declined abruptly, reflecting the position of the LPME at Taiping (Fig. 7). Forams disappear from a sandy limestone layer bearing detrital quartz and feldspar that is located 2.4–2.3 m below the LPME (“foram gap”; Fig. 7), but the re-appearance of most species in the immediately overlying beds indicates a local facies-controlled disappearance rather than an extinction event.

Four microfacies types were recognized at Taiping: (1) MF1: foraminiferal packstone; (2) MF2: algal-foraminiferal packstone; (3) MF3: sandy carbonate mudstone; and (4) MF4: dolomitized wackestone (Fig. 7). MF2 is characterized by greater fossil diversity and a higher abundance of algae than MF1, implying an open-marine platform environment. MF3 contains abundant quartz and feldspar grains, representing strong detrital input. MF4 is marked by a low abundance and low diversity of fossil fragments (dominantly ostracods), although many fossil fragments cannot be identified because of dolomitization. Dominance of ostracods and a dark micritic matrix indicate a relatively restricted platform environment.

### 3.3. Lung cam section

A total of 17 species of foraminifers belonging to 17 genera were identified in the uppermost Permian of the Lung Cam section (Fig. 9), including two genera of fusulinids (Nankinella spp. and Reichelina sp.; Fig. 10). Nankinella spp. and Glomomidiella nestellorum are the most abundant species of this assemblage. The basal Triassic microbialites yielded no foram specimens. However, foram range data for Lung Cam are likely to be incomplete owing to relatively poorer fossil preservation than at Wengna and Taiping because of extensive micritization of bioclasts, making it impossible to identify many specimens to the genus or species level. A “foram gap” similar to those at Wengna and Taiping is present at Lung Cam about 15 cm below the lithologic contact.

Four microfacies types were recognized at Lung Cam: (1) MF1: Bivalve-ostracod packstone; (2) MF2: algal-foraminiferal packstone-grainstone; (3) MF3: clast-bearing mudstone; and (4) MF 4: dolomitized ostracod wackestone (Fig. 9). MF1 samples have a dark micritic matrix, suggesting a relative deeper environment. MF2 samples are characterized by diverse fossil types, indicating an open-platform environment. The clast-bearing mudstone of MF3 contains mica and black clasts and lacks fossils, indicating increased siliciclastic input. MF4 samples contain mainly ostracods, suggesting a restricted inner-platform environment, which is consistent with their stronger dolomitization.

### 3.4. Permian-Triassic boundary microbialites (PTBM)

Each of the three study sections contains the PTBM, which represent an “anachronistic facies” (Baud et al., 2007) that developed widely in the aftermath of PTB crisis and that can provide insights into paleoenvironmental conditions following the extinction (Ezaki et al., 2003, 2008; Lehrmann et al., 2003, 2007; Pruss et al., 2006; Kershaw et al., 2007, 2012a; Yang et al., 2011).

At Wengna, the microbialite is gray, digitate and thrombolitic in structure (Fig. 2). It is assigned to MF4 (dolomitized gastropod wackestone). In the basal PTBM (76–86 cm, Fig. 5), bioclasts consist of 1–2%
Fig. 6. Foraminifers from the Wengna section. (A) Parareichelina sp., WN0104 (specimen number); (B) Palaeofusulina sinensis, WN0327; (C–D) Nankinella sp., C, WN1404, D, WN021505; (E) Palaeofusulina sinensis, WN1515; (F) Reichelina sp., WN0205; (G) Cribogenerina sp., WN0408; (H) Climacaminina valvuloideus, WN0407; (I) Palaeotextularia sp., WN1021; (J) Colaniella sp., WN1127; (K) Agathammina pusilla, WN0708; (L) Robuloides lens, WN0901; (M) Frondina permica, WN0110; (N) Neodiscus plectogyraeformis, WN1517; (O) Dagmatina chanakchiensis, WN0639; (P) Postendothyra guangxiensis, WN0405; (Q) Postendothyra sp., WN1103; (R) Glomomidiella nestellorum, WN1513; (S) Calvezina ottonmana, WN1214; (T) Nodosinelloides tenueperta, WN1354; (U) Nodosinelloides camerata, WN1335; (V–W) Pachyphloia ovata, V, WN1375, W, WN0401; (X) Pachyphloia robusta, WN1125; (Y) Ichthyofrondina palmata, WN0331; (Z) Protonodosaria sp., WN0406; (a–b) Rectocorunspira kalhori, a, WN1611, b, WN1709; (c) Rectostipulina quadrata, WN0603; (d) Diplophoia inaequalis, WN0631; and (e) Geinitzina uralica, WN1902. All scale bars are 0.1 mm in length.
gastropods and < 10% ostracods, microconchids, and small foraminifers such as Rectocornuspira kalhori (Fig. 6A, B). In the upper PTBM (86–100 cm, Fig. 5), total fossil frequency increased to 20–30%, with larger numbers of gastropods in the interbeds but no significant changes in the abundances of foraminifers and ostracods (Fig. 5). Several more foraminiferal taxa, including Frondina permica, Nodosinelloides aequiampla, and Geinitzina uralica, are found in the upper PTBM although their abundances are low (0–4%). Two probable calcified microbes (Renalcis-like and coccoidal forms) and a few small (200–600 μm) microcochids, identified by their spiral tube (longitudinal view) or donut-shape (transverse view), have micritic wall structures. The Renalcis-like microbe is characterized by a chambered structure, whereas the coccoidal microbe consists of small micritic spherules organized in clots/clusters and surrounded by sparry matrix (Figs. 5E, 11E).

At Taiping, the microbialites are dark thrombolites consisting of a digitate micritic framework enclosed in sparry cement (Fig. 3C). Total fossil abundances were 8–20%, with dominance of ostracods in both the shelly layers and the micritic matrix. The few foraminifers were preserved in the micritic matrix. In contrast, two probable calcified microbes (Renalcis-like and coccolidial forms) were preserved within areas of sparry cements (Fig. 7F), although they were enclosed by chambered belts (Fig. 11F) and dark micritic clots (Fig. 11E), respectively.

At Lung Cam, limited sampling of the PTBM obviates a comprehensive description. We noted that a sample from the basal Hong Ngai Formation belonging to MF4 (dolomitized ostracod wackestone) is characterized by occurrences of coccolidial micritic clots and abundant bioclasts (dominated by 20% ostracods) (Fig. 9). The similarity of microfacies types and skeletal compositions with the Wengna and Taiping sections suggests that the PTBM at Lung Cam was also a thrombolite.

4. Discussion

4.1. Secular variation in fossil assemblages and extinction events

The stratigraphic distributions of fossil taxa in the Wengna and Taiping sections exhibit similar patterns, with the following characteristics: (1) bioclasts in the pre-LPME Upper Permian are dominated by algae and foraminifers; (2) the Lower Triassic microbialites contain only ostracods, gastropods, microconchids, and rare foraminifers; and (3) the abundant and diverse Upper Permian foraminifer assemblages were replaced by sparse, low-diversity assemblages in the Lower Triassic, showing that forams experienced the same abrupt extinction at the LPME as marine invertebrate taxa (Figs. 5, 7). The Lung Cam section displays some unique features that distinguish it from the other two study sections: (1) the Upper Permian contains abundant molluscs and ostracods in addition to foraminifers, and algae are much rarer; (2) ostracods comprise up to 20% of the Lower Triassic microbialite facies, but no other bioclast type was found (note: only one sample was analyzed from the microbialite facies at Lung Cam, so this result may not be fully representative); (3) foraminifera exhibit a stepwise disappearance pattern in the uppermost Permian, with no obvious single extinction horizon (Fig. 9). However, the apparent stepwise loss of foram taxa may reflect the Signor-Lipps Effect, in which incomplete preservation/identification of stratigraphic ranges obscures the signal of a mass extinction event (Rampino and Adler, 1998). The comparatively poor preservation of bioclasts at Lung Cam may have contributed to this effect.

The fossil assemblages of the study sections, which accumulated on different platforms in the Nanpanjiang Basin, thus provide evidence for a single abrupt extinction (i.e., the LPME) that was associated with the
lithologic transition from Upper Permian bioclastic limestones to Lower Triassic microbialites. This extinction event led to the rapid disappearance of diverse fossil groups across the Nanpanjiang Basin, including all calcareous algae, sponges, brachiopods, as well as most foraminifers, e.g., *Nankinella* spp., *Reichelina* spp., *Palaeofusulina* spp., *Pachyphloia* spp. and *Robuloides* spp. This finding is consonant with results from other shallow platform successions in South China, Japan, and Europe (Payne et al., 2007; Wang et al., 2009; Song et al., 2009b, 2013).

A second extinction event of earliest Griesbachian (earliest Triassic) age, sometimes called the earliest Triassic mass extinction (ETME), corresponds to the contact of the *H. parvus* and *I. staeschei* Zones (Bed 28 at Meishan D; Song et al., 2013) and postdates the LPME by ~60 kyr (Burgess et al., 2014). This event records the loss of diverse fossil groups, including foraminifers, brachiopods, and conodonts (Jiang et al., 2007; Chen et al., 2009; Song et al., 2009a, 2013; He et al., 2015). This extinction event is distinct from the preceding LPME event, as both are clearly developed in multiple sections of the Yangtze Platform (e.g., Huangzhishan and Meishan D). This second extinction event is found within the *I. staeschei* conodont Zone at Meishan D, i.e., which is correlative with the demise of PTBM in the Nanpanjiang Basin (Chen et al., 2009; Song et al., 2013). Unfortunately, we suspect that the presented study interval of these three sections do not extend far enough upsection into the demise of PTBM to record this second extinction event (Fig. 12).

Changes in benthic invertebrate community composition on carbonate platforms are often related to changes in water depths (Madi et al., 1996; Flügel, 2004). In this study, the abundances of fusulinids increased from < 5% in the lower part of each section (0–60 cm at Wengna; 0–620 cm at Taiping) to > 40% just below the LPME (60–75 cm at Wengna; 620–730 cm at Taiping) (Fig. 12). Since fusulinids favored clear, shallow waters, and fusulinid-enriched biofacies have been observed during Permian regressions (Dawson and Racey, 1993; Ross, 1995), we interpret the enrichment of fusulinids in the uppermost Permian of these two study sections as an indicator of a shallowing trend (Figs. 5 and 7). At Lung Cam, although vertical changes in fusulinid abundance are less clear, a decrease in bivalves upsection combined with a microfacies shift from MF1 (molluscan packstone) to MF2 (algal-foraminiferal packstone-grainstone) support the shallowing interpretation. Based on the high-resolution zircon U-Pb
Fig. 9. Skeletal composition and foraminiferal distribution in the Lung Cam section. MF1: molluscan packstone; MF2: algal-foraminiferal packstone-grainstone; MF3: clast-bearing mudstone; MF4: dolomitized wackestone. Fossil frequency = fossil count / total count × 100% (based on point-counting in thin sections).

Fig. 10. Foraminifers of the Lung Cam section. (A) Palaeontactularia sp., LC0B02 (specimen number); (B) Clionacmmina sp., LC17T07; (C–D) Dagmarita chanakchiensis, C, LC2B12; D, LC2609; (E) Paraglobivalvulina sp., LC12B02; (F–H) Hemigordius spp., F, LC506, G, LCS09, H, LCS06; (I–J) Ichthyofrondina palmata, I, LC12B03, J, LC2613; (K–M) Glomomidella nestellorum, K, LC817, L, LC802, M, LC803; (N) Rectostipulina quadrata, LC810; (O) Reichelina sp., LC17T09; (P–Q) Nankinella spp., P, LC505, Q, LC510; and (R–S) Pachyphloia sp., R, LC17T06, S, LC19T02. All scale bars are 0.1 mm in length.
timescale of Burgess et al. (2014), this interval represents ~20–30 kyr based on an average sedimentation rate of 2.6 cm/kyr) prior to the LPME (based on the thickness and estimated average sedimentation rate in (Burgess et al., 2014).

4.2. Spatial variation in fossil assemblages and oceanographic controls

The Upper Permian bioclastic limestones of the present study sections contain much greater abundances of fusulinids and algae (up to 50%) than the correlative interval of the Meishan D section (< 20%). This difference is attributable to their paleogeographic locations. Meishan D was located on the upper slope of a carbonate ramp (Fig. 1) that was subject to moderate terrigenous detrital inputs (Tong and Yin, 2002; Algeo and Twitchett, 2010), and some combination of a siliciclastic substrate and greater water-column turbidity suppressed growth of fusulinids and algae. In contrast, the carbonate platforms of the Nanpanjiang Basin, on which the present study sections are located (Fig. 1), were largely free of siliciclastic influence (Lehmann et al., 2001, 2003, 2007; Algeo and Twitchett, 2010). In addition, Meishan D contains relatively greater abundances of bivalves and ostracods (> 20%) than the present study sections (< 10%) (Fig. 12). These taxa appear to have flourished more successfully than fusulinids and algae under conditions of elevated terrigenous detrital inputs, owing to their wide tolerances of variations in nutrient levels, substrate conditions, and watermass salinities (Attrill et al., 2000; Fraschetti et al., 2005; Dunlop et al., 2008).

Even within just the Nanpanjiang Basin, distinct spatial variations in fossil abundances are apparent among the three study sections: (1) bivalve fragments are rarely recorded at Wengna, comparing to their higher abundances at Taiping and Lung Cam; (2) ostracods are significantly enriched at Lung Cam; and (3) fusulinids are much more abundant in the uppermost Permian bioclastic limestone at Wengna and Taiping than at Lung Cam (Figs. 5, 7, 9 and 12). These differences are attributable to the locations of individual carbonate platforms in the
Nanpanjiang Basin, with the Great Bank of Guizhou (Wengna section) being close to the Yangtze Platform, whereas the Pingguo and Jinxi Platforms (Taiping and Lung Cam sections, respectively) were located on the Panthalassic margin of the South China Craton (Fig. 1). Several factors may have influenced these patterns of spatial variation, especially (1) water depths, and (2) proximity to the open ocean. Fusulinids and algae show a strong preference for shallow waters (as at Wengna and Taiping), whereas bivalves and ostracods show preferences for deeper-water conditions (as at Lung Cam; n.b., a depth control on marine faunas was also documented by Song et al., 2013). Proximity to the open ocean influenced nutrient levels, with stronger upwelling of nutrients at Lung Cam leading to a higher density of grazers (e.g., ostracods and bivalves) and a smaller mass of algae. This pattern accords with observations of increased grazing pressure in modern eutrophic systems (Kotta et al., 2004).

4.3. Pre-LPME “foram gap” and “detrital event”

A “foram gap” was discovered at variable distances below the LPME in all three study sections: 40 cm at Wengna, 240 cm at Taiping, and 15 cm at Lung Cam below the formation contacts (Fig. 12). Although all foram species disappeared completely within the foram gap, the majority of them reappeared in the overlying strata. For example, 25 out of 30 taxa reappeared at Wengna 17 out of 23 reappeared at Taiping (Fig. 7), and 11 out of 17 reappeared at Lung Cam (Fig. 9). In particular, most of the wide-ranging Late Permian forms like Nankinella spp. and Pachyphtoia spp. reappeared following the foram gap, and the taxa that did not reappear were generally the ones that were less common prior to the gap. The foram gap was associated with an influx of siliciclastic pressure in modern eutrophic systems (Kotta et al., 2004).

Fig. 12. Comparison of skeletal composition changes among the three study sections. LPME = latest Permian mass extinction, PTB = Permian-Triassic Boundary, ETME = earliest Triassic mass extinction. U-Pb radiometric dates are from Burgess et al. (2014). Skeletal composition data for Meishan are from Kaiho et al. (2006) and Chen et al. (2015). Note change in vertical scale at Meishan between the Changxing and Yinkeng formations.
Li et al., 2016], enhanced soil erosion [Kaiho et al., 2016; Zhou et al., 2017], elevated terrestrial inputs [Dudás et al., 2017], and declines in ammonoid size and morphological complexity [Kiesling et al., 2018].

The detrital event may reflect an increase in terrestrial erosion prior to the LPME, a hypothesis that is consistent with the larger and better-documented increase in erosion that accompanied the LPME. The increase in erosion at the LPME is recorded by enhanced soil erosion, higher marine shelf sedimentation rates, more radiogenic seawater Sr isotopes, and greater concentrations of clay minerals in marine sections [Retallack, 2005; Sheldon, 2006; Algeo et al., 2007, 2011; Algeo and Twitchett, 2010; Song et al., 2015]. The trigger for erosion may have been acid rain and die-off of terrestrial vegetation as a consequence of the Siberian Traps eruptions [Newell et al., 1999; Ward et al., 2000; Algeo et al., 2011]. The occurrences of siliciclastics in the uppermost Permian carbonates of our sections are unusual in that they occur before the LPME, but they may represent a precursor perturbation that resulted in a transient increase in detrital fluxes. Burgess and Bowring (2015) provided evidence that an initial pulse of Siberian Traps magnetism triggered ecosystem perturbations up to 300 kyr prior to the LPME, whereas the LPME probably marks the main flood basalt eruption stage. The mechanism for transporting siliciclastics onto distal carbonate platforms in the Nanpanjiang Basin is not certain, but we hypothesize that large turbid plumes generated through massive soil erosion may have helped move siliciclastics offshore.

4.4. Faunal composition and environmental implications of PTBMs

Microbialites took the place of bioclastic limestones during the LPME, marking the most significant lithological and biotic transition on shallow carbonate platforms across South China (Figs. 2, 3) and in equivalent settings in Europe [Frass et al., 2006; Baud et al., 2007; Xie et al., 2010; Yang et al., 2011; Kershaw et al., 2012a]. The PTBMs were deposited on the underlying uppermost Permian bioclastic limestones along the “basal PTBM diastem” (Figs. 2, 3; also see Yang et al., 2011; Kershaw et al., 2012a). Yin et al. (2014) examined the biostratigraphic zonations of dozens of P-Tr boundary sections of different facies and concluded that part or all of the Clarkina meishanensis and Hindeodus changxingensis zones are commonly missing in shallow platform successions on the northern margin of the Yangtze Platform and on isolated platforms of the Nanpanjiang Basin. Where a hiatus is present in these shallow-marine sections, it is thought to represent an interval of 89 ± 38 kyr (as estimated by Baresel et al., 2017; it might be less in the present study sections based on the carbon isotope correlation in Section 4.3). Such a significant hiatus means that the details of biotic and environmental changes at the LPME (sensu stricto) cannot be reconstructed from shallow-carbonate successions in South China.

The growth morphology and abundance of marine invertebrate colonizers of the microbialites may provide environmental insights during the latest Permian and earliest Triassic following the basal PTBM diastem. The PTBMs in the Nanpanjiang Basin are mostly thrombolitic, which contrasts with the stromatolitic growth form of Lower Triassic microbialites on the northern margin of the Yangtze Platform and at localities in the western Tethys [Kershaw et al., 2007, 2012a; Adachi et al., 2017]. In addition, the PTBMs in the Nanpanjiang Basin have a much greater metazoan fossil content than coeval stromatolitic mats, which tend to contain few marine invertebrates. These patterns have analogs on the modern Bahamian Platform, where thrombolites are characterized by a mixed bacterial-metaphyte ecosystem of greater complexity than the dominantly microbial biotas of stromatolitic mats [Planavsky and Ginsburg, 2009; Tarhan et al., 2013]. Highly diverse metazoan assemblages are also present in thrombolites of Cambro-Ordovician age [Kennard and James, 1986] and in modern Lake Clifton, Western Australia [Moore and Burne, 1994; Konishi et al., 2001]. These relationships may reflect variation in rates of microbial calcification versus metazoan bioerosion [Garcia-Pichel et al., 2004]. The calcification rate is linked to the intensity of photosynthesis, which causes a local increase in watermass alkalinity, driving carbonate cement formation [Dupraz et al., 2009]. On the other hand, metazoan grazing partially destroys biogenic carbonates, creating gaps in microbial structures that are then more likely to grow into thrombolites [Kennard and James, 1986]. In this scenario, the balance of calcification to bioerosion is a function of light availability (mainly linked to water depth), nutrient input, and aqueous environmental conditions (e.g., temperature, salinity, and dissolved oxygen) that influence the abundance of metazoan grazers (cf. Moore and Burne, 1994).

The invertebrate faunal content of PTBMs has been examined in only a few studies [Payne et al., 2006; Yang et al., 2011; Forel et al., 2009, 2013; Tang et al., 2017]. Here, we quantified the main biotic components of the PTBM, including ostracods, gastropods, and two probable calcifying cyanobacteria (described as coccoidal and Renalcis-like) (Figs. 5E, 7F, 11E, F). At Wengna and Taiping, both coccoidal and Renalcis-like microbes were found in some samples although their contents are very low (< 2% in most samples). These cyanobacteria are thought to have been the primary builders of the microbialites [Lehrmann, 1999; Wang et al., 2005], but the quantified contents are too low to support this scenario. Ostracods are relatively abundant (2–15% in most samples from Wengna and Taiping, ~20% in Lung Cam samples), and Forel et al. (2009, 2013) proposed that they grazed on cyanobacteria in the PTBM. An additional faunal component of the PTBM is the microconchids, which are present in moderate abundances (2–5%) only at Wengna. They have previously been reported from PTBMs at other locales, e.g., Cili and Dajiang [Yang et al., 2011]. Although the growth of PTBMs has been attributed to anoxic seafloor conditions during the P-Tr transition, and marine hypoxia-anoxia in the aftermath of the LPME is well established [Lehrmann, 1999; Algeo et al., 2007, 2008; Knoll et al., 2007; Bond and Wignall, 2010; Liao et al., 2010, 2017; Brennecka et al., 2011; Tian et al., 2014b; Wang et al., 2015; Elrick et al., 2017], the quantified skeletal composition of our study sections does not support low-oxygen conditions as a major cause of PTBM growth. First, the association of diverse metazoan groups in the PTBMs suggests generally well-oxygenated conditions [Kershaw et al., 2009; Forel et al., 2009, 2013; Yang et al., 2011; Tang et al., 2017]. The present study demonstrates a similar relationship: bioclasts (mainly of gastropods and ostracods) comprise 5–20% of the PTBMs at Wengna and Taiping (Fig. 12). Second, redox conditions in the Permian-Triassic ocean-surface layer could not have been anoxic except for very brief intervals at most, because the ocean-surface layer would have been resupplied with oxygen from the atmosphere quickly (at a scale of days to weeks; Broecker and Peng, 1974) if it ever went anoxic. Brief episodes of anoxia might have developed as a consequence of upward chemocline excursions [Kump et al., 2005], for which the Nhí Tao section in Vietnam has provided evidence in the form of multiple, thin framboidal pyrite layers [Algeo et al., 2007, 2008]. However, the ocean-surface layer would have remained oxic probably > 99% of the time despite expanded anoxia at greater ocean depths (e.g., Feng and Algeo, 2014). Anoxia may have set the stage for a resurgence of microbialites by decimating metazoans at the LPME, but it is unlikely to have been a factor in sustaining microbial growth in the aftermath of the extinction event.

5. Conclusions

The foraminiferal distributions, skeletal variations and microfacies analyses documented in three shallow carbonate platform successions (Wengna, Taiping, and Lung Cam) from the Nanpanjiang Basin show common patterns during the P-Tr transition. All sections record (1) a transient influx of detrital siliciclastics just prior to the LPME, accompanied by a foram gap; (2) a single foraminiferal extinction event, at the level of the LPME, associated with a diastem; and (3) an abrupt replacement of bioclast-rich Upper Permian limestones by lowermost Triassic thrombolitic microbialites following the LPME. A general biotic decline and a shallowing trend in the pre-LPME Upper Permian indicate
that unstable marine environmental conditions developed prior to the mass extinction event. The post-LPME transition to a thrombolitic microbialite facies containing an abundant gastropod-ostracod biota was due mainly to decimation of Late Permian shallow-marine biotas and not to persistent anoxia in these surface-ocean systems. Shallow carbonate platforms in the Nanpanjiang Basin record a unique set of changes in lithologies, microfacies, and skeletal compositions (i.e., different from those in deeper-water settings) that provide significant insights into biotic and environmental responses to large-scale perturbations prior to and during the Permian-Triassic transition.

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