Multidisciplinary stratigraphy across the Permian-Triassic boundary in deep-water environment of the Dongpan section, south China

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Liuqiao area in south China is an ideal place for high-resolution definition of the deep-water Permian-Triassic boundary (PTB) and correlating deep-water and shallow marine PTB sequences. It contains contemporaneous deep-water basin and shallow marine platform facies deposited in a latest Permian archipelagic palaeogeographic setting. Multidisciplinary stratigraphic data were analyzed for the first time from a well-preserved deep-water PTB section (Dongpan section) and used to define and correlate the PTB in the Liuqiao area. By applying the PTB Stratigraphic set (PTBST) concept, some important stratigraphic characteristics across the PTB were discovered including: (1) different clay mineral compositions across the PTBST; (2) radiolarian biodiversity decreased abruptly and showed step-by-step extinction across the PTBST; and (3) the most negative excursion of $\delta^{13}C_{org}$ values occurred in the PTBST. The global correlation was also compared by multidisciplinary stratigraphy between the Dongpan section and GSSP in the Meishan section. The correlation was based on the lithostratigraphical, event-stratigraphic (the boundary clay beds), biostratigraphic (radiolarian fossil assemblages), and chemostratigraphic (organic carbon isotope excursion signals) evidence. We conclude that a well-defined PTB succession is recognizable in the deep-water section of Dongpan.

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Introduction

Both the shallow marine Permian-Triassic boundary (PTB) and the deep-water PTB strata are indispensable components for completely understanding the global life crisis across the Paleozoic–Mesozoic transition. However, owing to the low biomass content in deep marine environments, research on the biota and the correlation of the deep-water PTB sequence has not been as successful as the research on shallow marine PTB. Until now, only limited data have been available from the deep-water PTB (Ishiga 1994; Blome & Reed 1995; Fang Nianqiao & Feng Qinglai 1996; Kawuwa 1996a, b; Catalano et al. 1991).

The definition and subdivision of the deep-water PTB strata is more difficult than for the shallow marine PTB equivalents. Firstly, the common biostratigraphic approach of defining the deep-water PTB is sometimes hard to attain with high resolution because of the need for high biotic abundance to allow a meaningful statistical delineation of the PTB to be attained. Secondly, definition of the PTB in marine sections has been largely based on high-resolution conodont biostratigraphic records (initial occurrences of *H. parvus)* (Jin et al. 1997). But this approach often poses severe restrictions for some deep-water sections that have a sparse fossil record, lack index fossils, have an ambiguous/mixed assemblage, or are devoid of fossils across the anticipated boundary interval. Finally, knowing how to compare the particular characteristics of the deep-water PTB events with the shallow marine PTB is still a significant problem at present. It is suggested that alternative boundary-indicative markers are needed to overcome these predicaments and to enhance the resolution of the deep-water PTB interval. In other words, multidisciplinary stratigraphy is required to subdivide and define the PTB sequence with high resolution.

Although less well known than the famous global stratotype section (GSSP) at Meishan in the Zhejiang province, southern China (Yin et al. 1996, 2001), a deep-water PTB section (Dongpan section) also exists in the Liuqiao area, southwestern Guangxi province, south China (Fig. 1) (Meng et al. 2002). In this area, there existed a deep-water basin and shallow marine platform at the same time during the latest Permian, in an archipelagic palaeogeographic setting (Feng et al. 1996; Yin et al. 1999; Yan et al. 2002). Because of the close geographic proximity between these two contrasting depositional environments, the Liuqiao region has great potential for serving as a key reference area for correlating

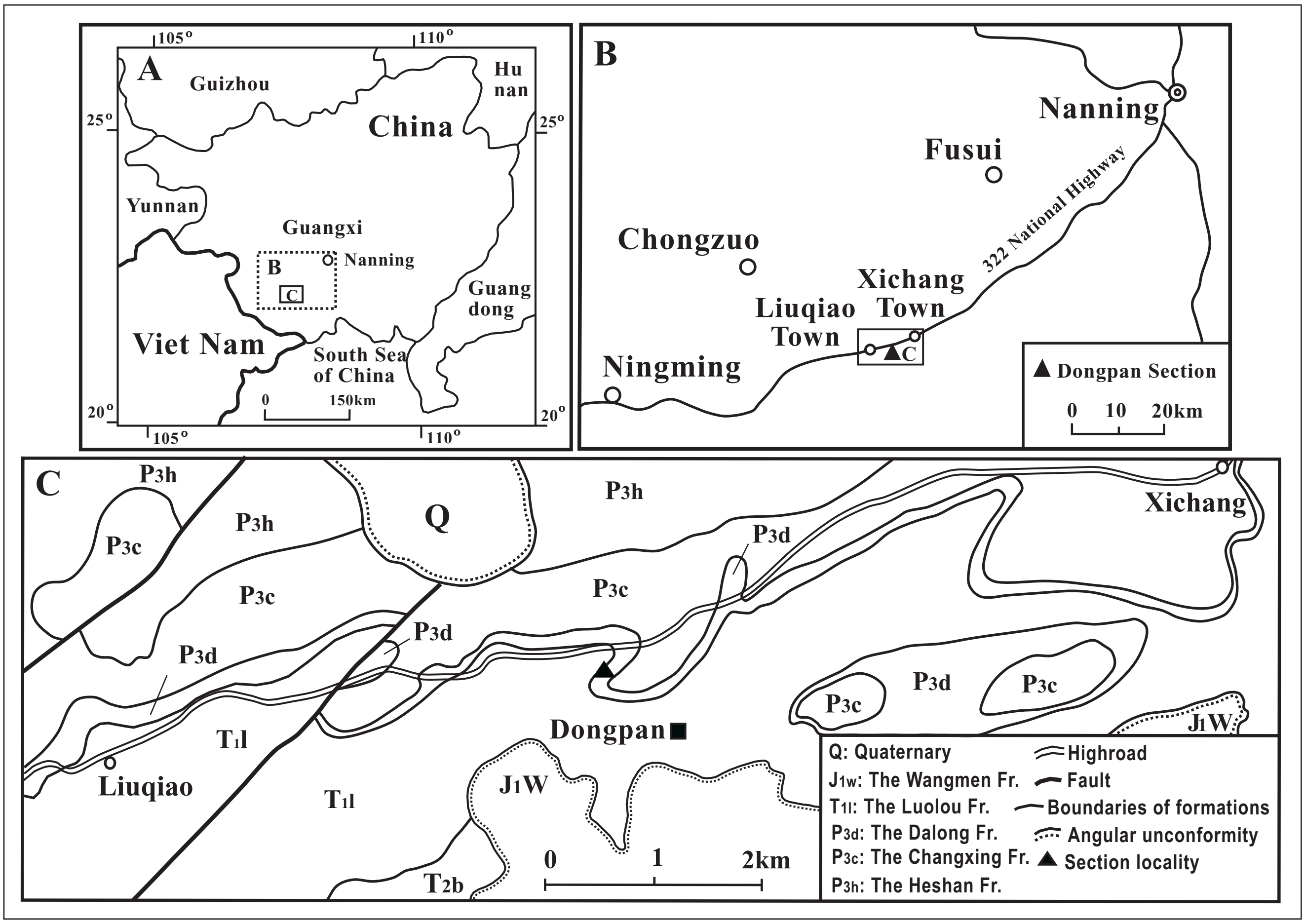

Fig. 1. Location and geology of the Dongpan section in the Liuqiao area.

deep-water and shallow marine PTB sequences.

Our study provides a detailed analysis of clay mineral, organic carbon isotope and radiolarian data from a deep-water PTB section at Dongpan that is characterized by very thick strata with a uniform facies. Consequently, it becomes possible to subdivide and define a deep-water PTB sequence with high resolution, as well as correlating deep-water and shallow marine PTB sequences directly.

Geologic setting

The research area of Liuqiao (Fig. 1) is tectonically a part of the Yangtze Plate, south China (Yin et al. 1997). The uppermost Permian strata of the Liuqiao region in southwestern Guangxi consist of about 84 m of pale-grey, sponge- and algae-bearing skeletal limestone (uppermost Permian organic reef). This grades upward into 40 m of dark, thin-bedded silicalite, tuff-bearing silicalite, mud-bearing silicalite, and silica-bearing mudstone (Dalong Formation) containing an abundant pelagic fauna and is interbedded with abundant pale claystone. The overlying lowermost Triassic consists of yellow mudstone interbedded with pale claystone, that grades upward into thin-bedded calcareous mudstone (Luolou Formation) containing abundant bivalves and ammonoids. In the later Permian, the crust broke apart and subsided in this region characterized by volcanics and sedimentary rock. A rapid rise in relative sea level followed, and the organic reef on the margin of the calcarceous plate was submerged. Thus, simultaneously a deep-water basin adjacent to a shallow plate became established in the Liuqiao region during the latest Permian (Feng et al. 1996; Yin et al. 1999; Yan et al. 2002).

The Dongpan section is situated about 4 km northeast of the Liuqiao area (Fig. 1). The outcrop of Dongpan rocks is well exposed and may be one of the best PTB-sections for studying the mass extinction and the other correlative geologic events. Diagnostic conodonts have not been discovered in the Dongpan section. However, bed 12 contains abundant foraminifera, ostracods and bivalves including *Promyalina* sp., *Posidonia* sp., *Palaeoneilo qinzhouensis* n. sp. and *Claraia liuqiaoensis* n. sp.; and the ammonoids *Huananoceras* cf. *perornatum* Chao et Liang, *Qianjiangoceras* sp. and *Laibinoceras* cf. *com-*

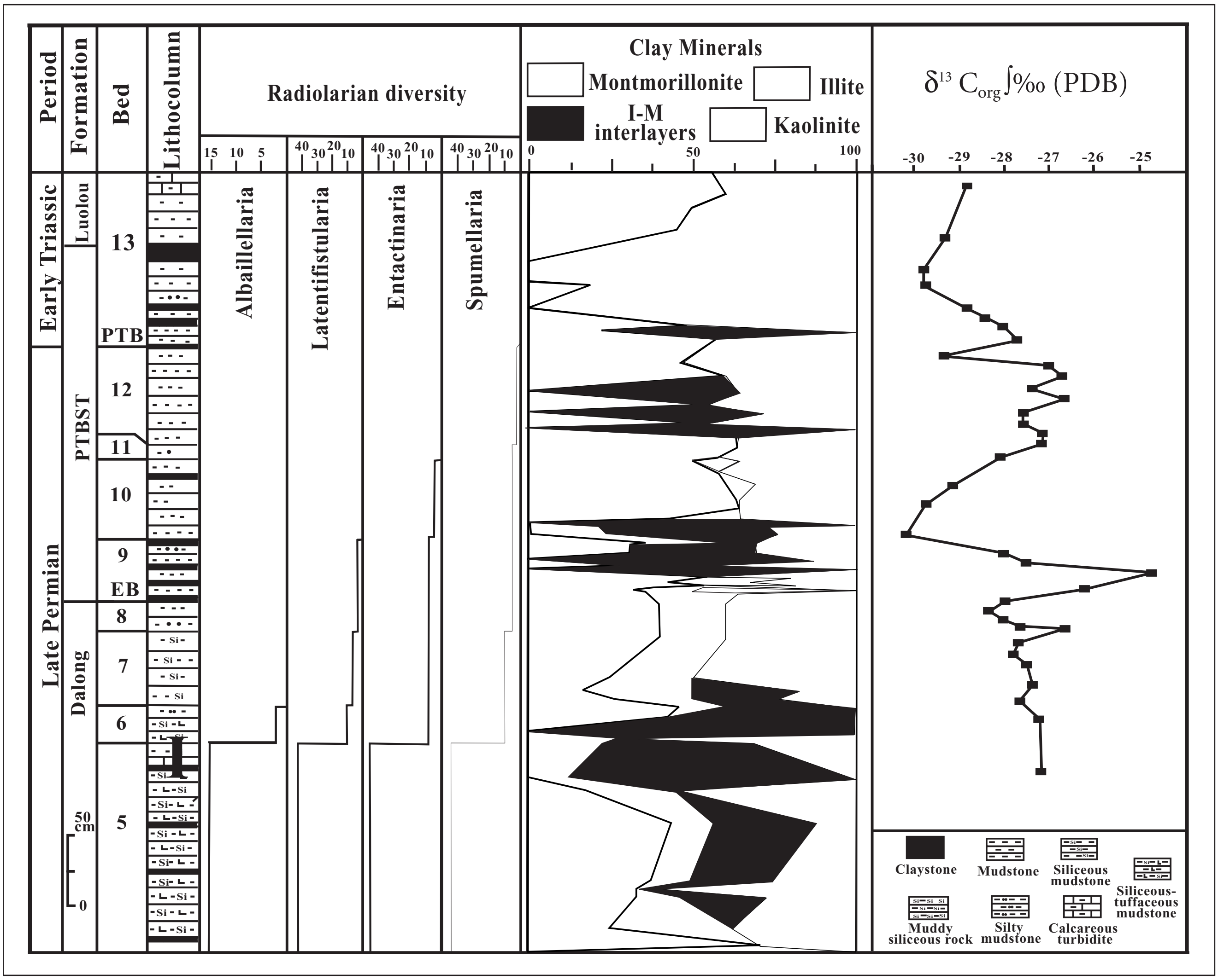

Fig. 2. Multidisciplinary high-resolution correlation of the Permian–Triassic boundary in the Dongpan section.

pressum Yang, which are typical fossils in the Late Permian. In comparison, bed 13 is characterized by abundant bivalves *Claraia dieneri, C. griesbachi* (Bittner), *C. hunanica* (Hsü 1937), *C.* cf. *C. wangi* (Patte), *C. dongpanensis* n. sp., *Palaeoneilo qinzhouensis* n. sp., *Bakevellia* sp. and *Entolium* sp., many specimens of which often occurred in the Early Triassic in south China (Yang et al. 1987; Zhao et al. 1981). *Ophiceras* sp. and *Ophiceras tingi* Tien occur in the base of bed 13. These ammonoids are index fossils in the Early Triassic. Therefore, the PTB at the Dongpan section should be placed between beds 12 and 13.

Multidisciplinary stratigraphy

In this study, fresh samples were collected from the top of the Dalong Formation including beds 5 to 12, and the basal part of the Luolou Formation including bed 13, spanning an interval of 15 m across the PTB in the Dongpan section (Fig. 2). Standard laboratory analytical techniques were applied in the preparation of these samples for analyses of clay minerals, organic carbon isotopes and radiolarians in the State Key Laboratory of Geo-processes and Mineral Resources, China University of Geosciences.

PTB succession lithostratigraphy

A set of clay rock beds associated with the Dongpan PTB section is persistently developed in the study area (Fig. 2). Of special note is the regular vertical (stratigraphical) succession of three clayrock beds, usually characterised by the vertical stacking of interbedded clay and mudstone (bed 9), followed by mudstone beds (beds 10 to 13-8), which in turn are followed by a second clay bed (bed 13-9). This regular succession of clayrock beds is similar in succession to the PTB beds in the Meishan section (GSSP), south China, where it is characterized by two clay beds (beds 25 and 26) in the lower part, a micrite bed (bed 27) in the middle, and another clay bed (bed 28) in the upper part (Fig. 2) (Yin et al. 2001). It is also common in other PTB sections outside China, such as the Abadeh section (Iran), the Nammal section (Pakistan), and the Dorasham section (Russia) (Yang et al. 1991). We adopt the term 'Permian–Triassic Boundary Stratigraphic Set' (PTBST) for this distinct and ubiquitous succession of PTB beds in recognition of its stratigraphic persistence and stability across South China and throughout the world (Peng et al. 2001, 2002). The concept has been proved very useful as an alternative marker for recognizing and defining the PTB position in sections where no definitive biostratigraphic markers are available. Furthermore, we regard the clayrock beds (bed 9) at the base of this succession as the Event-stratigraphic Boundary (EB). This distinct EB below the PTB is represented by an abrupt loss of Late Permian fossils. In the Meishan section the major extinction event is interpreted to occur at the base of bed 25 (Jin et al. 2000).

Clay mineral eventostratigraphy

The X-ray diffraction analysis shows different clay mineral compositions and other special mineral content among those clay rocks and/or mudstones of the Dongpan section (Fig. 2). There are three different clay mineral assemblage zones. These can be identified as Upper Permian (zone I, beds 5 to 8), PTBST (zone II, beds 9 to 12), and Lower Triassic (zone III, bed 13). Zone I is characterized by abundant kaolinite (with an average of 10-15%). In zone II, the clay minerals across the PTBST are dominated by illite–montmorillonite interlayers (ranging from 30% to 90%). In zone III, the clay minerals are mainly composed of illite (with an average of 37%) in the Lower Triassic. Illite–montmorillonite interlayers and some special mineral constituteents such as zircon, apatite, hexagonal dipyramid quartz, and some other accessory minerals of acidic lava are mainly found in the PTBST, which reflect their volcanic origin. This kind of clay rock composition is characteristic of marine PTB clayrocks at the GSSP in the Meishan section, as well as in other sections in south China (Yang et al. 1991, 1993). Furthermore, illite gradually increases in the rocks throughout the section, indicating a relative sea level fall because more continental detritus is carried into the sedimentary basin. The largest scale regression event occurs at the top of bed 6, which is comparable with the one that occurs at the top of bed 24e in the Meishan section. Therefore, these particular characteristics of the PTB clay rocks and/or mudstones in the Dongpan section may provide reliable auxiliary markers for high-resolution demarcation of the deep-water PTB.

Radiolarian biostratigraphy

Four orders of radiolarian fossils (*Albeillellaria, Latentifistularia, Entactinaria* and *Spumellaria*) have been found in the deep marine PTB sections at Dongpan and are abundant mainly in the Dalong Formation (Late Permian). Until now, no radiolaria have been found in the Louluo Formation (Early Triassic). Based on the stratigraphic distribution of radiolarian species diversity, the deep marine radiolaria in the study area have been subdivided into three distinct evolutionary stages (Fig. 2).

Stage 1(bed 5) is dominated by a Late Permian *Neoalbaillella optima* assemblage, in view of the appearance of *Neoalbaillella optima, Albaillella triangularis* and *Albaillella levis* in albaillellids from this section. These are index fossils of the *Neoalbaillella optima* assemblage (Ishiga et al. 1982). Additionally, this assemblage contains *Albaillella yaoi* and *Albaillella* sp. 3 which seem to appear in an upper position of the *N. optima* Assemblage Zone according to the stratigraphic distribution of Late Permian *Albaillella* in the the Gujo- hachiman section, Japan (Kuwahara 1999). Therefore, we suppose that the *N. optima* Assemblage Zone in the Dongpan section is latest Permian in age, but does not extend up to the end of the Permian. From the lowermost part of bed 5 to the upper part of bed 5, the species diversity increases gradually and reaches a peak at the top of bed 5, where up to 151 species have been recognized. It then declines sharply in bed 6. This indicates a bloom of radiolaria before its final disappearance. In the Late Permian, *Albaillella* is abundant up to the top of bed 5, with 2 genera and 15 species. Some new species of *Neoalbaillella optima, Albaillella triangularis, Albaillella flabellate, Albaillella levis, Albaillella* sp.1, *Neoalbaillella* sp.2, *Albaillella yaoi yaoi, Neoalbaillella miniscuta* can also be found. Furthermore, there are still some other Permian radiolaria in this interval. These consist of some species of *Entactinia*, *Copicyntra, Hegleria, Triplanospongos, Foremanhelena, Ishigaum.* In bed 5, the presence of the abundant deep-water radiolarian *Albaillella* indicates a water depth of nearly 500m (Kozur 1993).

Stage 2 (PTBST, beds 6 to 12) is marked by an abrupt drop of radiolarian frequency and is dominated by the *Klaengspongus spinosus* Zone. Only 28 species are found across the PTBST where most radiolaria still exhibit Late Permian aspects similar to those in Stage 1, in contrast to 151 species found in the Upper Permian deposits. *Albaillella* is abundant up to the top of bed 5, but declines sharply to one species only in bed 6 and disappears completely beyond bed 6-3. This suggests that *Albaillellidae* has already vanished before the extinction of all Permian radiolaria. Interestingly, a Permian Albaillellidae-absent radiolaria assemblage mainly composed of *Entactinia* sp., *Entactinosphaera larga, Bicavatus wani, Copicyntra ai, Copicyntra, Paracopicyntra, Copicyntroides* sp., *Hegleria mammilla, Uberinterna virgispinosum,* New genus, *Palaeolithocyclia, Palaeolithocyclia* sp. and *Ormistonella robusta.* covers the *N.*

optima Zone in the upper part of our study section, which is similar to the *Klaengspongus spinosus* Zone defined by Gu & Feng (2002).

Stage 3 (bed 13) is marked by the extinction of all Permian radiolaria because no radiolarian fossils are found in the Lower Triassic Luolou Formation, which clearly contrasts with the diversified radiolaria in the Late Permian. This might be due mainly to radiolarian extinction during the Late Permian ecologic crisis in marine settings and the continued adverse environmental conditions in the Early Triassic, which lead to the marked ecological recovery lag in Early Triassic biota (Erwin 1993, 1994).

Organic carbon isotope chemostratigraphy

δ^{13} C_{org} values in the Dongpan section vary from -30.3‰ to -24.8‰ with an average of -27.8‰ and δ^{13} C_{org} curves across the PTB are shown in Fig. 3.
Three distinct stages of δ^{13} C_{org} can be recognized as Upper Permian, PTBST, and Lower Triassic, respectvely. δ^{13} C_{org} values in the Dongpan section vary from -30.3‰ to -24.8‰ with an average of -27.8‰. In the Upper Permian (Stage 1, from bed 5 to bed 8), the δ^{13} C_{org} readings are mainly composed of heavy values, which appear to change less significantly and have a narrow range between -27.2‰ and -28.2‰ with an average of -27.7‰. During the PTBST stage (Stage 2, from bed 9 to bed 12), the values of δ^{13} C_{org} begin to drop to form the main excursion and are then followed by a partial recovery that starts to decrease gradually at the middle of bed 9 (-24.8‰), reaches its lowest value (-30.3‰) just above the bottom of bed 10 and then gradually increases up to -27.1‰ at the bottom of bed 12. In the Lower Triassic (Stage 3, within bed 13), the values of δ^{13} C_{org} gradually decline with ^{13}C-depleted values ranging from -29.7‰ to -26.6‰.

The stratigraphic trend of the δ^{13} C_{org} curve outlined above can be correlated with the changing trends of the δ^{13} C_{org} curve found at the well-known marine PTB section of Meishan (GSSP) in south China (Cao et al. 2002). A suggested significant organic carbon isotope stratigraphic correlation between both sections is shown in Fig. 3. There are remarkable similarities and differences between the δ^{13} C_{org} trends of both sections. The Meishan section shows a similar trend of the δ^{13} C_{org} curve with that of the Dongpan section in Stage 1 and Stage 2. The most negative excursion occurs in bed 26 of the Meishan section, similar to the most depleted values in bed 10 in the Dongpan section. Regarding differences between both sections, the recovery towards more enriched δ^{13} C_{org} values persists throughout the Lower Triassic in the Meishan section (bed 27). But continued ^{12} C-depleted values are found in the Dongpan section (bed 13), which shows the marked recovery lag in the Early Triassic. In general, this correlation between both sections based on δ^{13} C_{org} data suggests that carbon isotopes are of substantial help for establishing global correlations when age-diagnostic conodonts are absent. In fact, carbon isotopes have been used as chemostratigraphic markers to identify the PTB because of their distinct, worldwide negative $\delta^{13}C$ excursion in marine and terrestrial environments worldwide. This excursion has been found in marine limestones (Holser & Magaritz 1987; Baud et al. 1989; Krystyn et al. 2003), marine organic carbon (Magaritz et al. 1992; Wang et al. 1994; Isozaki 1997; Krull et al. 2000; Sarkar et al. 2003), terrestrial organic carbon (Morante 1996; Krull & Retallack 2000; Stemmerik et al. 2001; Twitchett et al. 2001; de Wit et al. 2002), and pedogenic carbonate (MacLeod et al. 2000).

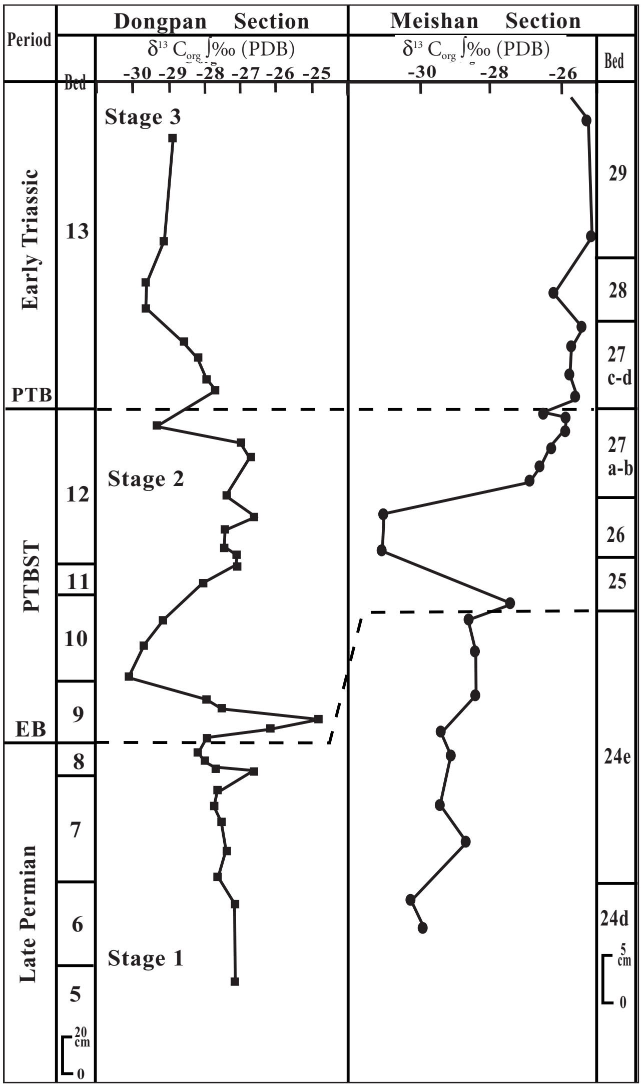

Fig. 3. Correlation of organic carbon isotopes between the Meishan and Dongpan sections.

The relationship between radiolarian extinction and $\delta^{13} C_{org}$

The study of the radiolarian biostratigraphy in the Dongpan section shows an abrupt decrease in the diversity and abundance of radiolaria across the PTBST. The results show a clear change of radiolaria from being abundant in Late Permian, scarce across PTBST, and extinct in Early Triassic. The results also reveal a characteristic 'step-by-step extinction' for radiolaria. The radiolarian extinction has been subdivided into four distinct stages across the PTBST, namely the Albeillellaria extinction, the Latentifistularia extinction, the Entactinaria extinction and the Spumellaria extinction, in this order. Since the PTBST represents a community with poor diversity after the main extinction event, we adopt the term 'disaster facies' for this distinct and ubiquitous unit which represents an oceanic event that is related to the PTB extinction (Schuber & Bottjer 1992).

The most important biostratigraphic and chemostratigraphic feature of the Dongpan section is the relationship between the 'disaster facies' across the PTBST and the carbon isotopic excursion. The close co-occurrence between the 'disaster facies' and the isotopic excursion in $\delta^{13} C_{org}$ in the Dongpan section suggests that this 'disaster facies' is linked with the PTB and that it is not caused by local changes in one particular environment. Therefore, the change in carbon behavior across the PTB presented here is likely related to a certain unusual global phenomenon coinciding with the PTB mass extinction in both terrestrial and marine environments. Notably, the $\delta^{13} C_{org}$ excursion does not exactly coincide with the PTB extinction in the Dongpan section, because the major extinction event occurs in bed 7, while the most negative excursion occurs in bed 10. This indicates that the marine ecosystem collapse precedes the onset of the carbon isotopic negative excursion. Twitchett et al. (2001) suggest that the extinction event is not caused by a '^{13}C-depleting' event, but that the δ^{13} C negative excursion is probably the result of biotic changes or extinction during the crisis or is related to external environmental factors following the crisis.

Conclusions

Combining multidisciplinary evidence from the lithostratigraphy (applying the PTBST concept), eventostratigraphy (the boundary clay beds), biostratigraphy (radiolarian fossil assemblages), and chemostratigraphy (organic carbon isotope excursion signals), a deep-water PTB succession that is closely correlated to its shallow marine counterpart in the Meishan section in south China, is recognizable using high resolution stratigraphic methods in the Dongpan section in southwest China.

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