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ORIGINAL PAPER

The prelude of the end-Permian mass extinction predates a postulated bolide impact

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Abstract The mass extinction at the Permian–Triassic Boundary (PTB) is said to have been abrupt and probably caused by an extraterrestrial impact. However, evidence from the Global Stratotype Section and Point (GSSP) of the base of the Induan at Meishan, China, shows that the biotic crisis began prior to the level, in beds 25 and 26 at which the postulated impact event occurred. Evidence of such an earlier biotic crisis occurs in other sections in South China, and in central and western Tethyan regions. This event is characterized by the extinction of a range of faunas, including corals, deep-water radiolarians, most fusulinids and pseudotirolitid ammonoids, and many Permian brachiopods. In all sections, this extinction level is usually a few decimeters to meters below that of the main mass extinction in the event beds (25 and 26) at Meishan, and their correlatives elsewhere. This earlier extinction event happened before the postulated bolide impact at the level of beds 25 and 26, and constrains interpretation of the mechanisms that brought about this greatest mass extinction.

Keywords Prelude · End-Permian · Mass extinction · Tethyan · South China

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The mass extinction at the Permian–Triassic Boundary (PTB), the most severe biotic crisis in Earth's history, was regarded as abrupt (Rampino et al. 2000) and probably induced by an extraterrestrial impact (Basu et al. 2003; Becker et al. 2001, 2004; Kaiho et al. 2001). However, this scenario is not compatible with the long-term decline of major groups of taxa that preceded their final extinction towards the end of Permian (Erwin 1993; Yang et al. 1993). Our recent researches are based on three PTB sections in South China (Fig. 1) representing carbonate shelf (Liangfengya section), intracratonic slope in carbonate shelf (Meishan section) and deep water (Dongpan section) environments. In addition to the main extinction phase at the event bed level (beds 25 and 26), associated with a postulated bolide impact, our researches reveal an earlier commencement—the prelude of mass extinction.

Earlier extinction in South China

At Meishan (Fig. 1), where the GSSP of the base of the Induan Stage marking the base of the Triassic and

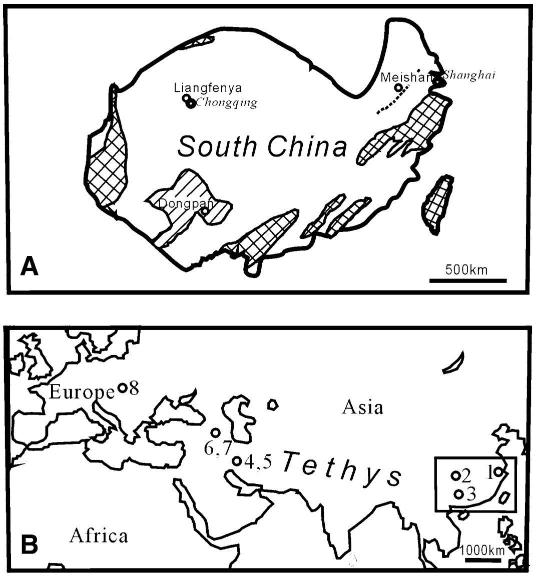

Fig. 1 Location of sections. **a** South China: *cross-hatch* oldland, *oblique lines* deep water, *blank* shelf, *dotted line* boundary between inner and outer shelves (to the east and west respectively). **b** Eastern Tethys sections: *1* Meishan, *2* Liangfengya, *3* Dongpan. Central Tethys sections: *4,5* Abadeh and Shahreza, *6,7* Ali Bashi and Zal. Western Tethys section: *8* Balvany-north

the Permian–Triassic boundary (PTB) is defined (Yin et al. 2001), it has long been recognized that a mass extinction, together with volcanism, anoxia and a possible bolide impact, occurred at the level of the claybeds immediately underlying the PTB; these claybeds (beds 25 and 26) are called the event beds. However, our researches show that the biotic and environmental changes were initiated in bed 24e, a 10 cm bed below the event beds, or even in the beginning of bed 24 (Fig. 2). An analysis of lipid molecular records reveals two phases of 2-MHP index minima (with values of 1.2–1.7%) across the PTB, probably reflecting the microbial (cyanobacterial) response to the PTB crisis (Xie et al. 2005). The first phase shows a minimum 2-MHP index value from bed 24e to bed 25, indicating the onset of cyanobacterial change which may reflect a decline in basic aquatic productivity. The second minimum, in beds 27 and 28, was approximately synchronous with an earliest Triassic extinction (see Conclusion). Each minimum is followed by an abrupt and pronounced maximum (6.6%) in beds 26 and 29b, respectively. These maxima lag behind the extinctions and probably record changes in the planktonic community after the decimation of marine invertebrates (Xie et al. 2005).

Size reduction of conodonts that commenced in bed 24e reflects the commencement of environmental stress (Luo et al. 2006). Statistics of the conodont *Neogondolella* (Table 1), one taxon that survived the PTB crisis, were taken from our laboratory records. Because the *Neogondolella* species are the same in beds 24c, d, and e, the length measurements of complete individuals were taken at random. Size average (X) is based on the equation: $X = 1/N\sum f_i y_i$, where X is the average size, N the total number of individuals, f the ranked size, and y the number of individuals in each ranked size. Measurements of the size of 391 *Neogondolella* individuals shows that bed 24e is marked by the onset of a sharp reduction in average size (from 0.63–0.69 to 0.54 mm) as well as a pronounced trend to juvenile or dwarf size (Table 1; Fig. 2). This may reflect deterioration in the conditions of the conodont habitat.

At Meishan the $\delta^{13}C_{carb}$ (carbon isotope composition of carbonate) began to decline slowly from bed 23, then rapidly in bed 24e, with a total reduction of 2.3‰ (Fig. 2; Cao et al. 2002). Furthermore, a sharp enhancement of aryl isoprenoids, biomarkers diagnostic of anoxygenic photosynthesis by Chlorobiaceae, was recorded in bed 24 (Grice et al. 2005). The coincidence of these lines of evidence suggests that an earlier biotic and environmental crisis had commenced in bed 24e, prior to the events of beds 25 and 26.

In the Liangfengya section (Fig. 3) in Chongqing City, South China, 1,100 km west of the GSSP (Fig. 1), the latest Changhsingian lithology changes from limestone to argillaceous limestone and marl from the base of bed 41, marking increased terrigenous imput (Yang et al. 1987, 1993). This level corresponds with the decline of $\delta^{13}C_{carb}$ from 2 to ±0.5‰. It also coincides with the disappearance of fusulinids, corals, pseudotirolitid ammonoids and part of the Permian brachiopods and non-fusulinid foraminifers. Beds 43 and 45 correlate with the event beds (25 and 26) at Meishan, because they share the essential features of those beds (volcanogenic claybeds immediately below the PTB (FAD of *Hindeodus parvus* in bed 46) and a decline in $\delta^{13}C_{carb}$, from ±0.5 to –1‰). Thus, at Liangfengya the prelude of extinction was at the base of bed 41 and therefore occurred prior to the event beds 43–45. This initial extinction was first reported as ‘an important line of biotic decline’ related to the end-Permian regression which greatly reduced habitat space (Yang et al.1993; Yin et al. 1996). Wignall and Hallam (1996) attributed it to the progressive decline of benthic oxygen levels, which culminated in anoxia at the PTB.

The Dongpan section in Guangxi Province, South China (Fig. 1), presents another example of multiple extinctions through a continuous, shallowing upwards sequence below the PTB (Fig. 4). The PTB is located between beds 12 and 13, based on occurrences of the

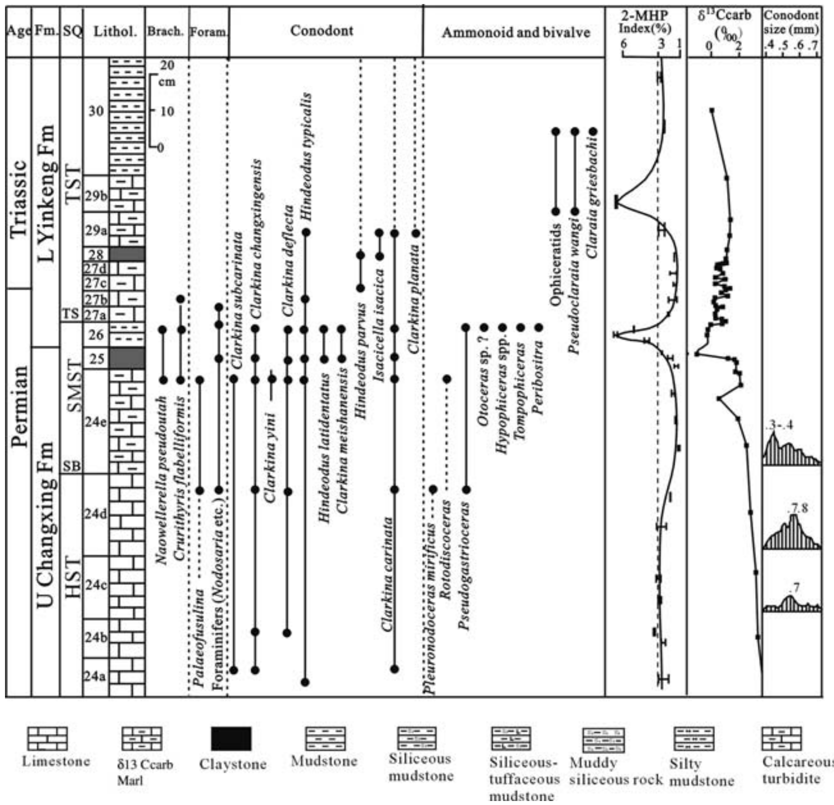

Fig. 2 PTB strata in the Meishan section, showing the initial biotic and environmental changes in bed 24e. Abbreviations: *Brach*. brachiopod, *Foram.* foraminifer, *Fm* formation, *Lithol.* Lithology, *SQ* sequence stratigraphy; 2-MHP (2α-methylhopane) index is the ratio of 2-MHPs to hopanes lacking additional methyl substituents; it reflects the abundance of cyanobacteria relative to general bacteria [*curve* adapted from Xie et al. 2005 with *error bars* reflecting the measurement error: 2σ of >3 measurements; in bed 24e it drops to a minimum (1.2%)]. Conodont size traces represent the average size of *Neogondolella* in beds 24c–24e, with a histogram for each bed showing the size distribution curve and modal size value (mm). In contrast to the normal distribution (0.7–0.8 mm) in beds 24c and 24d, the distribution curve for bed 24e shows a pronounced deviation toward small size (0.3–0.4 mm), reflecting a dominance of dwarf or juvenile forms

Table 1 Population size and distribution of *Neogondolella* in bed 24, Meishan (revised fromLuo et al. 2006)

Bed	Size of *Neogondolella* population (length in mm)									Population size curve	
Bed no.	≤0.2	0.3–0.4	0.5	0.6	0.7	0.8	0.9	1.0–1.1	≥1.2	Average	Distribution	Mode (mm)
24e	18	46	21	23	7	18	6	9	4	0.5414	Deviated to juvenile	0.3–0.4
24d	17	27	24	21	32	32	22	23	8	0.6282	Normal	0.7–0.8
24c	3	2	2	5	10	4	2	4	1	0.6879	Normal	0.7

index Permian ammonoid *Huananoceras* cf. *perornatum* in the former bed and the Triassic ammonoid *Ophiceras tingi* in the latter. The silica content also declined at the PTB. Late Changhsingian beds 2–5 are dominated by radiolarites, and yield representatives of all four radiolarian orders (Albaillellaria, Latentifistularia, Entactinaria, Spumellaria). This interval is regarded as bathyal because abundant Albaillellaria and thin-shelled psychrophilic ostracodes (Palaeocopida, Podocopida) usually indicate water depths greater than 200 m (Catalano et al. 1991). The first phase of the end-Permian extinction occurred at the base of bed 6 where, of 137 radiolarian species, 53% became extinct (Feng et al. 2006). Albaillellarians and psychrospheric ostracodes disappeared, calcareous foraminifers were largely replaced by agglutinated forms, and brachiopods radiated abruptly (He et al. 2005). The loss of biogenic silica is paralleled by a lithological change, from bedded chert (bed 5) to siliceous mudstone (bed 7), and by an increase in terrigenous clasts (percentage of feldspar weight, Fig. 4). Feng et al. (2006) claimed that a second extinction phase, with the loss of 35% of radiolarian genera, occurred at the base of bed 8; this is not evident in Fig. 4, which only shows the numbers of

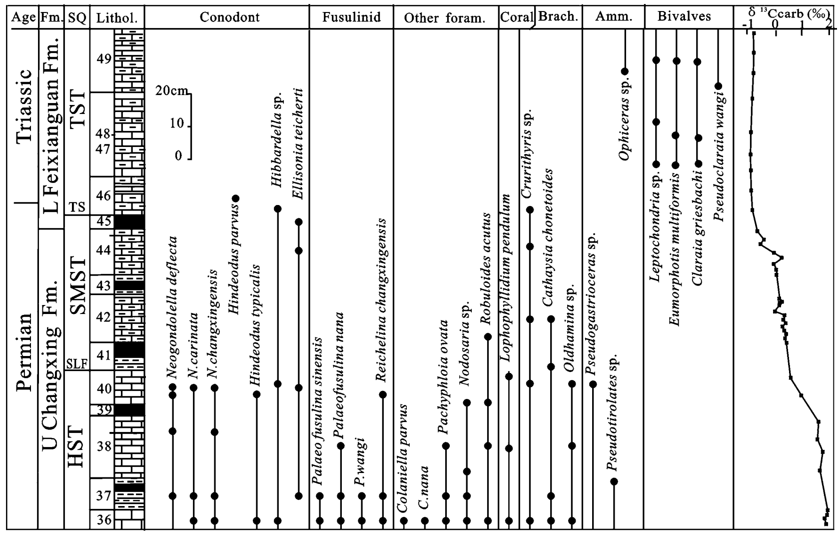

Fig. 3 PTB strata in the Liangfengya section. Abbreviations and key as in Fig. 2, with Amm.—ammonoid. Beds 43 and 45 are volcanogenic because they contain B-quartz, automorphic apatites, glass sphaerules and altered pellets containing Si, Al, Mg and Fe, and are microscopically laminate, suggestive of the presence of illite–montmorillonite. Note the FAD of *Hindeodus parvus* in bed 46

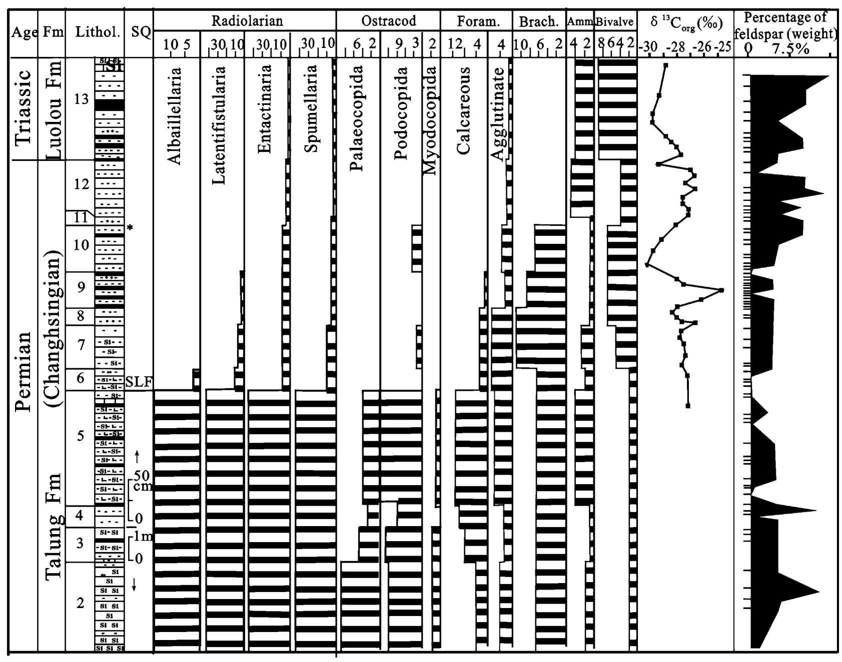

Fig. 4 PTB strata in the Dongpan section. Abbreviations and key as in Fig. 2, with Amm.—ammonoid. Only the numbers of species are represented in the columns for biota, because of the large diversity. *Horizontal bars* in column of 'percentage of feldspar: sample levels. Note change of scale between beds 3 and 4

species. A third phase in the end-Permian extinction, at the base of bed 11, is marked by the disappearance of brachiopods and a decrease in the diversity of radiolarians, foraminifers and ostracodes; ammonoids and bivalves become dominant above this level. A conspicuous negative $\delta^{13}C_{org}$ excursion, recorded in bed 10, just below this third extinction phase, is reminiscent of event bed 26 at Meishan. Xia et al. (2004) reported three end-Permian radiolarian crises from sections in SW Japan; these are correlated with, in ascending order: (1) the base of the *Clarkina zhangi-Clarkina yini* zone, or approximately the base of bed 24 at Meishan; (2) the base of the *Clarkina meishanensis* zone or the base of bed 25 at Meishan; (3) the top of the *Clarkina meishanensis* zone or approximately the top of Bed 26 at Meishan. Here in Japan the second and third of these crises together correspond to the main extinction in the event beds (25 and 26) at Meishan. From these correlations it is evident that in Guangxi and SW Japan there was an earlier phase in the end-Permian extinction (bed 6 at Dongpan) prior to the main extinction phase (event beds of Meishan). In British Columbia an earlier radiolarian crisis has been reported 1.5 m below the first appearance of *Hindeodus parvus* (Wignall and Newton 2003).

Comparable loss of faunas at the 'important line of biotic decline' below the event beds has been observed at other PTB sections in South China, such as Huaying in Sichuan Province and Yanshi in Fujian Province (Yang et al. 1993). Collectively, this event is characterized by the extinction of a range of fauna, including corals, deep-water radiolarians, most fusulinids and pseudotirolitid ammonoids, and many Permian brachiopods.

Earlier extinction in Tethys

In the Abadeh and Shahreza sections in central Iran (Korte et al. 2004a, b), and the Zal section of NW Iran (Korte et al. 2004c), $\delta^{13}C_{carb}$ decreases markedly in the *Clarkina yini* zone which, according to Mei et al. (1998), is coeval with bed 24 at Meishan. Coincidentally, in the Abadeh section, pseudotirolitid ammonoids disappeared below the base of *C. yini* zone, i.e., about 1 m below the boundary claybed (IJRG 1981), paralleling the situation in the Liangfengya section. In the Ali Bashi section (Julfa) in northwest Iran (Baud et al. 1989; Kakuwa et al. 1999), a decrease in $\delta^{13}C_{carb}$ started in the upper part of the *Paratirolites* limestones (*C. yini* zone). A drop of about 2 ‰ occurs between the two highest beds of these limestones, which also have an impoverished fauna and can be correlated precisely with bed 24e at Meishan. In the central Tethys region therefore, the prelude of extinction is marked by the disappearance of pseudotirolitids and a decline in $\delta^{13}C_{carb}$ at about the same horizon as bed 24 at Meishan, or in the *C. yini* zone.

In the western Tethys, in the Balvany-north section in the Bükk mountains, Hungary (Haas et al. 2004, 2006), the prelude of extinction (the first biotic decline sensu Haas et al.) occurred in the topmost limestone beds (6–2 and 6–3: 10–15 cm thick), which immediately underlie the 1 m thick boundary shale bed (BSB, bed 7). A dramatic decrease in biogenic components (from 20% to less than 5%) that occurs in these topmost limestone beds coincides with the beginning of a gradual negative $\delta^{13}C_{carb}$ shift (from 2 to near 0‰) that continues into the BSB. A second biotic decline is recorded in the upper third of the BSB, where the gradual negative $\delta^{13}C_{carb}$ shift changes to a much stronger, sharp and symmetric negative peak. The BSB correlates with the claybeds (event beds) 25 and 26 at Meishan because both yield the index conodont *Hindeodus praeparvus* and sharp negative $\delta^{13}C_{carb}$ peak. Here again there is a first biotic decline (beds 6–2 and 6–3) corresponding to bed 24e at Meishan. Mineralogical and geochemical analyses failed to reveal any evidence for extraterrestrial effects in the Bükk mountains.

Discussion

The above data show that, prior to the main extinction at the PTB, a prelude of the end-Permian extinction occurred throughout Tethys and further afield. This earlier event corresponds to the *Clarkina zhangi*–*Clarkina yini* zone, or bed 24e or, at some localities, the whole of bed 24 at Meishan, and is usually within one meter, or only a few decimeters, below the level of the event beds (25 and 26) and their correlatives, depending on the depositional rate in the different sections. Signor-Lipps effect caused by sampling bias seems unlikely in view of the quasi-synchronous correlation of sections throughout Tethys and the statistics of large numbers of samples, e.g. radiolarian species at Dongpan and *Neogondolella* sizes at Meishan. Although a pre-PTB decrease in $\delta^{13}C_{carb}$ has been found in many sections throughout the world (e.g. Baud et al. 1989), it is not easy to recognize a pre-event-bed biotic extinction and environmental crisis. This is firstly because the Meishan GSSP section, on which most papers on bolide impact and mono-phase extinction models are based, is highly condensed. A widely quoted statistical analysis claiming a mono-phase extinction (Jin et al. 2000) was based on fossils collected, on average, at intervals of 30–50 cm; bed 24e is, however, only 10 cm thick, and thus may not have been sampled specifically by these workers. Only with close, high-resolution sampling can adequate biostratigraphic and chemostratigraphic records be obtained from such a thin bed. Secondly, it is difficult to identify the pre-event-bed change because most sections lack such a bed. Only in sections with a detailed and continuous conodont zonation, such as the Iranian sections, or those with horizons that are synchronous with the event beds at Meishan, such as the Iranian and Hungarian sections, can beds coeval with bed 24e and its changes be recognized.

The prelude of extinction in bed 24e was not, however, separated by a non-extinction interval from those that happened later in the event beds 25 and 26. Instead, the general decline of the biota and $\delta^{13}C_{carb}$ was followed and greatly enhanced in beds 25 and 26 by a number of possibly interrelated catastrophic events, including flood basalt eruption, carbon-cycling change and a postulated bolide impact, which made the latter the main phase of the extinction. The earlier extinction event is thus regarded as the prelude of the main phase. Nevertheless, it is significant that the prelude occurred well before the postulated end-Permian extraterrestrial impact event, thus constraining simplified explanations of the greatest extinction and implying different mechanisms of change.

Assuming a depositional rate of 0.4 cm per 1,000 years for the upper Changing Formation (Jin et al. 2000), the 10 cm-thick bed 24e would represent 25, 000 years.

Conclusion

There are at least two end-Permian events of extinction. The earlier one, the prelude of extinction, corresponds to the base of bed 24e in the GSSP at Meishan. The later one, the main phase of extinction, corresponds to the event beds in the GSSP, or more precisely, to a sudden diversity decrease in bed 25 and a subsequent decline in bed 26, with the extinction of most Permian taxa at the top of that bed (Fig. 2). In the earliest Triassic at Meishan, a third one corresponding to the base of bed 28 has been widely reported (e.g. Yang et al. 1993; Yin et al. 1996; Wignall and Hallam 1996). These phases belong to the PTB interval and the PTB mass extinction was, therefore, multi-phase. The multi-phase nature and the timing of prelude, which commenced well before a postulated bolide impact event, constrain the causal mechanisms of this greatest mass extinction in geological history with a string of interrelated catastrophic events (Benton 2003). Our study favors mechanisms associated with Earth-bound processes and its intrinsic evolution, rather than an extraterrestrial impact.

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