Front. Earth Sci. China 2007, 1(2): 129–141
DOI 10.1007/s11707-007-0017-2

REVIEW ARTICLE

Recent achievements on the research of the Paleozoic–Mesozoic transitional period in South China

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Abstract This is a review of research achievements on the Permian–Triassic transition in South China. It comprises of five parts: (1) advances on the biostratigraphy and eventostratigraphy of the Meishan Section, the Global Stratotype Section and Point (GSSP) of the Permian–Triassic boundary (PTB); (2) advances on the PTB research of deep water facies, especially the Dongpan Section in Guangxi; (3) advances on the PTB research of terrestrial facies, especially the Chahe Section in Guizhou; (4) correlation of the global change and biotic extinction between the PTB and modern times and its revelation to the status and future of the earth and mankind; and (5) the pattern and causality of the Permian–Triassic extinction. In the last part, it is concluded that the Permian–Triassic transitional interval constitutes a prolonged crisis period ranging from end-Guadalupian extinction to the end of Early Triassic, totaling 14 Ma. The environmental crisis and mass extinction peaked at the PTB, which displayed multiphase extinction rather than just one phase. Commencement of an extinctions prelude prior to the postulated bolide impact implies that the causes of PTB extinction largely lie in the intrinsic developments of the earth, especially those related with the integration of Pangea.

Keywords Permian–Triassic transition, South China, protracted crisis, multiphase extinctions

The Paleozoic–Mesozoic transition is a turning period in geological history, during which extremely widespread and profound global changes happened, which led to the greatest biotic extinction in the Phaenerozoic. Vigorous researches have been taken on this topic, especially in South China which, due to its continuous stratigraphic record and relatively complete accumulated data, is an ideal region to do in-depth researches on this important period. This paper attempts to make a review on what have been done on this topic.

Received February 20, 2007; accepted March 8, 2007

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1 Advances on the biostratigraphy and eventostratigraphy of the Meishan Section D, Changxing County, South China, the GSSP of PTB

1.1 Advances on the biostratigraphy of the GSSP of PTB

New results since the establishment of Global Stratotype Section and Point (GSSP) (Yin et al., 2001) include researches on sedimentology (Zheng, 2006), molecular biostratigraphy (Wang, 2007; Xie et al., 2005), radiolarians (He et al., 2005b), foraminifers (Song et al., 2006) and palynomorphs (Zhang K X et al., 2004). A synthesized and refined conodont zonation of the Permian–Triassic boundary (PTB) strata at Meishan Section D, based on Jiang et al. (2007) and Zhang et al. (2007), is shown in Table 1.

Based on the Zal Section of Iran, Kozur (2007) suggested the insertion of *Neogondolella iranica* and *Ng. hauschkei* zones between the *Ng. yini* zone and *Ng. meishanensis* zone, and insertion of a *Merrillina ultima* zone between the *H. praeparvus* zone and *H. parvus* zone. Wardlaw and Davydov (2005), however, recognized *Ng. hauschkei* at Meishan but declined it as a separate zone. *Ng. iranica* was said to have occurred in Huangshi, Hubei, but not yet in Meishan (Kozur, pers. comm.). The *Merrillina ultima* zone is only regional and not applicable in Meishan.

With bed-by-bed careful sampling and correlation, the conodont zonation of PTB becomes more detailed and its duration becomes shorter. With the establishment of *I. staeschei* zone (Jiang et al., 2007), the *parvus* zone is now only 4 cm thick at Meishan. However, this should not lead to the

Table 1 Conodont zonation (Jiang et al., 2006; Zhang et al., 2007)

Bed No. of Meishan Section D	Conodont zonation *Hindeodus-Isarcicella*	*Neogondolella-Neospathodus*
93–111		*Ns. cristagalli-Ns. dieneri*
73–92		*Ns. kummeli*
52–72		*Ng. tulongensis-Ng. planata*
29b–51	*Isarsicella* (*Italized*) *isarcica*	
27d–29a	*I. staeschei*	*Ng. taylorae*
27c	*H. parvus*	
27a–b	*H. changxingensis*	
26		*Ng. meishanensis meishanensis*
25		
24c–e	*H. praeparvus*	
24b		*Ng. changxingensis yini*
24a	*H. latidentatus*	

negation of the *H. parvus* zone as a biozone because a biozone is a "biostratigraphic unit regardless of thickness or geographic extent" which may be as thin as one single bed (Murphy and Salvador, 1999). During critical periods of geological history, under environmental stress, the evolutionary rate of certain organism taxa may be accelerated to as high as several tens of times of that during ordinal and stable development, and a biozone may thus only occupy "a single bed". Such situation happens at the PTB crisis. However, as the GSSP is defined at the FAD of *H. parvus*, we are ready to shift the PTB downward, e.g. to bed 27b, if anytime *H. parvus* is proved to occur in bed 27b.

Cao and Shang (1998) doubted that some bedding surfaces of bed 27 may be hard-grounds and thus represent hiatuses. There are also doubts that the *H. parvus* zone may be a condensation zone with mingled fossils of different ages. These challenges are important because the International Guidelines emphasize that "no disconformities, unconformities, cryptic paraconformities or time-breaks in sedimentation any longer than a brief diastem can be tolerated close to a GSSP" (Cowie et al., 1986, B5g), and that "stratigraphic condensation" or "extremely low rates of sedimentation may result in fossils of different ages and different environments being mingled or very intimately associated in a very thin stratigraphic interval, even in a single bed" (Murphy and Salvador, 1999). Anyhow, Zheng (2006) recently indicated that the bedding surfaces of bed 27 are subaqueous exposures which merely experienced dehydration and compaction. There are no obvious cementation and thus are not hard-grounds. As to fossil condensation, since the establishment of the *H. parvus* zone at Meishan, all formal reports have confirmed that it is capable of global correlation without such condensation. The thin bed 27 can be traced in the whole South China (Peng et al., 2001), and so is the fossil *H. parvus*. Based on event correlation with other sections by CONOP method, Wardlaw and Davydov (2005) confirmed that all events are consistent relative to each other and there is no missing zone or sedimeqwntation at Meishan Section. At this stage, it may be safe to say that the GSSP of PTB at Meishan is free of hiatus and fossil condensation (mingling), although it should be admitted that bed 27 was deposited under a very low sedimentary rate.

1.2 Advances on the eventostratigraphy of the GSSP of PTB

1.2.1 Two phases of environmental crisis and mass extinction

At Meishan Section, biotic crises are closely related with the stressed environments. Recent molecular researches show that there are two cycles of rise and fall in response to the environmental changes. Each cycle began with the flourishing of green sulphur bacteria (Chlorobiaceae) at bed 24e and bed 27 (Grice et al., 2005), followed by the two phases of extinction at beds 24e–25 and 28–29, mainly represented by animals (Fang, 2004; Yang et al., 1993; Yin et al., 2007a), and ended up with the flourishing of cyanobacteria at beds 26 and 29 (Xie et al., 2005). It is to be noted that the 2-methylhopane (2-MHP) index representing cyanobacterial abundance shows two ebbs at beds 24e–25 and 27–28, synchronous with or a little later than the flourishing of green sulphur bacteria (Xie et al., 2005, Fig. 3). Wang (2007) reported a pristine-abundant event with high values of Pr/Ph and Pr/nC_{17} at beds 23–26, denoting a marine extinction coupled with anoxic environment. Recently, a detailed molecular biostratigraphic research on the PTB strata of Meishan Section D shows that the AIR index curve representing the abundance of green sulphur bacteria experienced multiple negative excursions, and corresponds to negative excursions of the redox indicator—pristine/phytane ratio curve. The former represents a photic zone euxinia, whereas the latter represents a reductive environment, so these coincident fluctuations indicate that the environments were under a very unstable situation and the redox condition changed abruptly (Fig. 1) (Huang et al., 2007).

The 18 genera and 50 species of Late Changxingian non-fusulinid foraminifers at Meishan also suffered two phase extinctions. Only two genera and eight species survived to beds 23 and 24 with an extinction rate of 91% and 71% at species and generic level respectively, and they all disappeared at the second phase (beds 28 and 29) (Song et al., 2006).

Measurements of the size of 391 individuals of the conodont *Neogondolella*, one taxon that survived the PTB crisis, show bed 24e is also marked by the onset of a sharp reduction in average size (from 0.63–0.69 to 0.54 mm) as well as a remarkable deviation to juvenile (early death?) or dwarfed size in bed 24e. This marks a deterioration of conodont habitat (Luo et al., 2006).

Carbon isotope stratigraphy (Cao et al. 2002; Li, 2003) has shown that, besides the worldwide negative excursion just below PTB, a general decline tendency already began at bed

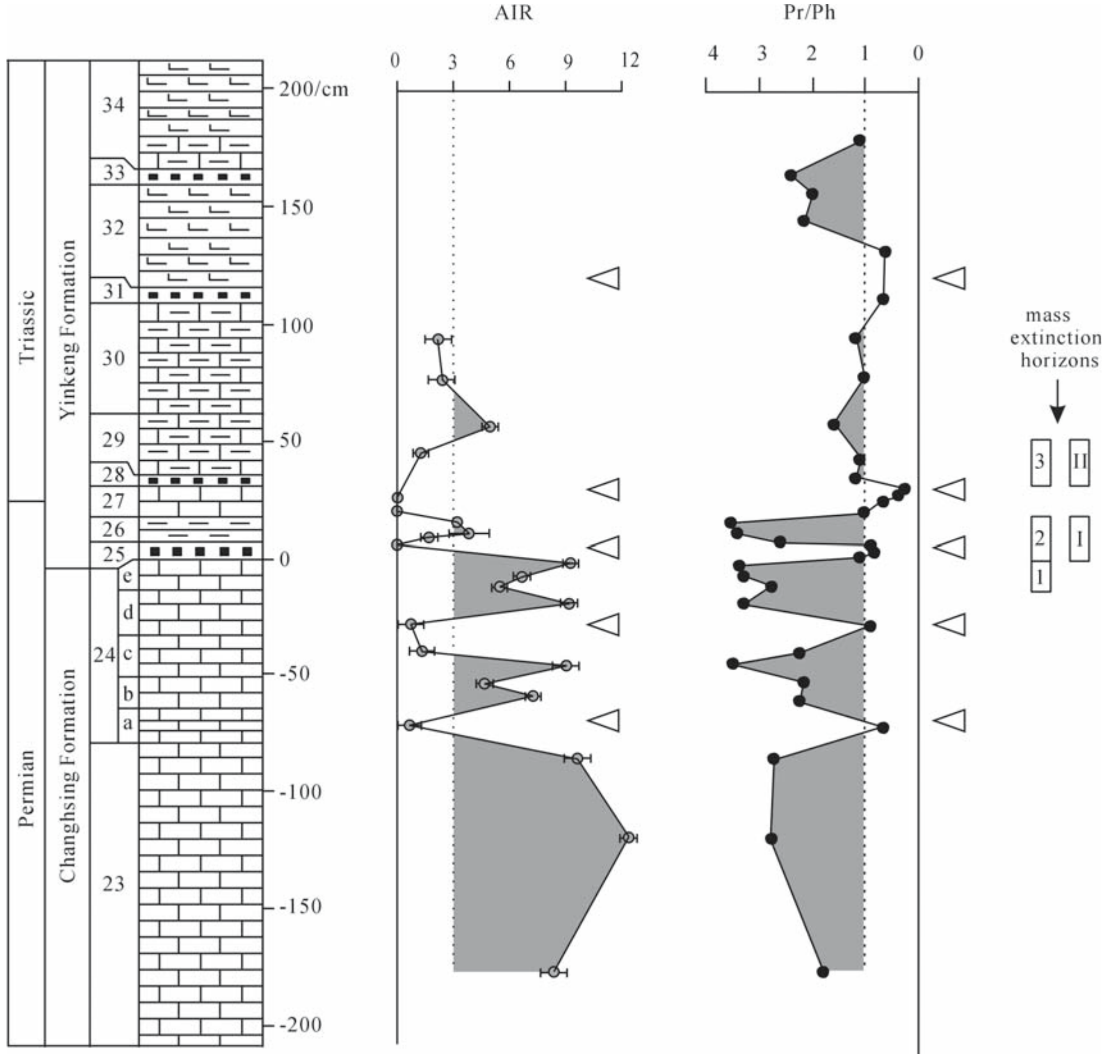

Fig. 1 Plots showing the variation trends of the AIR index of green sulfur bacteria and the Pr/Ph throughout the Meishan Section (after Huang et al., 2007). Triangles denote the episodes of sulfide toxicity at photic zone. Shaded areas indicate the relatively aerobic periods. The AIR index, an indication of the redox condition of the sedimentary environments, is an aryl isoprenoid ratio by calculating the proportion of the short-chain C_{13}–C_{17} relative to the intermediate chain C_{18}–C_{22} aryl isoprenoids. The AIR value is not available at some beds due to the low concentration of aryl isoprenoids. The numbers labeled on the right of the figure denote the individual phases of the faunal mass extinction, among which 1, 2 and 3 are from Yang et al. (1993) and Yin (1996), and I and II are from Jin et al. (2000)

24, prior to the event beds (beds 25 and 26) and its equivalents in Hungary (Haas et al., 2007) and the Alps (Farabegoli et al., 2007). A preludial negative excursion exists at bed 24e (Cao et al., 2002). However Li's (2003) Changhsingian carbon isotope curve displays much stronger oscillation than previous results, the cause of which needs further investigation.

1.2.2 Advances on other signatures of events

A research on Late Changhsingian to Early Induan palynomorphs shows that a large amount and diversity of palynomorphs of terrestrial origin have been discovered at beds 26 and 34 (Zhang K X et al., 2004), many of which show signals of fire disaster and soot, favoring volcanic effect.

Li Y F et al. (2005) confirmed the existence of fullerenes in the white clayrock (bed 25), first reported by Becker et al. (2001). They discovered that the spike of fullerene abundance occurs at the dark gray microlayer (25B) at the base of bed 25, then gradually decreases to the overlying red microlayer (25R) and becomes much less in bed 25 itself (Fig. 2). Investigations of the $^{3}He/^{4}He$ (10^{-6}) ratio in fullerenes have been taken in the Lanzhou Laboratory, CAS, but the measurements are too scattered to render definite results to confirm or deny the data given by Becker et al. (2001).

It is noteworthy that in the PTB clayrocks of terrestrial sections along the Yunnan–Guizhou border, existence of fullerenes has been primarily detected. The horizons are the claybed of beds 68 and 71, Chahe Section (Fig. 4) and the claybed of bed 49b, Zhejue Section. Moreover, fullerenes

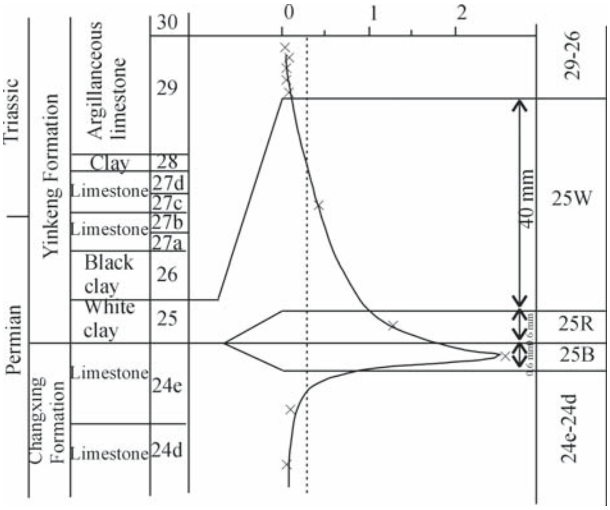

Fig. 2 Distribution of fullerenes anomalies at the PTB beds of Meishan Section (unit of abscissa: ng/g)

with similar abundance as that of Meishan have been detected at the underearth and roof carbonaceous claybeds, as well as in the interbedded clay of gangues, of the coal beds of Late Triassic Yipinglang Formation, Yunnan (Liang, pers. comm.). This implies that fullerenes may be of the earth's intrinsic origin.

Liang and Ding (2004) reported that the gypsum found in the boundary clay (bed 25) yields extraordinarily negative delta values ($\delta^{34}S = -9.2‰$ or $-4.6‰$). If these values represent the original syndepositional values as they suggested, it is important because sulfidic sea water has been reported for the P/T interval in Australia and Greenland (Nielson and Shen, 2004; Grice et al., 2005).

2 Advances on the PTB research of deep water facies—the Dongpan Section, Hushui County, Guangxi (Fig. 3)

This section has been extensively investigated for its lithology (Meng et al., 2005), sedimentology (Meng et al., 2004), clayrocks (Zhang et al., 2006a), carbon isotope (Zhang et al., 2006), radiolarians (Feng et al., 2006a, b, c), foraminifers (Gu et al., 2005), brachiopods (He et al., 2005a), ostracods (Yuan et al., 2006), bivalves (He et al., 2007a) and ammonoids (Bu et al., 2006). The PTB was delineated between beds 13 and 12 by typical Permian and Triassic ammonoids

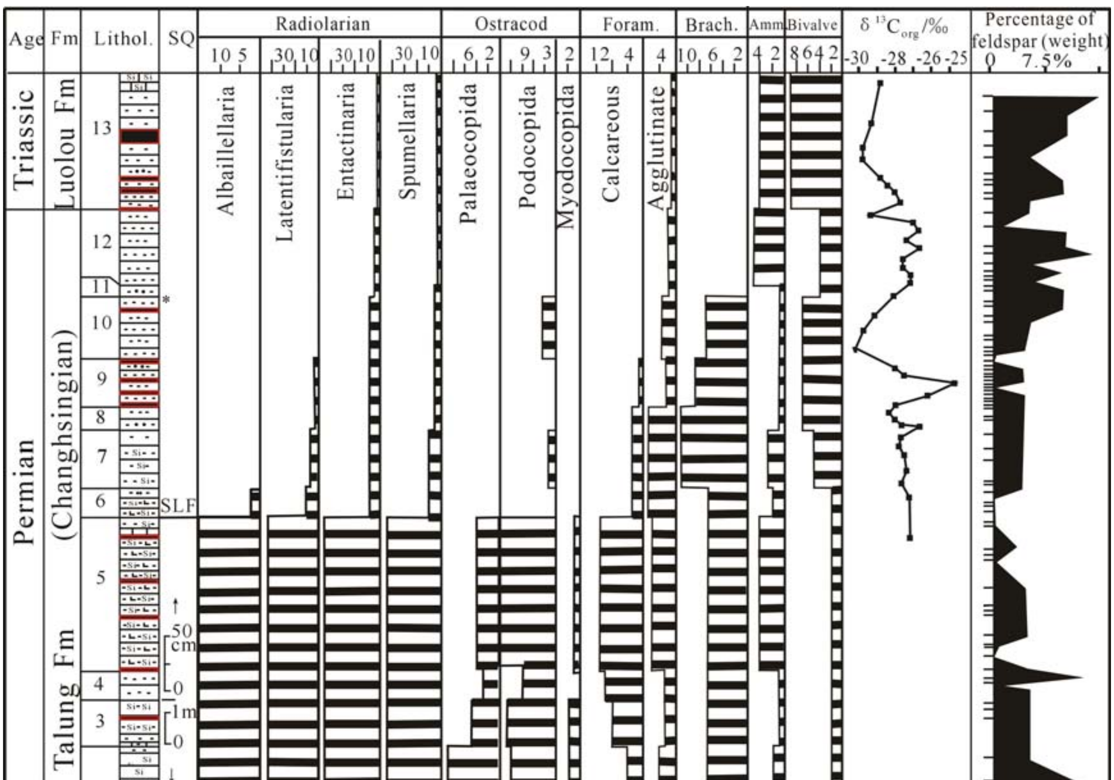

Fig. 3 Synthetic column of PTB strata at the Dongpan Section. Amm. Ammonoid; Brach. Brachiopod; Foram. Foraminifer in siliceous rocks; Fm. Formatiom; Lithol. Lithology. SQ. sequence stratigraphy. Horizontal bars in the left column: sampling horizons. Because of the large diversity, each biotic column only shows the number of species

(Feng et al., 2007). These researches have made this section one of the most representative PTB sections of deep water facies. A more detailed report on three worthwhile aspects is as follows.

2.1 The extinction episodes of Late Changhsingian organisms at Dongpan Section

Late Changhsingian radiolarians experienced three stages: radiation stage, extinction stage and survival stage (Feng et al., 2006a, b, c, 2007). During the radiation stage (beds 1–5 of the Dongpan Section), 49 genera and 134 species belonging to all four radiolarian orders have been discovered. About 1/3 are new species, some of which have highly specialized morphology and extraordinary skeleton. These phenomena denote that the radiolarians of Dongpan Section were highly diversified at this stage. During the extinction stage (beds 5–7), they suffered two crises. The first crisis occurred at the beds 6/5 boundary, where 65% species and 36% genera disappeared, including nearly all Alberaillellarians. This is a crisis at the species level because its extinction rate is remarkably higher than that at the generic level. The second crisis occurred at the bed 7/8 boundary where, of the survived taxa, 59% species and 71% genera disappeared, thus mainly a crisis at the generic level. This crisis discriminated all but one species of order Latentifistularia, seven species and two genera of order Entactinaria, and eight species and six genera of order Spumellaria. The first extinction is stronger than the second because it discriminated 36% genera, leaving only one survived species each in 51% genera and substantially declined the total radiolarian abundance. This implies that the radiolarian populations were destroyed through the first stroke. Regionally, this extinction is correlated with the blank interval above the *A. yaoi* zone of the Gujo–Hachiman Section, SW Japan (Xia et al., 2004) and the prelude extinction of Meishan (bed 24e), thus is a large-scale extinction event. The survival stage (from bed 8 to the Smithian of Lower Triassic) is characterized by very low radiolarian diversity and abundance, and lack of siliceous deposits in contrast to the underlying beds. All survived radiolarians are eurytypic, small, simple and spineless, and no new species originated in that interval. This is typical of radiolarian survival stage across the PTB in other parts of the world. It is notable that the thin shell psychrophilic ostracods experienced similar stages at the Dongpan Section (Yuan et al., 2006).

Altogether, 21 species of 14 genera of small foraminifers have been discovered in the siliceous rocks of Dongpan Section. It shows a disparate distribution between beds 2–7 and beds 8–10. Beds 2–7 are characterized by relatively high abundance and diversity (15 species) with diversified nodosarids, while in beds 8–10 only four species remain with just one nodosarid species. A diversity decline of 65% at species level occurred between beds 5 and 6. This small foraminifer assemblage belongs to deep water facies. Besides the small foraminifers in siliceous rocks, 25 species of 12 genera of normal foraminifers have been described from the calcareous interbeds, which are similar to the simultaneous neritic assemblages of South China (Gu et al., 2005).

In addition to the above-mentioned two extinction phases (beds 6/5 and 8/7), there exists a third extinction level at beds 11/10 above the ebb of negative excursion of $\delta^{13}C_{org}$ curve, represented by brachiopods, foraminifers, ostracods and partly bivalves (He et al., 2007b).

2.2 The four stages of organic carbon isotope ($\delta^{13}C_{org}$) (Zhang et al., 2006) (Fig. 4)

In stage 1 (beds 6–8), values of $\delta^{13}C_{org}$ remained stable at an average of −27.53‰. In stage 2 (beds 9 and 10), the $\delta^{13}C_{org}$ curve shows a conspicuous negative shift from the zenith at the middle of bed 9 (–24.8‰) to the ebb at the base of bed 10 (−30.25‰), which may correspond to the negative excursion of bed 26 at Meishan, because both immediately follow a major extinction event (beds 5–7 at Dongpan and beds 24e–25 at Meishan). Stage 3 (beds 11–12) shows the rebound of $\delta^{13}C_{org}$ curve until it reaches a relatively high value at the base of bed 12 (–27.14‰), the range of shift being 5.44‰. In stage 4 (from the PTB bed 13 up) the values of $\delta^{13}C_{org}$ oscillate at a large scope between −29.66‰ and −26.61‰, with a general depleted pattern. Comparison of the isotope curves between Dongpan and Meishan shows general concordance of the three earlier stages but the fourth one is different. At Meishan the curve tends to recover from bed 27 onward (higher than −26‰) while at Dongpan it stays depleted of $\delta^{13}C_{org}$. This may reflect that the Triassic biotic recovery lagged behind more in Dongpan than in Meishan.

2.3 Paleoecologic implications of paleo-environment at Dongpan Section

The beds 2–5 are considered as bathyal because abundant Albaillellaria and thin-shell psychrophilic ostracods usually indicate water depth of >200 m. 11 species and seven genera of ichnofossils representing a *Nereites* ichnofacies are discovered in beds 5–8, which also denotes that these siliceous beds are bathyal. Abundant *Chondrites* in these beds imply that the environment was anaerobic. Brachiopods flourished in beds 7–10 of Dongpan, just after the extinction of radiolarians. In another section in southern Guizhou, Chen et al. (2006) reported a mixed brachiopod assemblage of deep-water facies. Both assemblages belong to non-tropical assemblage in contradiction with the equatorial paleolatitude in which South China was located. The reasonable explanation may be that they represent deep water faunas. The Liliput effect of Dongpan brachiopods gradually strengthened towards the PTB, peaked at beds 6/5 and 11/10 boundaries respectively, and displayed two tendencies: the relatively larger taxa gradually become less abundant, their shells become smaller, and the relatively smaller taxa become more abundant (He et al., 2007b). Such effect in brachiopods mimics that of the PTB conodonts at Meishan Section (Luo et al., 2006), and also reflects a deteriorating environmental stress.

3 Advances on the PTB research of terrestrial facies—The Chahe Section, Weining Co., Guizhou Province (Yang et al., 2005; Yu et al., 2007; Yin et al., 2007c)

3.1 Accurate delineation of terrestrial PTB (Fig. 4)

After correlation of six central and western Guizhou sections from neritic through epeiric to terrestrial facies, a bed-to-bed correlation of the PTB strata was established (Peng et al., 2001). Of special significance is that, with careful biostratigraphic control, the lower and upper volcanic claybeds corresponding to beds 25 and 28 of Meishan Section D respectively, can be found in the neritic section of Gaowo, Anshun County near Guiyang and traced to the terrestrial section of Zhejue and Chahe along the Guizhou–Yunnan border. At the Chahe Section of Weining County, western Guizhou, bipyramid hexagonal quartz and zircon grains have been found in the illite-montmorillonite lower 10 cm claybed (Bed 67f) and an upper 13 cm claybed (68a–c) (Zhang et al., 2004, 2006b). Both are considered to be of volcanic origin and correlated with beds 25 and 28 of Meishan Section D respectively, considering the biotic changes over- and under-lying the claybed. Because bed 67a and 67b①–③ consists of Permian palynomorphs, the PTB has to lie somewhere between bed 67b④ and 68a. This allows the location of terrestrial PTB within an interval of less than 80 cm (thickness of bed 67), which is so far the most accurate location of terrestrial PTB over the world. Isotopic U/Pb dating of the zircons sampled from bed 68a gives an average age of 250.1 ± 2.5 Ma, corresponding to the age of the upper claybed (bed 28) of Meishan Section D.

3.2 Biostratigraphy of Chahe Section

Five palynomorph assemblage zones have been established for the Upper Xuanwei Formation (Changhsingian) of Chahe. The PTB beds consist of the following three of the five zones (Peng et al., 2005; Yu et al., 2007).

Assemblage V (beds 70–81): Early Triassic *Lundbladispora-Limatusporites-Taeniaesporites* assemblage dominated by gymnosperm pollen.

Assemblage IV (beds 67b④–69): an interval zone consists of a few fungal spores and miospores of undeterminable age. At the neighboring Zhejue Section, this interval corresponds to a zone of abundant fungal spore, reminiscent of the fungal spike discovered elsewhere in the world.

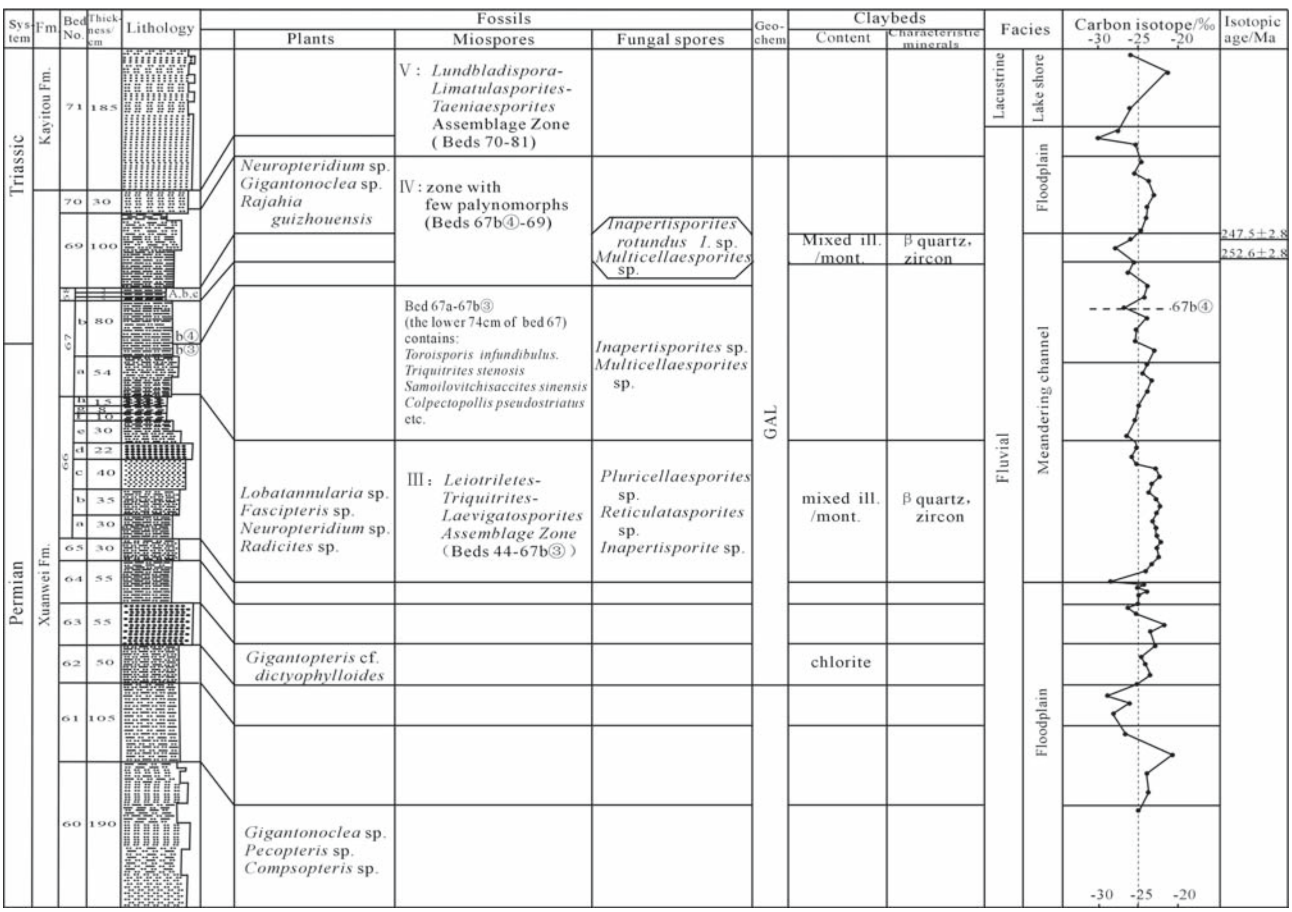

Fig. 4 Synthetic column of PTB strata of Chahe Section (reproduced from Yin et al., 2007c). Fm. formation; Geochem. geochemical characters; GAL. geochemical anomaly layers

Assemblage III (beds 44–67b③): Late Permian *Leiotriletes-Triquitrites-Laevigatosporites* assemblage dominated by spores of filices and pteridosperms (>70%).

The PTB strata from beds 60–69 yield *Gigantopteris nicotianaefolia-Labatannularia multifolia* flora, which is typical for the Late Permian of South China and the Cathaysian paleobotanic region (Yu et al., 2007). Those appeared in bed 69 are less diversified and less abundant, and are thus considered as Triassic relicts of this flora. However, it is noteworthy that this is so far the only region where the *Gigantopteris* flora survived to the earliest Triassic. The final extinction of the *Gigantopteris* flora above bed 69 corresponds to the second extinction at Meishan and confirms a two-phase extinction in the terrestrial section.

3.3 Chemostratigraphy of Chahe Section

Inorganic geochemistry of the Chahe Section demonstrates that geochemical anomaly layers (GAL) including beds 63–69 exist near the PTB. The geochemical anomalies of GAL cover common elements, trace elements and REE. It is notable that such a GAL also exists in neighboring sections including the terrestrial Zhejue Section and the littoral Mide Section (about 60 km SE), so it is a common phenomenon of PTB strata in the Yunnan–Guizhou border area. That the GAL occurred prior to the PTB implies that, like in the marine regime, the environmental deterioration already commenced before the main extinction at PTB (Yu et al., 2007; Yin et al., 2007c).

4 Correlation of the global change and biotic extinction between the PTB and modern times and its revelation to the status and future of the earth and mankind

Steffen et al. (2004) made a worldwide investigation of the modern global changes, and reached the conclusion that: "The Earth is currently operating in a no-analogue state….. The nature of changes now occurring simultaneously in the earth system, their magnitudes and rates of change are unprecedented in human history and perhaps in the history of the earth". "Extinction rates are increasing sharply in marine and terrestrial ecosystems around the world" (Steffen et al., 2004). Evidently both the PTB and modern times belong to extraordinary turning points of geological history, so a correlation between the two is of significance. On the one hand, the PTB time displays only the results of past global change and biotic extinction in a very condensed record; it gives a general pattern, but leaves a lot of imaginary space for the actual process and causality. In this aspect researches of modern process and dynamics may inform us by way of uniformitarianism. On the other hand, the modern time is but merely a twinkling of the geologic time; we do not know the whole course of global changes, especially their consequences in the future. In this aspect, the whole course of PTB global change and biotic extinction may serve as a revelation, which can inspire us of the status quo and the future of the earth and its organisms, thus prompt us to adjust the relationship between mankind and nature.

Based on parallel researches of both PTB and modern times, a comparison of global changes between both is given in Table 2. The comparison shows a general tendency toward environmental deterioration and crisis of both, except that those of the modern times are less severe, or in the initial stage.

The extinction curve since 1600 has been published based on statistics of extinct species given by WCMC (Groombridge, 1992). We have also used the method of "species-area curve" (Dobson, 1996) to cross-check the results of modern diversity loss and forest area decrease in Asia, Africa and Latin America. A curve of relative extinction rates during PTB and modern times was given (Fig. 5). Comparison of stage-subdivision of the Permian–Triassic mass extinction with that of current species extinction shows the similarity between the modern curve and the preludial part of the PTB curve. It verifies that extinction rates are increasing in an anti-parabolic curve in marine and terrestrial ecosystems around the world in recent centuries, and the modern time is experiencing the initial stage of extinction. "The earth is now in the midst of its first great extinction event caused by the activities of a single biological species (humankind)" (Steffen et al., 2004).

5 The pattern and causality of the Permian–Triassic extinction

5.1 Different viewpoints concerning the pattern and causality of this greatest extinction in geologic history

Concerning the pattern of the PTB extinction, there are at least three different viewpoints: (1) the PTB extinction was a sudden and monophase one occurring at beds 25–26 (Jin et al., 2000); (2) the PTB extinction was sudden but double-phased; in addition to the first sudden extinction at bed 25, there was a second extinction that occurred from the base of bed 28—the extinction of ammonoids of the *Hypophiceras* faunule, Permian relict bivalves and relicts of the *Gigantopteris* flora (Fang, 2004); (3) the PTB extinction is double-phased as in (2) but not so sudden. It had a prelude prior to bed 25 (Xie et al., 2005; Yin et al., 2007a, b).

Causality is related to patterns. A sudden and monophase extinction usually favors a bolide impact that caused the extinction. Pros of this viewpoint include: postulated very short range of extinction (Rampino et al., 2000); range statistics of 333 species showing that most genera disappeared suddenly within a short interval at the base of bed 25 (Jin et al., 2000), fullerenes with "extraterrestrial" ^{3}He ratios (Becker et al., 2001), Fe-Ni-Si particles of "meteoritic" origin

Table 2 Comparison of modern global changes with those at the PTB

Global changes		PTB	Modern
Atmosphere	Ultraviolet radiation	Probable strengthened (Visscher et al., 2004)	Strengthened (Alpen, 1998)
	$p(CO_2)$	$(3\ 314 \pm 1\ 097) \times 10^{-6}$ by volume, two times of that of Permian (Retallack, 2001, 2002)	Rapidly increase from 270×10^{-6} to 330×10^{-6} in last 150 years (Xie et al., 2004a, b)
	Carbon circle	Strong negative shift of $\delta^{13}C$ reflected change of carbon pool (Xie et al., 2007)	Negative shift of $\delta^{13}C$ reflected change of carbon pool (Xie et al., 2004a, b)
	Temperature	Increase (Retallack, 2002)	Increase (Retallack, 2002)
Hydrosphere	Chemical content of sea water	Aragonitic sea, high Mg/Ca ratio (Yan and Wu, 2006)	Aragonitic sea, high Mg/Ca ratio (Yan and Wu, 2006)
	Disoxic, stratified water mass	Global (Grice et al., 2005; Huang et al., 2007)	Local
	Acidified	Probable (Liang, 2002; Wang, 2007)	Acidic rain
	Heavy metals	Increase of content (Yang et al., 1993; Yu et al., 2007)	Locally contaminated
Lithosphere	Volcanism	Strengthened (Yin et al., 1992; Racki, 2003)	Strengthened
	Paleomagnetic superchron	Mixed (Menning, 1995)	Mixed
	Weathering	Strengthened (Ward et al., 2000)	Strengthened (Li et al., 2005)
Biosphere	Environmental stability	Unstable (Payne et al., 2004; Huang et al., 2007; Tong et al., 2007)	Unstable
	Animal	Multiphase extinction (Yin et al., 2007a)	Severe diversity loss; species extinction accelerated (Raven, 2002)
	Reef ecosystem	Extincted first (Stanley, 2001)	Bleached; regionally extincted
	Tropical forest	Disappeared (Yu et al., 2007)	Severely fragmented; locally disappeared (FAO, 2001; He et al., 2004)
	Micro-organisms	Flourish (Wang et al., 2005; Xie et al., 2005)	Locally and temporarily flourish

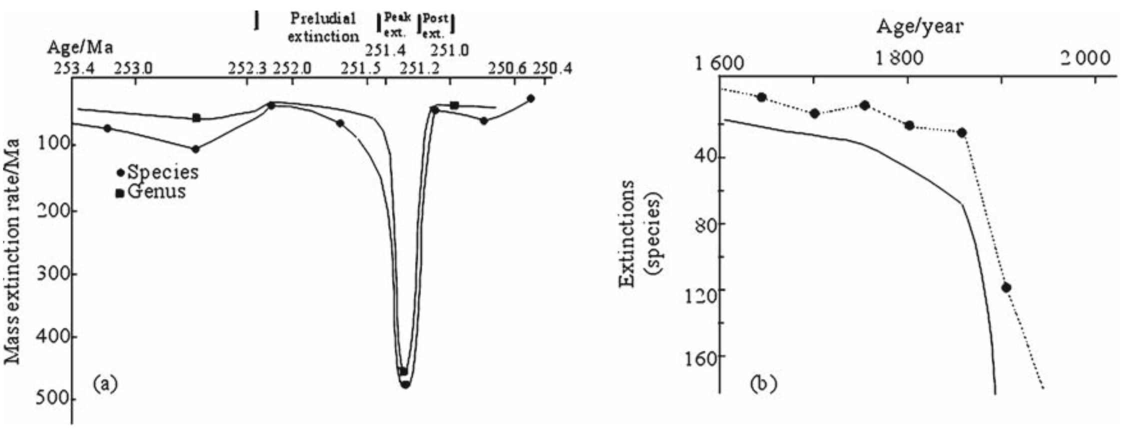

Fig. 5 Comparison of extinction curves between the PTB extinction (a) and modern extinction (b) (modified after He et al., 2004). The abscissa of A represents the ages of each substage (Ma), data from Jin et al. (2000)

(Basu et al., 2003), gigantic sulphur release (Kaiho et al., 2001), a possible but disputed bolide impact at Bedout, offshore NW Australia (Becker et al., 2004).

On the other hand, multiphase (double or more) extinction (Yang et al., 1993; Wignall and Hallem, 1996; Yin, 1996; Chen, 2005) would necessitate intrinsic causes from within the earth. Pros of this viewpoint include: Pangea integration and related regression (Yang et al., 1993; Yin et al., 2007a), volcanism (Yin et al., 2002; Racki, 2003) and superanoxia (Wignall and Hallam, 1992; Grice et al., 2005).

Moreover, it is calculated that large-scale methane release, induced either by extraterrestrial or intrinsic causes, was necessary for the worldwide negative $\delta^{13}C$ excursion beneath PTB (Berner, 2002).

5.2 Length of the Permian–Triassic crisis

The crisis at the Paleozoic–Mesozoic transitional period is not a catastrophe that happened instantaneously at the PTB, but consists of many crisis stages from Late Permian to Early

Triassic. It includes a descending (extinction) part and an ascending (recovery) part. The descending (extinction) part, 7–9 Ma in duration, can be subdivided into two crisis stages—the end-Guadalupian extinction between Middle and Late Permian and the PTB extinction. After the end-Guadalupian extinction, the Paleozoic biota experienced steady decline during the whole Lopingian until the PTB extinction (Yin et al., 2007a). The ascending (recovery) part occupies the whole Early Triassic, 5–6 Ma in duration, during which biotic recovery and $\delta^{13}C_{carb}$ oscillation happened in 3–4 stages (Payne et al., 2004; Zuo et al., 2006; Tong et al., 2007). The whole crisis, enduring about 14 Ma, is the most prolonged extinction-recovery crisis in Phanerozoic. Chronologically, it coincides with the integration zenith—initial disintegration of Pangea and with the great regression-transgression circle; the later induced the strongest Phaenerozoic regression (Holser and Margaritz, 1987). Causal relation between them has been discussed by Yin et al. (2007a).

5.3 Commencement of an extinction prelude prior to the postulated bolide impact (Fig. 6)

Evidences of this prelude include the following aspects:

(1) At three shallow water sections including the Meishan Section, a preludial extinction (bed 24e at Meishan) has been recognized. It consisted of the extinction of corals, most fusulinids and pseudotirolitid ammonoids, many brachiopods (Yin et al., 2007b), low ebb of cyanobacteria and flourishing of green sulphur bacteria (Xie et al., 2007), and miniaturization of conodonts (Luo et al., 2006).

(2) Paleontological researches have proved that in deep water facies (Dongpan Section) various taxa disappeared at different horizons prior to the PTB. Thus, there should be multiphase extinctions before PTB. Correlation of $\delta^{13}C_{org}$ negative excursion with Meishan reveals that the extinction of radiolarians and ostracods at bed 6/5 may correspond to the prelude in Meishan.

(3) The existence of GAL in terrestrial and littoral sections like Chahe and Mide denotes that abrupt environmental shifts happened before the PTB in these environments.

(4) In various sections belonging to different facies, a first negative excursion of $\delta^{13}C$ appears before the main excursion, which regularly occurs right beneath the PTB.

(5) Similar phenomena happen also in many localities along Tethys (Farabegoli et al., 2007; Haas et al., 2007).

5.4 The multiphase nature of the PTB extinction

Of the two descending (extinction) stages of the Permian–Triassic crisis, the PTB extinction is the main stage. It consists of two phases: the continuous prelude-main phase constitutes the end Permian extinction and the epilogue constitutes the earliest Triassic extinction. The main phase has been much discussed. The epilogue corresponds to the upper volcanogenic claybed (bed 28) at Meishan (Yang et al., 1993; Yin, 1996). This phase witnessed the overall extinction of Permian relicts that survived through the main phase, including Permian type animals like *Hypophiceras* (ammonoids), *Towapteria* (bivalves), *Hindeodus* (conodonts), *Waagenites* (brachiopods) and the *Gigantopteris* flora (Fig. 6).

In the deep water Dongpan Section, different taxa became extinct at different horizons. Radiolarians disappeared at the horizons of beds 6/5 and 8/7, deep water paleocopid ostracods at the horizon of beds 6/5, foraminifers at the horizons of beds 7/6 and 11/10 and brachiopods within bed 10. Thus, the PTB extinction in deep water facies is also multiphase (Feng et al., 2007).

The traditional pattern showing abrupt, nearly vertical descent of the biodiversity curve at the Permian–Triassic interval (Sepkoski, 1997) seems too catastrophic. It would be more realistic to draw this part of the curve in a more stepwise way.

The protracted and multiphase nature of the Permian–Triassic crisis necessitates an explanation of the causality other than an instantaneous catastrophe. The extraterrestrial impact as the main cause of the PTB extinction was largely excluded, due to the existence of a prelude prior to the main extinction which was postulated by some authors as caused by bolide impact, and the multiphase nature that can be hardly explained by bolide impact because its probability is only once in tens or hundreds million years (Yin et al., 2007a, b).

Intrinsic and inter-sphere changes from the earth as the cause of this crisis, such as Pangea integration and its by-effects, have been put forth in many papers and will not be re-iterated here. The great end-Permian sea-level fall, which was considered as one of the main causes of the preludial mass extinction, was supported by two new finds by Wu et al. (2006a, b) in Xiushui, Jinagxi Province and Laolongdong, Chongqing. They also reported another sea-level fall at the earliest Triassic, which needs more investigations. One additional by-effect worthwhile noting is the aragonite sea coupled with high Mg/Ca ratio, which reached its zenith during the Permian–Triassic transition, as well as the Precambrian–Cambrian transition (Yan and Wu, 2006). Such sea water chemical change may have implications on shell fauna and their preservation. This cyclic phenomenon is closely related to sea-level cycle and thus to Pangea integration also. The Siberian trap used to be considered as the main volcanic factor that caused the PTB extinction. However, the Emeishan flood basalt as a large igneous province emplaced roughly simultaneously with the end-Guadalupian extinction (Xu et al., 2007), and the medium-acidic volcanisms along Panthalassa and Tethys took place during Permian-Triassic transition (Yin et al., 2007a). Considering the protracted nature of Late Permian biotic crisis, the effect of Emeishan trap and the medium-acidic volcanism on the end-Guadalupian and PTB extinctions should not be under-estimated.

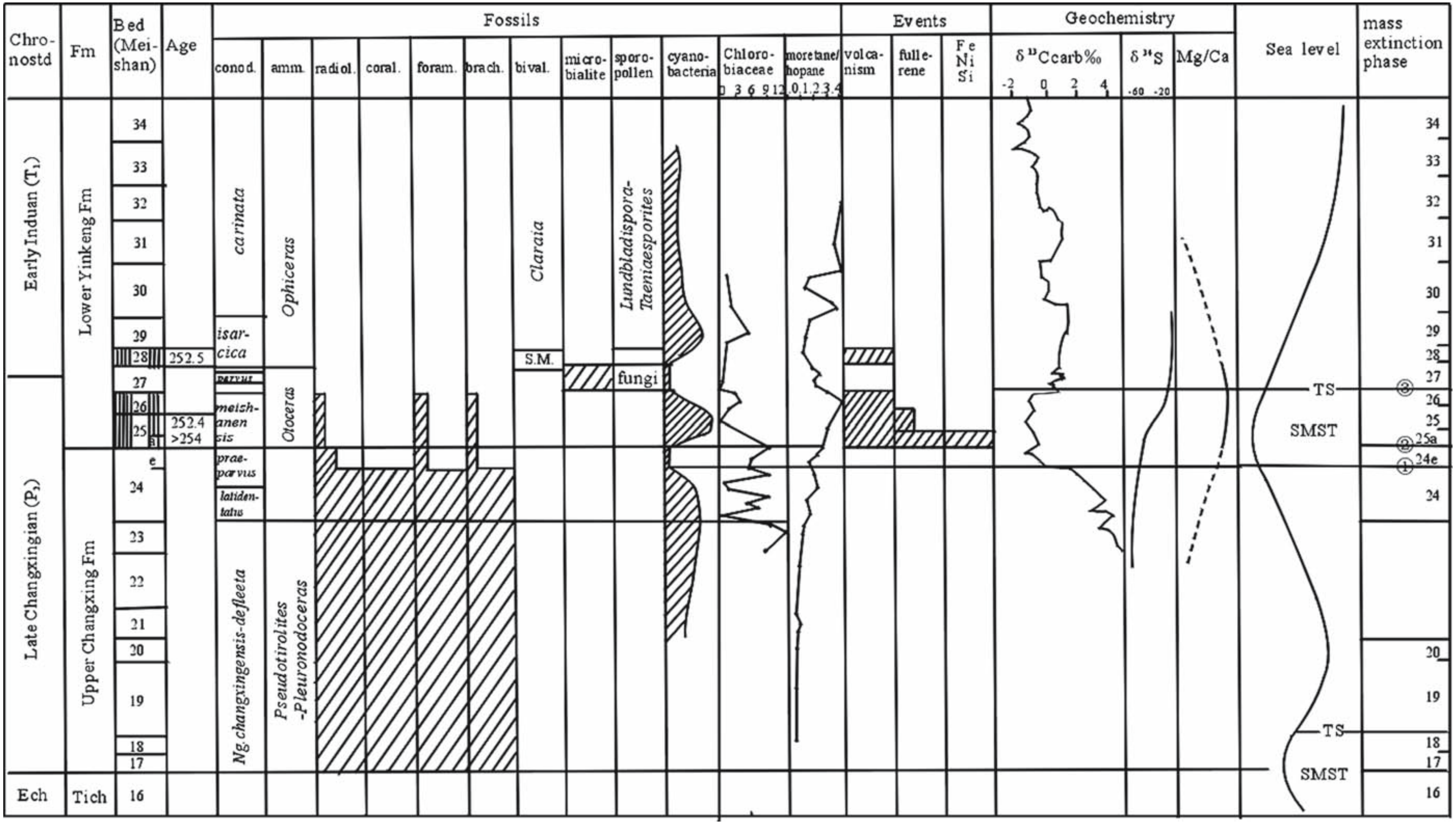

Fig. 6 Synthetic column of PTB eventostratigraphy in South China. amm. ammonoid; bival. bivalve; brach. brachiopod; conod. conodont; foram. foraminifer; Fm. formation; radiol. radiolarian; ① prelude; ② main episode; ③ epilogue; conodont zones are in *Hindeodus-Isarcicella* lineage unless headed by *Ng. (Neogondolell*a). References: $\delta^{13}C$ (Cao et al., 2002); $\delta^{34}S$ (Liang and Ding, 2004); age (Mundil et al., 2001, 2004 for 252.4 only); blue algae (Xie et al., 2005); chlorobiaceae (Grice et al., 2005); Mg/Ca (Yan and Wu, 2006); Fe,Ni,Si (Kaiho et al., 2001); fullerene (Li et al., 2005); microbialite (Wang et al., 2005); moretane/hopane (Wang, 2007); radio. radiolarians (Feng et al., 2007); S.M. small molluscs (Wang et al., 2005); sea level (Zhang et al., 1997); sporopollen (Zhang K X et al., 2004); column, other fossils and volcanism (Yin, 1996; Yin et al., 2001); the cyanobacteria part is based on the curve of 2-MHP (2α-methylhopane) index (Xie et al., 2005), which is the ratio of 2-MHPs to hopanes lacking additional methyl substituents. It reflects the abundance of cyanobacteria relative to general bacteria. In bed 24e it dropped to a minimum

Acknowledgements This paper has incorporated research results of many Permian–Triassic researchers at home and abroad, to whom we extend our sincere thankfulness. We thank Professors Tong Jinnan, Wu Shunbao, Yang Fengqing, Drs Huang Junhua and Zhang Shuxing for their valuable advices to this paper. We also thank many students who helped with sampling in the field, logging in the lab and drawing the figures of the manuscript. Funding for this work was provided by the National Natural Science Foundation of China (No. 40232025).

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