Two deep marine oxygenation events during the Permian-Triassic boundary interval in South China: relationship with ocean circulation and marine primary productivity

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1. Introduction

The Permian-Triassic (P-T) mass extinction (*ca*. 251.9 Ma) is the largest of the "Big Five" extinction crises in both marine and terrestrial settings (Stevens, 1977; Kerr, 2001; Zhang et al., 2014; Zhou et al., 2021). Biotic species suffered a severe loss of about 90% of marine invertebrate and 80% of terrestrial vertebrate taxa (Smith and Ward, 2001; Lehrmann et al., 2003;

Retallack et al., 2003; Ward et al., 2005; Zhou et al., 2021). In the marine environment, extinctions displayed a preferential selectivity for biota with heavy calcification and limited elaboration of respiratory organs (Knoll et al., 1996; Erwin, 2006; Payne et al., 2007). On land, the terrestrial ecosystem collapse and devegetation led to an earliest Triassic “coal gap” accompanied by a dramatic turnover from typical Permian floras to those dominated by lycopsids and ferns or conifers (Smith and Ward, 2001; Retallack et al., 2003; Ward et al., 2005; Yin et al., 2007; Cui et al., 2017; Song et al., 2018; Zhou et al., 2021). There documented evidence that the extinctions occurred earlier on land than in the marine environments (Shen et al., 2011; Kaiho et al., 2016; Liu et al., 2017; Zhou et al., 2017; Xiao et al., 2018).

A number of causes have been proposed for the P-T marine mass extinction events, including global warming, sea-level fall, marine anoxia, salinity change, ocean acidification, or a combination of these (e.g., Stevens, 1977; Isozaki, 1997；Grice et al., 2005a; Hinojosa et al., 2012; Joachimski et al., 2012; Kershaw et al., 2012a；Yin et al., 2014；Baresel et al., 2017; Zhang et al., 2018a; Li et al., 2021; Zheng et al., 2021; Zhou et al., 2021; Wu et al., 2022). Many of these potential causes appear to be linked to the massive volcanism in the Siberian Traps Large Igneous Province (e.g., Song et al., 2013; Chen et al., 2014; Zhou et al., 2021).

The excellent exposures of continuous uppermost Permian through lowermost Triassic marine strata on the South China Block have long been a focus for detailed studies of the P-T mass extinction episode (e.g., Wignall et al., 1995; Isozaki et al., 2007；Yin et al., 2014；Saitoh and Isozaki, 2021). A detailed conodont biostratigraphy established in these sections provides a high-resolution biostratigraphic and correlation framework for these P-T studies in South China (e.g., Jiang et al., 2007; Sun et al., 2012; Yin et al., 2014; Zhang et al., 2014). These studies led to the Global Stratotype Section and Point (GSSP) for the P-T boundary being placed at the Meishan section in the northeastern part of South China (e.g., Yin et al., 2014; Shen et al., 2015; Wu et al., 2022). Paleogeographical reconstructions place the South China Block in low latitudes (< 30°N) during this time interval, with its northern margin facing the Paleotethys ocean and the southern margin facing the Panthalassa Ocean (Muttoni et al., 2009; Yin et al., 2014；Xiao et al., 2018).

Episodes of marine anoxia are an important mechanism for killing marine organisms. Therefore, among the multitude of P-T studies in South China, investigations of marine redox conditions have been conducted by applying multiple methods to sedimentary sections that were deposited at different water depths and under various paleogeographic conditions (**see literature in Table. 1**). The array of intensive studies has resulted in important controversies on how to interpret the marine redox history through the P-T boundary interval (Bond and Wignall, 2010; Loope et al., 2013; Proemse et al., 2013; Xiao et al., 2018; Li et al., 2021; Xiang et al., 2021). Studies of P-T sections from different depositional settings and/or applying various redox proxies to the same P-T section can yield conflicting marine redox results and interpretations (e.g., Kershaw et al., 2012b；Lehrmann et al., 2015; Li et al., 2016; Huang et al., 2019; Xiang et al., 2020). The incongruent interpretations of marine redox variations heavily impede an overall understanding of environmental scenarios for the P-T mass extinction episodes.

In order to better understand the marine redox history through the P-T boundary interval and the end-Permian mass extinction events in South China, this study summarizes and reassesses a large boyd of marine redox studies (**Table 1**) spanning the conodont zones mainly from *Clarkina changxingensis* to *Isarcicella isarcica* (**Fig. S1**) in South China (Paleotethys). The Paleotethys redox history is then compared with more extensive Panthalassa Ocean. The synthesis suggests there were two deep marine oxygenation events during the P-T boundary interval, and their occurrences are argued to be possibly related to changes in ocean circulation and marine primary productivity.

2. Permian-Triassic stratigraphic records of marine redox variation in South China

During the P-T transition, South China was an isolated continental block lying to the east of the supercontinent Pangea (Isozaki et al., 2007; Muttoni et al., 2009; Saitoh et al., 2014) (**Fig. 1**). Within the South China Block, a central, shallow-marine Yangtze Platform was bounded by the Kangdian Oldland on the east, by the Cathaysian Oldland and Yunkai Oldland on the west, by deep-water Northern Marginal Basin on the north and by the deep-water Hunan-Guizhou-Guangxi Basin on the south (Yin et al., 2014; Lei et al., 2017; Zhang et al., 2018b; Wu et al., 2022) (**Fig. 1**). The Northern Marginal Basin includes the northern slope of the Yangtze Platform and the deep-sea Qinling seaway of the Paleotethys (Feng et al., 1997; Yin et al., 2014). The Hunan-Guizhou-Guangxi Basin, also known as the Nanpanjiang Basin, contained many small and isolated shallow-water platforms surrounded by deep water that faced toward the Panthalassa Ocean (Feng et al., 1997; Yin et al., 2014). The suite of well-studied P-T marine sections are mainly concentrated into two realms: the northern part of the Yangtze Platform and adjacent Northern Marginal Basin; and the small isolated carbonate platforms and adjacent deep water troughs of the Hunan-Guizhou-Guangxi Basin (**Fig. 1**) (Lehrmann et al., 2003; Yin et al., 2014; Shen et al., 2015; Tian et al., 2015; Zhang et al., 2020; Wu et al., 2022). Previous P-T marine redox studies from these two realms provide a good opportunity to investigate P-T marine redox variations at different water depths (shallow vs. deep) and different paleogeographic locations (**Fig. 1**; **Table 1**). As shown below, the inferred redox conditions vary from oxic to euxinic conditions, and the definition and characterization of oxic, upper dysoxic, low dysoxic, anoxic and euxinic conditions and facies follow those proposed by Bond and Wignall (2010) (**Table 2**).

2.1. Northern Yangtze Platform Margin and the adjacent Northern Marginal Basin facing the Paleotethys ocean

*2.1.1. Basinal to slope P-T sections in the Northern Marginal Basin (**Fig. 2**)*

2.1.1.1. Xiaojiaba section, Guangyuan City, northern Sichuan Province (Wei et al., 2015; **Fig. S2**)

The Xiaojiaba section records a lower slope to basinal P-T deposition. The Xiaojiaba section is near the Chaotian section (detailed in 2.1.1.2), but was deposited at a slightly deeper water depth than the latter. The upper Permian Dalong Formation consists of lime mud-rich chert in its lower and middle parts, and of lime mudstone and siliceous or nodular limestone in its upper part. Volcanic tuff layers are abundant in the upper part, but only a few occur in the lower and middle parts. The Lower Triassic Feixianguan Formation consists of interbedded shale and lime mudstone. Many volcanic tuff layers are present near the base of the Feixianguan Formation, and no fossils are recorded in its lower part.

Based on detailed lithological correlations with the nearby Chaotian section where conodont and ammonoid biostratigraphy are well established, the mass extinction horizon in the Xiaojiaba section is placed at the contact between the Dalong Formation and the Feixianguan Formation, and the P-T boundary is assigned to a shale layer about 1 meter higher.

Multiple redox proxies including $\delta^{34}S_{py}$, C_{org}/P, Mo_{auth}, U_{auth} and the size distribution of framboidal pyrite, indicate that marine redox conditions changed from anoxic (occasionally euxinic) in the lower Dalong Formation to dysoxic/oxic conditions in the upper Dalong Formation through lower Feixianguan Formation, followed by a return to anoxic conditions. An oxygenation event (i.e., an increase in water column oxygen levels) occurred during the latest Permian (*C. taylorae* - *C. zhejiangensis* - *C. changxingensis* - *C. yini* conodont zones) on the basis of an increase in framboidal pyrite sizes and $\delta^{34}S_{py}$, and a decrease in C_{org}/P, Mo_{auth} and U_{auth} (Fig. S2). This oxygenation event co-occurred with a fall in primary productivity (indicated by a reduction in TOC, biogenic SiO_2 and Ba_{xs} (excess Ba)), a sea-level fall (based on subaerial exposure), increased influx of fine-grained terrigenous clastics (based on increase in REE and Al_2O_3, and lower Eu/Eu^*) and elevated volcanic activity (inferred from the increased abundance of tuff layers) (Fig. S2).

2.1.1.2. Chaotian section, Guangyuan City, northern Sichuan Province (Isozaki et al., 2007; Ji et al., 2007; Saitoh et al., 2014, 2021; Saitoh and Isozaki, 2021; **Fig. S3**)

The Chaotian section was located in a lower slope to basinal setting during the P-T boundary interval. The upper Dalong Formation of latest Permian (late Changhsingian) age is frequently bioturbated and consists mainly of calcareous/cherty (lime)mudstone with micritic limestone at the top, and contains abundant ammonoids, conodonts and radiolarians (Figs 6 A, B). The uppermost Dalong Formation spans the *C. taylorae* -*C. zhejiangensis*

-*C. changxingensis –C. yini* conodont zones (Isozaki et al., 2007; Ji et al., 2007). The lower Triassic Feixianguan Formation is largely unbioturbated and consists of micrite limestone with a basal marl bed that is barren of fossils but contains abundant pyrites (Figs 6C, D) (Saitoh and Isozaki, 2021). The P-T mass extinction is placed at the contact between the Dalong Formation and the Feixianguan Formation. The conodont *Hindeodus parvus* is known from the base of micrite limestone in the lowermost Feixianguan Formation at the base of the Unit F (Isozaki et al., 2007). The overlying *Isarcicella* Zone was assigned based on the co-occurrence of the conodonts *H. parvus*, *I. isarcica* and *I. staeschei* (Isozaki et al., 2007; Ji et al., 2007).

In the lower-middle portion of the Dalong Formation, the low degree of bioturbation, decreased burrow size, absence of trace fossils, high TOC content and abundance of framboidal pyrite are suggestive of anoxic water conditions (Saitoh et al., 2014，2021). In contrast, in the uppermost Dalong Formation (mainly the *C. taylorae -C. zhejiangensis -C. changxingensis yini* conodont zones), the common occurrence of burrows (Fig. 6A), increase in ichnofabric index, low TOC and relative rarity of framboidal pyrite indicate oxic to dysoxic water conditions immediately before and during the end-Permian mass extinction (Saitoh et al., 2014, 2021) (Fig. S3), suggesting an oxygenation event. This enhanced oxygenation co-occurred with a rapid sea-level fall. Above the level of the end-Permian mass extinction in the lowermost Feixianguan Formation (*H. parvus* and *Isarcicella* conodont zones), the absence of bioturbation and other trace fossils and the abundance of framboidal pyrites (Fig. 6C, D) suggest that anoxic water returned in the aftermath of the extinction (Saitoh and Isozaki, 2021).

2.1.1.3. Shangsi section, Guangyuan City, northern Sichuan Province (Wignall et al., 1995;

Xiang et al., 2016; Shen et al., 2021; **Fig. S4**)

During the P-T boundary interval, the Shangsi section was deposited in a lower slope to basinal setting in shallower water depths than nearby Chaotian section that is described above (Wignall et al., 1995; Shen et al., 2021). The Dalong Formation of latest Permian (Changhsingian) age consists of micrite limestone that is organic-rich in the lower part and chert-rich in the upper part. The Feixianguan Formation of earliest Triassic (Induan) age consists mainly of thin-bedded alternations of micrite and argillaceous limestones. The P-T mass extinction horizon is placed within the uppermost part of the Dalong Formation (Wignall et al., 1995). The P-T boundary was assigned within the Bed 28 at the lowest occurrence of the conodont *H. parvus* (Wignall et al., 1995; Xiang et al., 2016; Shen et al., 2021).

Based on iron speciation proxies and redox-sensitive elements (Mo, V and U) (Xiang et al., 2016), the uppermost *C. wangi* through middle *C. subcarinata* conodont zones have been interpreted as times of euxinic bottom-water conditions. The upper *C. subcarinata* conodont zone, the *C. changxingensis* - *C. yini* - *C. meishanensis* Assemblage Zone and the *H. changxingensis* Zone were mainly periods of anoxic conditions. However, an oxygenation event was indicated by oxic water conditions occurring immediately below and during the end-Permian mass extinction interval (*C. meishanensis* and *H. changxingensis* conodont zones), which is supported by lower values of Fe_{HR}/Fe_{T}, Fe_{Py}/Fe_{HR}, Mo_{xs}, U_{xs} and V_{xs} (Fig. S4). The redox proxies in the overlying *H. changxingensis, H. parvus and I. isarcica* conodont zones of the earliest Triassic indicate anoxic conditions with sporadic euxinic conditions. These redox variations are consistent with other sedimentary features (fossil diversity, bioturbation degree) and size distributions of framboidal pyrites (Wignall et al., 1995; Bond and Wignall, 2010). The oxygenation event immediately below and during the end-Permian mass extinction horizon has been proposed to be related to a decrease in primary productivity at that time (Xiang et al., 2016).

2.1.1.4. Changtanhe section, Cili County, Hunan Province (He et al., 2012, 2013; **Fig. S5**)

The Changtanhe section was deposited in a marine slope setting during the P-T boundary interval. The Dalong Formation of latest Permian age consists mainly of laminated wackestone, with thin mudstone and shale beds becoming more common towards the top. Abundant and diverse fossils (including radiolarians, foraminifers, sponge spicules and echinoderms) are found in the Dalong Formation. The overlying Daye Formation of earliest Triassic age consists mainly of lime mudstone, marlstone and micrite limestone.

The end-Permian mass extinction horizon is placed at the top of the Dalong Formation where radiolarians, sponges and most of the foraminifers disappear. Marine redox conditions based on the size distribution of framboidal pyrite suggest lower dysoxic water conditions developed during the latest Permian, which shifted to be partly anoxic just below the P-T extinction horizon. The decreased oxygen level is accompanied with a decrease of the diversity of benthic organisms. Immediately after the extinction horizon, framboidal pyrites start to increase in size and even disappear in the interval of 0.4 to 0.48 m above the extinction boundary, thereby representing upper dysoxic to oxic water conditions and indicating a post-extinction oxygenation event (Fig. S5). Meanwhile, the TOC contents show a sharp decrease at this oxygenation event from lower dysoxic to upper dysoxic-oxic conditions across the mass extinction horizon (Fig. S5). This oxygenation event is also supported by the simultaneous increase in abundance of fossils (ammonites, brachiopods, bivalves and microconchids). After the oxygenation event, the water redox conditions returned again to lower dysoxic conditions, and fossils became rare.

2.1.1.5. Ganxi section, Puyang County, Sichuan Province (Lei et al., 2017; Wu et al., 2022; **Fig. S6**)

The Ganxi section was deposited in an upper slope setting during the P-T boundary interval (Wu et al., 2022). The Dalong Formation of latest Permian mainly consists of lime mudstone in the lower part and of marly limestone with interbedded lime mudstone in the upper part. The Daye Formation of earliest Triassic consists mainly of lime mudstone. A few volcanic ash beds occur within the uppermost Dalong Formation and the lowermost Daye Formation.

Based on conodont biostratigraphy and correlation with the Meishan reference section, the mass extinction horizon is assigned to be at the base of the Daye Formation, and the P-T boundary is placed within Bed 237 in the lower Daye Formation (Lei et al., 2017). Marine redox conditions indicated by iron speciation and the Mo concentration data suggest mainly anoxic to euxinic conditions within the *C. wangi*, *C. changxingensis*, *C. yini* and *C. meishanensis* conodont zones (Fig. S6); and anoxic to oxic conditions prevailed within the *H. parvus* and *I. isarcica* conodont zones (Fig. S6). The $\delta^{34}S_{py}$ shows a positive excursion at the increasing oxygen levels (the oxygenation event) during the *H. parvus* and *I. isarcica* conodont zones, and the oxygenation event is consistent with lower values of TOC, Mo_{EF}, Fe_{HR}/Fe_{T}, and Fe_{Py}/Fe_{HR} (Fig. S6).

2.1.1.6. Meishan section, Changxing County, Zhejiang Province (Grice et al., 2005b; Isozaki et al., 2007; Huang et al., 2017; Li et al., 2016; **Fig. S7**)

The Meishan section was deposited in a marine upper slope setting during P-T boundary interval. The section, despite being highly condensed, was selected as the GSSP for the P-T boundary (Isozaki et al., 2007). The Changxing Formation of latest Permian consists of thin-bedded limestone, and the overlying Yinkeng Formation of earliest Triassic consists mainly of thin interbedded marlstone and mudstone (Huang et al., 2017). A few volcanic ash layers occur in the boundary interval. The mass extinction horizon occurs between Beds 24e and 25 (Li et al., 2016). The first occurrence of the conodont *H. parvus* in the middle of Bed 27 (base of 27c) defines the P-T boundary at the GSSP.

Different marine redox proxies applied to this section have led to different interpretations. Euxinic conditions of the photic zone during the P-T transition have been inferred from biomarkers (Grice et al., 2005b; Summons et al., 2006). In contrast, the size distributions of framboidal pyrites and changes in fossil content within the P-T boundary interval suggest unstable marine redox conditions (Li et al., 2016). Abundant small pyrite framboids (4 to 6 μm in diameter) and the absence of benthos within the *C. taylorae -C. zhejiangensis – C. changxingensis –C. yini* conodont zone interval indicate mainly anoxic conditions that were periodically disrupted by short-term oxic conditions with rare framboidal pyrites during intrusions of turbidity currents (Li et al., 2016). Upper dysoxic to oxic conditions during most of the *H. parvus* conodont zone suggest an oxygenation event and are indicated by the absence of framboidal pyrites, abundant trace fossils and diverse biota (Li et al., 2016) (Fig. S7). A return to anoxic water conditions in the *Isarcicella* Zone is suggested by the reappearance of small (5 μm in diameter) framboidal pyrites and the disappearance of trace fossils (Li et al., 2016).

Based on iron specification proxies, Xiang et al. (2020) suggested oxic to dysoxic water conditions in Beds 21-24d (corresponding to the *C. taylorae, C. zhejiangensis, C. changxingensis* and *C. yini* zones); anoxic water conditions with intermittently euxinia in Beds 24e to 28 (corresponding to the *H. parvus* and *I. staeschei* zones); and anoxic and ferruginous conditions in Beds 29 to 34 (corresponding to *Isarcicella* conodont zone) (Yin et al., 2014). At the level of the oxygenation event indicated by the absence of framboidal pyrites, abundant trace fossils and diverse biota, a decreasing trend of Fe_{HR}/Fe_{T} and Fe_{Py}/Fe_{HR} is observed and also indicates increasing oxygenation (Fig. S7).

*2.1.2. Shallow-marine P-T sections in Northern Part of Yangtze Platform (**Fig. 3**)*

2.1.2.1. Liangfengya section, Chongqing Municipality (Bond and Wignall, 2010; Li et al., 2021; **Fig. S8**)

The Liangfenya section records shallow-water, inter-reef platform carbonate deposition in the P-T boundary interval. The conodont biostratigraphy and carbon isotope correlations with the Meishan section suggest that the Liangfengya section is complete without an obvious hiatus that characterizes some shallow marine sections around the P-T boundary.

In the P-T boundary strata, the upper part of the Changxing Formation of latest Permian consists of fossiliferous limestone (Bed 1). The overlying lower part (Beds 2-8) of the Feixianguan Formation of earliest Triassic comprises alternating beds of shale and marlstone. The mass extinction horizon is recorded at Bed 8 by the disappearance of a fossil assemblage including mainly foraminifera, calcareous algae and Permian brachiopods. This bed is overlain by fine-grained lithologies (micrite limestone and marlstone) in which the lower interval (Beds 9-15) contains a low diversity of biota including microforaminifera, micrograstropods and ostracods, and the upper interval contains a few bivalves and abundant framboidal pyrites (Bed 16-18). The lowest occurrence of conodont *H. parvus* in the middle of Bed 10 marks the P-T boundary.

No framboidal pyrite is found in the bioclastic limestone of the Changxing Formation (Bed 1) or in the micrite limestones of the Feixianguan Formation (Beds 2 to 15) (Fig. S8). This suggests mainly oxic water conditions during the conodont zones of *C. changxingensis, C. yini*, *C. meishanensis*, *H. parvus* and *I. staeschei*. However, lower dysoxic to euxinic water conditions are inferred from abundant small framboidal pyrites (3 to 8 μm in diameter) in the marlstone and lime mudstone of the higher Feixianguan Formation (Beds 16 to 17) of the *I. isarcica* Zone (Fig. S8). The redox variations are also supported by changes in the fossil diversity and in the degree of bioturbation at the same sequence.

2.1.2.2. Laolongdong section, Chongqing Municipality (Liao et al., 2010; Li et al., 2021; **Fig. S9**)

The Laolongdong section is a shallow-marine P-T section (Liao et al., 2010). At the P-T boundary succession, the bioclastic limestone of the upper Permian Changxing Formation is sharply overlain by microbialites with well-preserved microfabrics (Figs 6E–G) at the base of the Feixianguan Formation. The contact between the bioclastic limestone and the overlying microbialites represents the mass extinction horizon. Although this contact seems conformable, it should be noted that it is characterized by pressure solution and so the possibility of depositional break or subaerial exposure exists at the contact (Liao et al., 2010). The microbialites are overlain by a laminated lime mudstone with few fossils. Based on carbon-isotope ($\delta^{13}C_{carb}$) correlation with the Meishan section, the bioclastic limestone of the Changxing Formation belongs to *C. changxingensis* -*C. yini* conodont zones, the microbialite belongs to *H. parvus* -*I. staeschei* conodont zones, and the overlying lime mudstone (Feixianguan Formation) belongs to the *I. isarcica* conodont zone (Li et al., 2021).

In terms of marine redox proxies, the abundant and diverse fossils and the absence of framboidal pyrites indicate oxic conditions prevailed during the deposition of the bioclastic limestone of the Changxing Formation (Fig. S9). Abundant small framboidal pyrites (mean diameter of ca. 8 μm) and reduced biodiversity suggest lower dysoxic conditions for the microbialites (base of the Feixianguan Formation) (Fig. S9). Remarkably, shelly benthic fossils occur commonly within the microbialites, and are associated with small framboidal pyrites, raising the prospect that these pyrites might be forming within anoxic/dysoxic microenvironments within the microbialites. In the overlying mudstone (lower Feixianguan Formation), abundant small framboidal pyrites with a mean size of about 7.66 μm suggest a continued oxygen depletion.

2.1.2.3. Zaixia section, Chongyang County, Hubei Province (Liu et al., 2010; Chen et al., 2011; Adachi et al., 2017; **Fig. S10**)

The Zaixia section is a shallow-marine P-T section. The upper Permian (Changhsingian) bioclastic limestone is overlain by sparsely fossiliferous microbialites, then by lower Triassic oolitic and micrite limestone without fossils. The mass extinction horizon is placed at the contact between the bioclastic limestone and overlying microbialites, but the contact records a depositional hiatus or erosive event of unknown duration. The appearance of the conodont *H. parvus* within the lower part of the microbialites suggests that the onset of microbialite formation may have been in the very latest Permian. Small (2.1 to 5.4 μm in diameter) framboidal pyrites found within the microbialites indicate oxygen-deficient water conditions (Adachi et al., 2017). Alternatively, biomarker analyses (e.g., Pristane/Phytane, Trisnorneohopane/Trisnorhopane) suggest (Fig. S10): (i) no severe anoxic event in this shallow-marine section; (ii) a transient development of more oxidizing marine conditions just above the mass extinction horizon; and (iii) more reducing conditions or enhanced salinity at the upward transition from microbialites to oolitic and micrite limestone in the earliest Triassic (Chen et al., 2011).

2.1.2.4. Gaohua section, Cili County, Hunan Province (Forel et al., 2009; Loope et al., 2013; Wang et al., 2016; **Fig. S11**)

The Gaohua section is a P-T section deposited under shallow-marine environments near the edge of a carbonate platform. The uppermost Changxing Formation of latest Permian consists mainly of bioclastic limestone. The Daye Formation of early Triassic consists of a basal unit of microbialites followed by alternating beds of micrite and oolitic limestone. The mass extinction horizon is defined at the contact between the Changxing Formation and the Daye Formation. The P-T boundary, as defined by the first occurrence of conodont *H. parvus,* is within the microbialites at the base of the Daye Formation. In terms of biostratigraphy, the uppermost Changxing Formation belongs to *H.* cf. *inflatus* conodont zone, the microbialites in the basal

Daye Formation belong to *H. parvus* zone, and the beds above the microbialites belong to the *I. isarcica* Zone.

Several redox histories have been put forward for this P-T section. Loope et al. (2013) suggested that this section was deposited under fully oxic water conditions throughout the P-T boundary interval, as indicated by the negative Ce anomaly (Fig. S11). This is consistent with the interpretation by Forel et al. (2009), who suggested oxic water conditions that allowed persistent deposit-feeding guilds to flourish through the P-T boundary interval in the section.

However, this oxic water interpretation is inconsistent with a framboidal pyrite study by Wang et al. (2016). An absence of framboidal pyrite within the uppermost Changxing Formation and the basal part of the microbialites of the Daye Formation suggests oxic water conditions (Wang et al., 2016). However, framboidal pyrites are present in the overlying part of the microbialites, and their size distribution (mean size between 4 and 8 μm) suggests lower dysoxic depositional conditions (Fig. S11). Above the microbialites, the absence of small framboidal pyrites within the oolitic limestone suggesting oxic conditions, but their occurrence in the micritic limestone suggests lower dysoxic conditions (Wang et al., 2016).

2.1.2.5. Panjiazhuang section, Changxing County, Zhejiang Province (Huang et al., 2019; **Fig. S12**)

The Panjiazhuang P-T section was deposited on a shallow-marine carbonate platform. The Changxing Formation of latest Permian consists of bioclastic limestone with diverse biota. Between the bioclastic limestone and overlying microbialites of the basal Daye Formation is a distinctive purple-red weathering crust, which is considered to be coeval with the P-T mass extinction horizon. The P-T boundary is placed at the base of the microbialites where the conodont *H. parvus* firstly occurs. The microbialites are overlain by thin-bedded micrite limestones with oncoidal and shelly interlayers.

Oxic water settings during the deposition of the upper Permian bioclastic limestone and the lower part of microbialites are indicated by the absence of framboidal pyrites (Fig. S12). In the upper part of the microbialites and in overlying micrite limestone, the occurrence of abundant framboidal pyrites (8 to 14 μm in diameter) suggests dysoxic conditions (Fig. S12). Notably, no framboidal pyrites are found in the oncoidal and shelly interlayers within the micrite limestone.

2.2. Hunan-Guizhou-Guangxi Basin facing Panthalassa Ocean

*2.2.1. Deep-marine P-T sections in the basin (**Fig. 4**)*

2.2.1.1. Dongpan section, Nanning City, Guangxi Province (He et al., 2007; Zhang et al., 2018b; **Fig. S13**)

The Dongpan section was deposited in a deep-marine slope to basinal setting during the P-T boundary interval. The uppermost Talung Formation of latest Permian (late Changhsingian) is dominated by cherty (lime)mudstone in Beds 2 to 12. The overlying Bed 13 at the base of the Luolou Formation of earliest Triassic (early Induan) is dominated by silty (lime)mudstone. Based on sedimentological and geochemical correlations with the Meishan section, the P-T mass extinction horizon is assigned within Beds 7 and 8 in the uppermost Talung Formation and the P-T boundary is placed at the contact between Beds 12 and 13.

Redox-sensitive trace elements (Co, Cr, Cu and V) indicate oxygen restriction from Bed 2 to the lower part of Bed 5 of the Talung Formation, followed by a change to a normal benthic oxygenation state that continues to increase towards Bed 12. This upward trend in increasing oxygenation during the latest Permian indicates an oxygenation event and is supported by: i) lower values of Cr/Al, Co/Al, Cu/Al, V/Al, V/Cr (Fig. S13); and ii) a decreasing ratio of calcareous foraminifera to agglutinated foraminifera, as, in the modern ocean, calcareous foraminifera dominate in the oxygen minimum zone and the ratio of calcareous foraminifera to agglutinated foraminifera decreases with increasing oxygen (Gooday et al., 2000; Levin et al., 2002). The increased oxygenation is also supported by a progressive increase in the intensity of bioturbation and abundance of trace fossils until extinction horizon in the Dongpan section. Moreover, this inferred rise in oxygen level is associated with sea-level fall (indicated by changes in radiolarian taxa), decreasing marine primary productivity (indicated by lower Ba/Al ratios and reduction in radiolarian diversity) and brachiopod miniaturization (He et al., 2007).

2.2.1.2. Penglaitan section, Laibin City, Guangxi Province (Shen et al., 2019; Xiang et al., 2021; **Fig. S14**)

The Penglaitan section was deposited in a deep-marine slope setting during the P-T boundary interval (Xiang et al., 2021). The Talung Formation of latest Permian consists mainly of mixed carbonate-siliciclastic-tuffaceous sediments, and the overlying Luolou Formation of earliest Triassic consists of interbedded lime mudstone and micrite limestone. The mass extinction horizon occurs at the top of Bed 141 within the Talung Formation. The P-T boundary is defined where the conodont *H. parvus* first occurs within Bed 142 at the contact between the Talung and the Luolou Formation.

Iron speciation proxies and absolute values of excess redox-sensitive elements (Mo, V and U) (Fig. S14) indicate there were mainly oxic water conditions with sporadic anoxia immediately prior to and during the end-Permian mass extinction horizon (up to bed 141; characterized by lower values of Fe_{HR}/Fe_{T}, $Fe_{Py}/Fe_{HR,}$ TOC and enrichment factors of redox-sensitive elements), which corresponds to the *C. meishanensis -H. preparvus* conodont zones, suggesting an oxygenation event. Environmental stresses (e.g., decreasing ocean temperatures shown by conodont $\delta^{18}O_{apatite}$ and increasing volcanism suggested by tuffaceous layers) have been proposed to begin before the end-Permian mass extinction event in the section (Shen et al., 2019). Decreasing oxygenation at the level of bed 142 is consistent with sudden disappearance of diverse biota and an enrichment of TOC and U concentration (Fig. S14).

*2.2.2. Shallow-marine P-T sections on the isolated carbonate platforms (**Fig. 5**)*

2.2.2.1. Dajiang section, Luodian County, Guizhou Province (Song et al., 2014; Liao et al., 2017; **Fig. S15**)

The Dajiang section records the P-T transition on an isolated, shallow-marine carbonate platform. The uppermost Permian part consists mainly of bioclastic limestone of the Wuchiaping Formation. The Lower Triassic part consists of microbialites overlain by thin-bedded, poorly bioturbated micrite limestone of the Daye Formation. Within the microbialites are several shelly interlayers containing small thin-shelled bivalves, gastropods and ostracods. The contact between the Wuchiaping Formation and the Daye Formation is an irregular surface thought to result from erosion and karstification and/or submarine dissolution (Liao et al., 2017). Both the mass extinction horizon and the P-T boundary (marked by the lowest occurrence of *H. parvus*) are defined at the base of the Daye Formation, thereby indicating a stratigraphic gap.

The lack of framboidal pyrite and the presence of diverse, abundant fossils within the Wuchiaping Formation suggest the development of oxic marine conditions prior to the mass extinction horizon (Fig. S15). Immediately above the mass extinction horizon, the sudden appearance of abundant small (mean diameter between 5 and 9 μm) framboidal pyrites in the Daye Formation suggests lower dysoxic to anoxic marine conditions during the deposition of the microbialites and overlying micrite limestone (Song et al., 2014; Liao et al., 2017). These earliest Triassic lower dysoxic to anoxic conditions are also reflected by: (i) small carapace size and high intraspecific variability of ostracods (Forel, 2013); (ii) low diversity and high abundance of small body-size “opportunistic” or “disaster” species; and (iii) increasing S_{pyrite}/TOC ratios and degree of pyritization values (Song et al., 2014) (Fig. S15). Notably, the framboidal pyrites in this microbialite layer are smaller than those in the coeval microbialites in the Cili and Laolongdong sections in the northern part of the Yangtze Platform.

2.2.2.2. Zuodeng section, Baise City, Guangxi Province (Yang et al., 2015; Fang et al., 2017; **Fig. S16**)

The Zuodeng section is a shallow-marine P-T boundary interval section located within the Debao isolated carbonate platform. The uppermost Heshan Formation consists of bioclastic limestone, and the lower Majiaoling Formation is comprised of microbialites in the lower part and micrite limestone in the upper part (Fang et al., 2017). There is an irregular contact between the two formations (Yang et al., 2015). The uppermost Heshan Formation yields abundant foraminifera of *Colaniella sp.* and *Palaeofusulina sinsensis*, which correspond to the *C. yini* conodont zone. The microbialites of the basal Majiaoling Formation yield conodonts belonging to the *H. parvus* and *I. staeschei* Zones. Within the microbialites, large-sized framboidal pyrites (mean size of ca. 15 μm) and abundant and diverse biota (including foraminifera, ostracods and microconchids) suggest lower to upper dysoxic conditions. This interpretation is consistent with the common occurrence, within the microbialites, of *Gakhumella* and *Renalcis*-like (unique to the post-EPME microbialites) calcimicrobes (possibly photosynthetic calcimicrobes) and of other taxa which require oxygen (Yang et al., 2015; Kershaw et al., 2021) (Fig. S16).

2.2.2.3. Taiping section, Pingguo County, Guangxi Province (Xiao et al., 2018; **Fig. S17**)

During the P-T boundary interval, the Taiping section was located on the small Pingguo Platform and displays an upward environmental change from a deeper basin to shallow-marine settings. The Heshan Formation consists of bioclastic limestone with some interbedded cherty limestone and cherts in the lower part (Fig. 6H). Permian fusulinid taxa (*Nankinella* sp. and *Reichelina* sp.) suggest a latest Permian age for the uppermost Heshan Formation. The overlying Majiaoling Formation of earliest Triassic consists of microbialites in the basal part overlain by oolitic limestone/dolostone. The microbialites at this location have yielded five species of *Hindeodus* (including *H. parvus*, *praeparvus*, *eurypyge*, *changxingensis* and *inflatus*). The contact between the Heshan Formation and Majiaoling Formation is a flat surface without signs of carbonate dissolution, although an irregular, carbonate-dissolved surface occurs 2 cm above the formation contact. At the contact of the two formations, the mass extinction horizon also coincides with the P-T boundary as indicated by the first occurrence of *H. parvus*.

Abundant small framboidal pyrites with low $\delta^{34}S_{pyrite}$ values occurring in both the uppermost Heshan Formation and the lower Majiaoling Formation indicate lower dysoxic to anoxic water conditions (Fig. S17). Euxinic-anoxic conditions are recorded in the uppermost Permian just below the P-T boundary (indicated by lower $\delta^{34}S_{py}$ and smaller framboidal pyrites), but there is an oxygenation event recorded in the microbialites during the earliest Triassic above the P-T boundary, as inferred from higher $\delta^{34}S_{py}$ and larger framboidal pyrites (Fig. S17).

3. Discussion on the P-T marine redox history recorded in South China

3.1. Inconsistent interpretations from different redox proxies

The large body of P-T marine redox studies in South China reveals that the interpretations from different redox proxies, even when applied into the same P-T section, can vary substantially (Bond and Wignall, 2010; Lehrmann et al., 2015; Xiao et al., 2018; Xiang et al., 2020). A good example is the Meishan GSSP section, for which the redox interpretation from iron speciation data (Xiang et al., 2020) is different to that deriving from other redox proxies (e.g., framboidal pyrites and trace fossils) (e.g., Li et al., 2016) (**Table 1**). A second example is the shallow-marine microbialites above the P-T boundary, for which anoxic (even sulfidic) conditions were mainly inferred from abundant small-size framboidal pyrites, biomarkers and U isotopes (Grice et al., 2005b; Liao et al., 2010; Nabbefeld et al., 2010; Luo et al., 2013; Lau et al., 2016), but dysoxic to oxic conditions were indicated by multiple lines including low total organic carbon (TOC) and total sulfur content, large-size framboidal pyrites in some cases, some biomarkers, Rare Earth Element (REE) and iodine chemistry, diverse bioclasts and upward-increasing bioclast size and abundance, and the presence of photosynthetic cyanobacteria within the microbialites (Lehrmann et al., 2015; Wang et al., 2016; Kershaw et al., 2018) (**Table 1; Figs 3 and 5**).

There are many possible explanations for these divergences, including the sensitivity of different proxies to redox changes, and the effects of early marine diagenetic alterations (Kershaw et al., 2018; Eroglu et al., 2021). Some of the potential artifacts affecting redox proxies are summarized below.

3.1.1. Redox sensitivity

Different redox proxies have different sensitivities to changes in marine redox For example, the residence time of U isotopes (*ca*. 400 kyr) may be too long to capture short-term redox changes, while the biomarkers may record more episodic or instantaneous seawater redox changes (Bond and Wignall, 2010; Chen et al., 2011; Li et al., 2021; Newby et al., 2021). Therefore, different marine redox history can be inferred from U isotopes and biomarkers, even they are measured in the same section. Multi-proxy approaches in the same rocks will provide the best picture of marine redox changes.

3.1.2. Artifacts affecting the iron speciation proxy

Early marine diagenesis within sediments can modify iron speciation data inherited from seawater properties, thereby leading to increases in Fe_{HR}/Fe_T and Fe_{py}/Fe_{HR} ratios while maintaining constant Fe_T/Al ratios (Eroglu et al., 2021). In the Meishan section, although higher Fe_{HR}/Fe_T and Fe_{py}/Fe_{HR} ratios in Beds 24e to 34 were suggested to indicate anoxic and/or ferruginous marine conditions, the Fe_T/Al ratios are relatively constant (Xiang et al., 2020) (**Fig.**

7). If the higher Fe_{HR}/Fe_T and Fe_{py}/Fe_{HR} ratios are related to anoxic and ferruginous marine conditions, one would also expect to see increasing Fe_T/Al ratios (Eroglu et al., 2021). It is possible that the iron speciation proxy data of the Meishan section may be altered during early marine diagenesis and can therefore be problematic to reflect marine redox conditions. In contrast, in the Shangsi and Penglaitan sections the iron speciation analyses through the P-T boundary interval yielded higher Fe_{HR}/Fe_T and Fe_{py}/Fe_{HR} ratios that were typically associated with increasing Fe_T/Al ratios (**Fig. 7**), thereby supporting the interpretation of marine redox conditions (Lei et al., 2017; Xiang et al., 2016, 2021; Eroglu et al., 2021).

3.1.3. Artifacts affecting the uranium isotope proxy

Early marine diagenesis in situations where there is a shallow redox boundary (i.e., the boundary changing from oxic to anoxic conditions within seafloor sediment porewater is very near the sediment-water interface) and dolomitization can drive a negative excursion of U isotopes (Romaniello et al., 2013), which otherwise could be interpreted as a fingerprint of marine anoxia (Zhang et al., 2018a). Li et al. (2018) reported an early marine diagenetic dolomitization event around the Permian-Triassic boundary interval in some South China sections. Therefore, the influence of early marine diagenesis and dolomitization on the P-T U isotope signals across the P-T boundary interval need consideration for a better understanding of marine redox conditions indicated by U isotopes in the absence of independent proxies.

3.1.4. Artifacts affecting the framboidal pyrite proxy

Framboidal pyrites can form both within an anoxic seawater column and as early diagenetic products in sediments (Gomes et al., 2018; Kershaw et al., 2018). For example, in microbial mats, Gomes et al. (2018) reported small pyrites (< 25 μm) with high $\delta^{34}S$ values at the mat surface, and large pyrite grains (> 35μm) with low $\delta^{34}S$ values from deeper parts of the same mats. The $\delta^{34}S$ trend of pyrites of different sizes and from different locations within the microbial mats has been suggested to be related to differential microbial metabolic activities, but the origin of varying $\delta^{34}S$ in different pyrites can be different in non-microbialite marine settings (Gomes et al., 2018). Proposed explanations for the observed trend in the microbialites are: high rates of sulfate reduction, partial closed-system sulfate consumption in microenvironments, and/or sulfide oxidation near the mat surface, leading to small pyrites with high $\delta^{34}S$ values; and slower sulfate reduction rates deeper parts in the mats, leading to large pyrites with low $\delta^{34}S$ values (Gomes et al., 2018).

An early diagenetic origin of some framboidal pyrites within the P-T microbialites of South China is supported by the coexistence of framboidal pyrites of widely varying sizes in sediments with low TOC content, and well-preserved microbial structures and microfossils (e.g., Figs 6F–G) (Luo et al., 2010; Wang et al., 2016; Gomes et al., 2018; Kershaw et al., 2018; Zhang et al., 2020). The widespread microbialites have been reported to have highly variable $\delta^{34}S$ values and higher $\delta^{34}S$ (both $\delta^{34}S_{CAS}$ and $\delta^{34}S_{pyrite}$) values than coeval sediments deposited in deeper marine, non-microbialite settings (Luo et al., 2010; Zhang et al., 2011; Xiao et al., 2018). The higher $\delta^{34}S$ values of the microbialites have been explained by low seawater sulfate concentrations (Luo et al., 2010) or early diagenetic influence (e.g., oxidation of framboidal pyrite) (Gomes et al., 2018; Johnson et al., 2021). Further, multiple other redox proxies applied into the microbialites suggest oxic conditions prevailed during their formation (Forel et al., 2009; Chen et al., 2011; Loope et al., 2013; Yang et al., 2015; Kershaw et al., 2018). Besides, redox proxies (including framboidal pyrites) of coeval landward and seaward non-microbialite sediments also suggest oxic conditions at the time of microbialite formation (Fig. 7). For the distinction of framboidal pyrites associated with P-T microbialites between early digenetic and water column origin, it is tentatively proposed: i) multiple redox proxies are applied to strata containing framboidal pyrites to ascertain whether the results/interpretations are consistent (water column origin) or not (diagenetic origin); ii) detailed petrological description of framboidal pyrites is carried out to evaluate whether the size and morphologies are approximated (water column origin) or not (diagenetic origin); iii) evaluate the relationship between framboidal pyrites and TOC, $\delta^{13}C$ and early diagenetic features, in light of the observation that early diagenetic framboidal pyrites tend to be associated with a decrease in TOC, the release of light carbon and the promotion of early cementation and preservation of primary sedimentary fabrics, while framboidal pyrites of water column are not; iv) an investigation of landward and seaward water redox condition adjacent to the localities developing microbialites containing framboidal pyrites to see if the redox conditions are consistent (water column origin) or not (diagenetic origin); v) advanced technologies, such as fine-scale and *in situ* analyses (e.g., secondary ion mass spectrometry) of $\delta^{34}S$ signals of pyrites of different sizes, are suggested to help better distinguish between origins from seawater and those rooted in early diagenesis in sediments. These could combine to understand the environmental implications of the framboidal pyrites observed in the P-T microbialites (Gomes et al., 2018; Johnson et al., 2021).

3.1.5. Artifacts affecting the biomarker proxy

Upwellings can influence the validity of redox proxies, like biomarkers and framboidal pyrites. Biomarkers in different P-T microbialites indicate low oxygen marine conditions in some places but normal oxic marine conditions in other places (Luo et al., 2013; Zhou et al., 2017). One potential explanation for the phenomena is that there was an influx of biomarkers transported from deeper depths via ocean circulation, such as the upwelling of deep anoxic water (Kershaw et al., 2018). For the occurrence of small framboidal pyrites in the earliest Triassic microbialites, the influence of upwellings was proposed to reconcile the coexistence with oxic indicators (such as diverse biota and negative Ce/Ce* anomaly) (Kershaw, 2015; Kershaw et al, 2016).

3.1.6. Evaluating results from multiple proxies

The above observations and discussions indicate that one must evaluate redox proxies in terms of potential effects of early marine diagenesis, of sensitivity to redox changes and of influence of local upwellings before accepting their interpretations about marine conditions. Therefore, multiple redox proxies should be used and compared to determine the marine redox conditions. After evaluating these types of sensitivity, diagenetic and upwelling influences on the reported redox proxies, this study proposed that dysoxic-oxic marine conditions are preferred for the *H. parvus* conodont zone in the marine upper slope settings such as in the Meishan section, based on evidence including decreasing values of Fe_{HR}/Fe_{T}, Fe_{Py}/Fe_{HR} and Mo, and increasing size or the absence of framboidal pyrites (Figs S6, S7). The dysoxic-oxic marine conditions are also proposed for the formation of the well-developed microbialites in the shallow marine settings, according to: i) in contrast with framboidal pyrites, multiple redox proxies applied to the microbialites suggesting dysoxic-oxic conditions (Chen et al., 2011; Loope et al., 2013; Yang et al., 2015; Kershaw et al., 2018); ii) the large variation of sizes and morphologies of framboidal pyrites (e.g., Yang et al., 2015;); iii) the co-occurrence of framboidal pyrites, low TOC, negative $\delta^{13}C$ excursion and early cementation features, as early diagenetic framboidal pyrites tend to decrease TOC, release light carbon and promote early cementation and preservation of primary sedimentary fabrics (Luo et al., 2010; Wang et al., 2016, Kershaw et al., 2018); and iv) the development of oxic marine conditions in coeval adjacent landward and seaward settings (Li et al., 2016, 2021).

3.2. Redox variation with water depth and with paleogeography

The high-resolution conodont biostratigraphy of the P-T sections deposited at different paleo-water depth settings enables a spatial and temporal compilation of marine redox variation in South China (**Fig. 8**).

3.2.1. Northern Margin of the Yangtze Platform and adjacent Northern Marginal Basin

During the latest Permian, upper dysoxic to oxic marine conditions characterize lower slope to basinal settings (Xiaojiaba, Chaotian and Shangsi sections) during the interval immediately before and during the P-T mass extinction horizon (mainly corresponding to *C. taylorae*, *C. zhejiangensis*, *C. changxingensis* and *C. yini* conodont zones). Before and after this interval of relatively oxygenated conditions, lower dysoxic to anoxic (even euxinic) conditions were prevalent (**Figs 2, 8**).

In contrast, lower dysoxic to anoxic (even euxinic) conditions were developed in upper slope settings (Changtanhe, Ganxi and Meishan sections) during the end-Permian extinction interval, but with an oxygenation event immediately after the P-T boundary that was mainly during *H. parvus -I. isarcica* conodont zone (**Figs 2, 8**).

The shallow-marine settings display two types of redox history based on the depositional facies and environmental conditions. The first kind is typified by the Liangfenya section in a more nearshore location with no development of microbialites above the P-T boundary (**Fig. S8**). That section indicates continuously oxic marine conditions during the deposition of the uppermost Permian bioclastic limestone through lowermost Triassic micrite limestone (*C. changxingensis*, *C. yini*, *C. meishanensis*, *H. parvus* and *I. isarcica* conodont zones).

The second type is the more seaward locations where microbialites occurred above the P-T boundary (Laolongdong, Zaixia, Gaohua and Panjiazhuang sections) (**Figs S9 to S12**). In those locations, an oxic marine redox condition is interpreted for the deposition of the uppermost Permian bioclastic limestone (*C. changxingensis*, *C. yini*, *C. meishanensis* conodont zones). An oxic marine setting is also proposed herein for the microbialites that formed during the earliest Triassic (*H. parvus* Zone) based on: (i) multiple sedimentological, fossil and geochemical evidence favoring oxic marine settings; (ii) a reevaluation of apparent anoxic indicators from small framboidal pyrites, U isotopes and biomarkers as being possibly affected by early redox sensitivity, early diagenesis and influence from local upwelling; (iii) consistency with the redox history of the more nearshore section (Liangfengya) and more seaward section (Meishan) that display coeval oxic marine settings. Accordingly, different with the open and deep marine framboidal pyrites, the formation of framboidal pyrites within shallow marine microbials may be heavily influenced by a closed system of early diagenesis characterized by anoxic porewater conditions (Gomes et al., 2018; Kershaw et al., 2018), as is supported by early diagenetic petrological features and low TOC of associated carbonate components, uneven pyrite size and morphologies and variable and heavier $\delta^{34}S_{py}$ values (Luo et al., 2010; Wang et al., 2016; Gomes et al., 2018; Kershaw et al., 2018; Zhang et al., 2020). In both types, the oxic condition of earliest Triassic is followed by a dysoxic-anoxic redox interval (corresponding to the conodont zone *I. staeschei*) associated with a marine transgression, although this interval is occasionally interrupted by oxic conditions expressed by oolitic and shelly sediments.

3.2.2. Hunan-Guizhou-Guangxi Basin facing Panthalassic Ocean

Deep marine slope to basinal P-T sections (Dongpan and Penglaitan) in the southern region record a similar redox history as those of the northern marginal basin (Xiaojiaba, Chaotian and Shangsi sections). An oxygenation event occurred immediately below and during the end-Permian mass extinction horizon. This event is sandwiched above and below by dysoxic to anoxic conditions (**Fig. 4**).

The shallow-marine sections on the isolated carbonate platforms display similar lithological features to the second type of shallow-marine sections of the northern margin of the Yangtz Platform. Mainly oxic-dysoxic marine conditions were present during the deposition of both the upper Permian bioclastic limestone and the basal Triassic microbialites.

3.3. Possible reasons for the P-T deep marine oxygenation events in South China

Based on the correlation of P-T marine redox conditions in South China (**Figs 2-5**), two deep marine oxygenation events are suggested to occur during the P-T boundary interval that affected different sedimentary environments. The first oxygenation event occurred immediately before and during the end-Permian mass extinction horizon, corresponding to the *C. taylorae*, *C. zhejiangensis* and *C. changxingensis yini* conodont zones. The second oxygenation event occurred during the *H. parvus -I. isarcica* conodont zones immediately after the P-T boundary. The first oxygenation event is recorded mainly in basinal to lower slope settings, whereas the second oxygenation event is apparent mainly in upper slope settings.

Variations in ocean circulation and marine primary productivity are commonly invoked as causes for changes of marine redox conditions (Kuypers et al., 2002; Meyer et al., 2011; Georgiev et al., 2015; Xiang et al., 2016). The first oxygenation event in deeper water settingsappeared around the end Permian mass extinction horizon and co-occurred with enhanced volcanic activities (e.g., Xie et al., 2007; Shen et al., 2021), climate cooling (Shen et al., 2010; Chen et al., 2016; Joachimski et al., 2020), decreased primary productivity (Zhang et al., 2007, 2018c; Algeo et al., 2010, 2011; Shen et al., 2014, 2015; Wei et al., 2015; Wu et al., 2022), a rapid (ca. 100 ky) sea-level fall (Kershaw et al., 2002; Yin et al., 2014), and increasing terrestrial influx (Korte et al., 2003; Xie et al., 2007). Likely, the oxygenation event may be caused by increased oxygen supply from shallow seawater, as is supported by enhanced ocean circulation driven by climate cooling related to volcanic activities releasing SO_2 (Shen et al., 2020; Newby et al., 2021) (**Fig. 9**). Moreover, given the time-equivalence with volcanic activities, it is feasible that there is a causal relationship between the rapid sea-level fall during the first oxygenation and climate cooling related to volcanism, and similar cases have been reported in the end-Triassic mass extinction events (Schoene et al., 2010).

While, during the oxygenation event in the basinal and lower slope settings, increased oxygen depletion in the upper slope settings are consistent with upwelling of deeper marine anoxic water (Li et al., 2016; Lei et al., 2017; Xiao et al., 2018). Meanwhile, the decreased marine productivity doesn’t favor expansion of oxygen minimum zone (OMZ) as the reason for oxygen depletion in upper slope settings (Wei et al., 2015; Xiang et al., 2016). On the other hand, the effects of upwelling may have been stronger in the southern part of South China facing Panthalassa, where shallow marine platforms also show oxygen depletion (e.g., Taiping section) (Xiao et al., 2018).

The second oxygenation event, which affected predominantly the upper slopes during the earliest Triassic, occurred during a time of greatly reduced marine primary productivity in the South China area (Shen et al., 2014, 2015; Zhang et al., 2018c; Wu et al., 2022). At this time, the very warm climate might have promoted ocean stratification and reduced upwelling of nutrient-rich deeper waters (Joachimski et al., 2012; Winguth and Winguth, 2012; Schobben et al., 2014; Chen et al., 2016) and, hence also contributed to changes of seawater chemistry (Heydari et al., 2013; Tavakoli, 2016; Li et al., 2018) and reduced marine primary productivity (**Fig. 9**). The dysoxic-anoxic conditions in lower slope-basinal settings (**Figs 2, 8**) are consistent with such a reduced ocean circulation. The second oxygenation event that mainly affected the upper slope settings in South China may be related to the low marine primary production and biomass extinction, which in turn led to less marine oxygen consumption by organic respiration and decomposition and consequently a recovery in oxygenation levels (Algeo et al., 2013; Xiao et al., 2018).

In contrast to marine redox fluctuations in slope and basinal settings, redox conditions in most shallow-marine settings are thought to have remained consistently oxic (and/or dysoxic) through the P-T boundary interval, including during the formation of the microbialites during the earliest Triassic, while some local areas may be influenced by the upwellings of deeper and oxygen-poor waters.

3.4. Correlation with carbon-isotope excursions in South China

Two marine negative $\delta^{13}C$ excursion events have been reported during the P-T boundary interval in South China (Krull et al., 2004; Song et al., 2013; Li et al., 2021; Wu et al., 2022); and both of these appear to be associated with the oxygenation events proposed in the study.

The first negative $\delta^{13}C$ excursion in both $\delta^{13}C_{carb}$ and $\delta^{13}C_{org}$ is present in both deep and shallow-marine settings during the end-Permian mass extinction interval (Newby et al., 2021). This is temporally consistent with the first oxygenation event recorded in basinal to lower slope settings. Possibly, enhanced oxidization and remineralization of organic matters that had previously accumulated under the recorded low oxygen conditions may serve as a possibility contributing to that negative $\delta^{13}C$ excursion by releasing large amounts of isotopically light carbon. Other suggested drivers of this excursion include volcanic CO_2, methane release, biomass kill, erosion of soil carbon, reduced organic matter burial (Berner, 2002; Krull et al., 2004; Payne and Kump, 2007; Retallack and Jahren, 2008; Algeo et al., 2011).

The second negative $\delta^{13}C$ excursion in $\delta^{13}C_{carb}$ and $\delta^{13}C_{org}$ is mainly present in the shallow-marine microbialite interval in the earliest Triassic above the P-T boundary (Krull et al., 2004; Liao et al., 2010; Kershaw et al., 2012b; Wang et al., 2016; Xiao et al., 2018; Wu et al., 2022), whereas a positive $\delta^{13}C$ excursion occurred in upper slope settings (e.g., Meishan, Shangsi, Chaotian) (Li et al., 2021; Zhou et al., 2021; Wu et al., 2022). The contrasting patterns of $\delta^{13}C$ excursion along a proximal-to-distal direction are unexplained hitherto. The shallow marine microbialites are benthic and well preserved, indicating that they formed in low energy and relatively restricted settings (Kershaw et al., 2012a). In relatively restricted, oxic shallow marine settings, isotopically light carbon released during organic decomposition may cause a local depletion in seawater ^{13}C and a negative excursion $\delta^{13}C_{carb}$ and $\delta^{13}C_{org}$ in the carbonate sediment. Similar patterns have been reported in modern shallow-marine carbonate settings at Florida, the Bahamas and Abu Dhabi (Lloyd, 1964; Patterson and Walter, 1994; Pederson et al., 2021). For the upper marine slope sections, reduced input of isotopically light carbon by decreased marine primary productivity (e.g., Shen et al., 2014) may have contributed to the positive $\delta^{13}C_{carb}$ and $\delta^{13}C_{org}$ excursion in the sediment. Previous studies also proposed a change in carbon source (e.g., influx of terrestrial carbon and changes in microbial composition) for the positive $\delta^{13}C$ excursion in the upper slope settings (Wu et al., 2022).

3.5. Implications for the P-T mass extinction events in South China

The two oxygenation events around the P-T boundary interval may provide some implications for environmental scenarios of the P-T mass extinction scenario in South China. For the first oxygenation event immediately before and during the marine mass extinction horizon, enhanced ocean circulation and sea level fall have been attributed to short-term climate cooling superimposed on the overall warming trend as a consequence of massive SO2 release by the emplacement of the Siberian Traps large igneous province (Wu et al., 2014; Baresel et al., 2017; Newby et al., 2021). Therefore, volcanic activities seem to have already occurred immediately before the marine mass extinction events. Terrestrial P-T extinction and deforestation related to volcanism have been reported to occur before marine mass extinction, which supports volcanic activities before the marine mass extinction events (Shen et al., 2011; Kaiho et al., 2016; Liu et al., 2017; Zhou et al., 2017; Xiao et al., 2018). This timing is also indicated by the wildfire biomarkers and black carbon (Xie et al., 2007; Zhou et al., 2021). On the other hand, although ocean anoxia has been argued as an important killing mechanism for end-Permian mass extinction events (e.g., Isozaki, 1997; Liao et al., 2010; Wu et al., 2022), this is inconsistent with the deep-water oxygenation event at the end-Permian mass extinction interval (Bond and Wignall, 2010; He et al., 2013), at least in some settings. However, combined with regression, the upwelling of deep and anoxic water may cause the biota crisis for shallow marine biota. The development of ocean anoxia has started considerably before the marine mass extinction events, and can’t account for the biotic turnover and extinction events on land (e.g., Bond and Wignall, 2010). This indicates clearly more complex scenarios than a simple death-by-anoxia model during the P-T mass extinction.

The second oxygenation event, which affected mainly the upper slopes during the earliest Triassic following the P-T boundary, occurred immediately prior to a second pulse of marine extinction from the *H. parvus* to the *I. isarcica* conodont zones (Song et al., 2013; Su et al., 2021). During this time, there was enhanced ocean stratification and a disturbance in the marine nutrient cycle and food web, as indicated by a negative excursion of $\delta^{15}N_{org}$ in the P-T sections of South China (Luo et al., 2011; Wu et al., 2022). In the shallow-marine settings, oxic conditions and localized food webs associated with the benthic microbialites may have provided ecological refuges for diverse shallow-marine biota (e.g., gastropods, bivalves and ostracods) after the end-Permian extinction. Those shallow-marine biota, however, suffered a wave of extinction during the following anoxia event associated with a sea-level rise over the shallow marine shelves.

3.6. Correlation of marine redox conditions between South China and Panthalassa

The first oxygenation event that affected South China seems to have also occurred in other localities in the Paleotethys and Panthalassa Ocean (**Fig. 10**). Based on the P-T section in northern Italy, Newton et al. (2004) has reported such a transient oxygenation event in deep water, which caused reoxidation of deep-water H_2S and consequent negative excursion of $\delta^{34}S$ and $\delta^{18}O$ of carbonate-associated sulphate. Newby et al. (2021) reported an ocean oxygenation event during the end-Permian mass extinction interval from shelf to abyssal settings in the low-latitude Panthalassa Ocean. The short-term oxygenation event was also supported by bioturbation and geochemical proxies (e.g., $\delta^{34}S$ values and positive Ce anomaly) in deep Panthalassan P-T chert sections (Kakuwa, 2008).

For the second oxygenation event, it has been mainly documented in South China showing decreased primary productivity, and not recognized in the Panthalassa, where, in contrast, there is evidence showing no-decreasing and even increasing primary productivity at that time (Algeo et al., 2010, 2011; Shen et al., 2015; Newby et al., 2021). Marine nitrogen nutrient has been recognized as an important control on the marine primary productivity (Falkowski, 1997; Moore et al., 2013; Buchanan et al., 2021). The P-T $\delta^{15}N_{org}$ isotope records show: decreasing (and low) $\delta^{15}N_{org}$ values across the P-T boundary in South China, Paleotethys realm (Luo et al., 2011; Wu et al., 2022); while increasing (and high) $\delta^{15}N_{org}$ values across the P-T boundary in the Panthalassa realm (Georgiev et al., 2015). A terrestrial influence on the $\delta^{15}N_{org}$ records is thought to be negligible (Luo et al., 2011; Radice et al., 2019; Wu et al., 2022), and main reasons for the nitrogen isotope variation are nitrogen fixation and denitrification related to upwellings (Robinson et al., 2012; Buchanan et al., 2021). When upwellings are frequent and strong, nutrient nitrogen from deep water would fertilize surface seawater and promote marine primary productivity and water column denitrification, leading to increasing and high $\delta^{15}N_{org}$ values; while sluggish ocean circulation limits upwelling and nitrogen supply to surface seawater (possibly nitrogen limited), leading to nitrogen fixation and decreasing$\delta^{15}N_{org}$ towards low values (Luo et al., 2011; Robinson et al., 2012; Buchanan et al., 2021; Wu et al., 2022). Thus, it appears that different ocean circulation and nutrient nitrogen cycle occurred between South China and Panthalassa around the P-T boundary (**Fig. 11**). In South China, sea-level fall and the paleogeographic configure of the time may lead to a restriction event (Hu et al., 2021; Zheng et al., 2021). In the relatively restricted setting, climate warming and increased precipitation related to intensified monsoon favor ocean stratification and decreasing upwellings. In the Panthalassa, due to much larger ocean size, no ocean restriction happened and enhanced monsoon activities may promote upwellings.

4. Conclusions

Synthesis and reevaluation of paleogeographically diverse studies of P-T marine redox conditions at different paleo-depths in South China reveal that two deep marine oxygenation events have occurred during the P-T boundary interval. The first oxygenation event occurred just before and continued through the main end-Permian mass extinction interval, and mainly affected the lower slope and basinal settings. This oxygenation event is recorded in other locations in the Paleotethys and Panthalassa realm. The first oxygenation event potentially had origins in enhanced deep-ocean circulation driven by short-lived climatic cooling associated with the release of large amounts of SO_2 during the eruptive phases of the Siberian Traps Large Igneous Province. The second oxygenation event recorded mainly in upper slope settings of South China may be related to climate warming, increased ocean stratification, reduced ocean circulation and a decline in marine primary productivity within a relatively restricted paleogeographic configuration. The complex P-T marine redox history at different paleo-depths in South China were driven by the combination of paleogeography, major climate changes, surface and deep-ocean circulation and changes in marine productivity.

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TABLES

Table 1. Marine redox-studied sections around the P-T boundary interval in Paleotethys and Panthalassa

Section	**Environmental setting**	**Marine redox proxy and interpretation**	**Reference**
Northern Marginal Basin sections in South China (Paleotethys)			
Meishan	Upper slope	Biomarkers: photic zone euxinic across the P-T boundary interval Framboidal pyrites, biota diversity, trace fossils: mainly anoxic in *C. taylorae* -*C. zhejiangensis* -*C. changxingensis* -*C. yini* zones; mainly oxic in *H. parvus* Zone; mainly anoxic in *Isarcicella* Zone Iron speciation: mainly anoxic, even euxinic in *H. parvus* Zone mainly anoxic, ferruginous in *Isarcicella* Zone	Grice et al., 2005b; Summons et al., 2006; Li et al., 2016; Xiang et al., 2020
Ganxi	Upper slope	Iron speciation and Mo element: anoxic, in *C. wangi*, *C. changxingensis*, *C. yini* and *C. meishanensis* Zones; anoxic to oxic, in *H. parvus* and *I. isarcica* zones	Lei et al., 2017

Changtanhe	Lower slope	Framboidal pyrites, fossil diversity and TOC content: anoxic, in the mass extinction horizon; oxic, immediately after the mass extinction event anoxic after the oxygenation event	He et al., 2013
Shangsi	Lower slope to basin	Iron speciation, redox-sensitive elements, fossil diversity and bioturbation degree: euxinic, in uppermost *C. wangi* to lower and middle *C. subcarinata* Zones; mainly anoxic, *C. changxingensis* -*C. yini* -*C. meishanensis* Assemblage Zone, to *H. changxingensis* Zone oxic in the mass extinction horizon (within *C. meishanensis* -*H. changxingensis* Zone) anoxic, *H. changxingensis* -*H. parvus* -*I. isarcica* zones	Wignall et al., 1995; Bond and Wignall, 2010; Xiang et al., 2016
Chaotian	Lower slope to basin	Framboidal pyrites, bioturbation, trace fossils and TOC content: oxic, in *C. taylorae* -*C. zhejiangensis* -*C. changxingensis* -*C. yini* Assemblage Zone; oxic, immediately above the mass extinction horizon; anoxic, in *H. parvus* and *Isarcicella* zones	Newton et al., 2009; Saitoh et al., 2021
Xiaojiaba	Lower slope to basin	Framboidal pyrite, $\delta^{34}S_{py}$, C_{org}/P, Mo_{auth} and U_{auth}: an oxygenation event in the end-mass extinction	Wei et al., 2015

		horizon	
Sections in Northern part of Yangtze Platform in South China (Paleotethys)			
Liangfengya	Shallow marine	Framboidal pyrites and bioturbation: oxic, in *C. changxingensis*, *C. yini*, *C. meishanensis*, *H. parvus* and *I isarcica* Zones; dysoxic to euxinic, in *I. staeschei* Zone	Li et al., 2021
Laolongdong	Shallow marine	Framboidal pyrites and fossil diversity: oxic, below the mass extinction horizon and P-T boundary; lower dysoxia, in *H parvus* Zone	Liao et al., 2010
Zaixia	Shallow marine	Biomarkers: no severe anoxia; an oxygenation event immediately above the mass extinction horizon;	Chen et al., 2011
Gaohua	Shallow marine	Ce anomaly and guilds: oxic across the P-T boundary interval Framboidal pyrites: an oxygenation event around the mass extinction horizon and followed by dysoxic	Forel et al., 2009; Loope et al., 2013; Wang et al., 2016
Panjiazhuang	Shallow marine	Framboidal pyrites: oxic across the mass extinction horizon	Huang et al., 2019
Deep-water sections in the Hunan-Guizhou-Guangxi Basin in South China (Paleotethys)			

Penglaitan	Lower slope to basin	Iron speciation and redox-sensitive elements: oxic across the mass extinction horizon (correspond to *C. meishanensis* -*H. preparvus* Zones)	Xiang et al., 2021
Dongpan	Lower slope to basin	Redox-sensitive elements: oxic across the mass extinction horizon	He et al., 2007; Zhang et al., 2018b
Sections in isolated carbonate platforms in the Hunan-Guizhou-Guangxi Basin in South China (Paleotethys)			
Dajiang	Shallow marine	Framboidal pyrites, fossil diversity, S_{pyrite}/TOC, Uranium concentration: oxic below mass extinction horizon and P-T boundary; lower dysoxic above mass extinction horizon and P-T boundary	Forel, 2013; Song et al., 2014; Lau et al., 2016; Liao et al., 2017
Zuodeng	Shallow marine	Framboidal pyrites and microorganism: lower to upper dysoxic, in the *H. parvus* and *I. staeschei* Zones	Fang et al., 2017
Taiping	Shallow marine to upper slope	Framboidal pyrites and $\delta^{34}S_{pyrite}$: lower dysoxic to anoxic in the mass extinction horizon and P-T boundary; an oxygenation event immediately above the P-T boundary	Xiao et al., 2018
Other marine sections in Paleotethys			
Demirtas	Shallow	REE, Ce/Ce* anomaly and bioclasts: oxic for latest	Loop et al.

(Turkey)	marine	bioclastic limestone and earliest Triassic microbialites; and anoxic in overlying early Triassic micrite	(2013)
Marine sections in Panthalassa			
Opal Creek (Canada); Gujo-Hachiman, Ubara (Japan)	Shelf to abyssal settings	Thallium isotope: a transient oxygenation at the end-Permian mass extinction	Newby et al. (2021)

Table 2. Characteristics of different redox conditions during deposition (Bond and Wignall, 2010)

Conditions	Framboid parameters	Sedimentary fabric
Euxinic (persistently sulfidic lower water column)	Small (mean 3-5 μm), abundant, with narrow size range. Framboids dominate pyrite fraction	Finely laminated
Anoxic (no oxygen in bottom waters for long periods	Small (mean 4-6 μm), abundant, with a few, larger framboids. Framboids dominate pyrite fraction	Finely laminated
Lower dysoxic (weakly	Mean 6-10 μm, moderately common, with a	Finely laminated

oxygenated bottom waters)	few, larger framboids and some crystalline pyrite	with rare bioturbation
Upper dysoxic (partial oxygen restriction in bottom waters)	Moderately common to rare, broad range of sizes, only a small proportion <5 μm. Majority of pyrite as crystals	Microburrowed. Bioturbation may obscure laminated fabric
Oxic (no oxygen restriction)	No framboids, rare pyrite crystals	Burrowed and/or massive

FIGURES

Fig. 1. Global and South China paleogeography during the P-T boundary interval. (A) Global paleogeography. The South China Block is indicated by the red frame. Modified from Xiao et al. (2018). (B) South China paleogeography. The sections in this study are indicated by red triangles. Northern margin sections: XJB = Xiaojiaba, SS = Shangsi, CT = Chaotian, LFY = Liangfengya, LLD = Laolongdong, GX = Ganxi, GH = Gaohua, CTH = Changtanhe, ZX = Zaixia, MS = Meishan. Southern margin sections: PJZ = Panjiazhuang, DJ = Dajiang, ZD = Zuodeng, PLT = Penglaitan, TP = Taiping, DP = Dongpan. Detailed descriptions of the sections are provided in the text. Modified from Yin et al. (2014).

Fig. 2. Interpretation of marine redox changes in deep marine basinal to slope P-T sections of

the Northern Marginal Basin, South China. PTB = Permian-Triassic boundary, EPME = end-Permian mass extinction horizon. Blue color = oxic to upper dysoxic; Yellow color = lower dysoxic to euxinic. Note: the blue-color interval with a red star represents the first oxygenation event near the EPME; and the blue-color interval with a yellow start represents the second oxygenation event in the earliest Triassic.

Fig. 3. Interpreted marine redox changes in shallow-marine P-T sections of the northern margin the Yangtze Platform. PTB= Permian-Triassic boundary, EPME= end-Permian mass extinction horizon. Blue color = oxic to upper dysoxic; Yellow color = lower dysoxic to euxinic.

Fig. 4. Marine redox changes in deep marine lower slope to basinal P-T sections in the Hunan-Guizhou-Guangxi Basin, South China. PTB= Permian-Triassic boundary, EPME= end-Permian mass extinction horizon. Blue color = oxic to upper dysoxic; Yellow color = lower dysoxic to euxinic. Note: the blue-color interval with a red star means first oxygenation event near the EPME.

Fig. 5. Marine redox changes in shallow-marine P-T sections in the isolated carbonate platforms within the Hunan-Guizhou-Guangxi Basin, South China. PTB= Permian-Triassic boundary, EPME= end-Permian mass extinction horizon. Blue color = oxic to upper dysoxic; Yellow color = lower dysoxic to euxinic.

Fig. 6. Photographs of Permian-Triassic marine strata and sedimentary features from South

China. (A) Burrows in the uppermost Dalong Formation (latest Permian), Chaotian section (sourced from Saitoh et al., 2021); (B) Abundant radiolarians in the uppermost Dalong Formation (latest Permian), Chaotian section (sourced from Saitoh et al., 2014); (C) Absence of burrows in the lowermost Feixianguan Formation (earliest Triassic), Chaotian section (sourced from Saitoh et al., 2021); (D) Gray marl with abundant pyrite particles (black dots), and a lack of burrows in the lowermost Feixianguan Formation (earliest Triassic), Chaotian section (sourced from Saitoh et al., 2014); (E) The transition from bioclastic limestone (latest Permian) to microbialites (earliest Triassic), Lalongdong section (sourced from Liao et al., 2010); (F) Well-preserved microfabrics of microbialtes (earliest Triassic) showing upward-branching architecture, Laolongdong section (sourced from Kershaw et al., 2018); (G) Calcimicrobes within microbialtes (earliest Triassic) showing well-preserved microfabrics (sourced from Kershaw et al., 2018); (H) Bioclastic limestone (latest Permian) under thin section, Taiping section (sourced from Xiao et al., 2018).

Fig. 7. Iron speciation data from the Meishan, Shangsi and Penglaitan sections. In the Meishan section, Fe_T/Al decreases across the P-T boundary (PTB), and then remains constant through the earliest Triassic. In the Shangsi and Penglaitan sections, no Fe_T/Al decrease occurs across the PTB. Data sources: Meishan from Xiang et al. (2020); Shangsi from Xiang et al. (2016); Penglaitan from Xiang et al. (2021).

Fig. 8. Selected P-T marine sections revealing spatial variations in marine redox conditions at different paleo-water depths. Note: the blue-color interval with a red star means first

oxygenation event near the EPME; and the blue-color interval with a yellow start means second oxygenation event in the earliest Triassic.

Fig. 9. A sketch showing the P-T marine redox changes. Two deep marine oxygenation events occurred during the end-Permian mass extinction interval (EPME) and during the *H parvus* conodont zone of earliest Triassic. SL= sea level.

Fig. 10. Marine redox variations at the P-T boundary interval in other localities in Paleotethys and Panthalassa. Data sources: Demirtas, Loope et al. (2013), Fig. S18; Opal Creek, Gujo-Hachiman and Ubara, Newton et al. (2004), Fig. S19.

Fig. 11. Comparison of P-T marine redox changes between South China and Panthalassa area. The first marine oxygenation event was recorded in both areas, while the second marine oxygenation event was recognized only in South China.