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Invited Review Article

Great Paleozoic-Mesozoic Biotic Turnings and Paleontological Education in China: A Tribute to the Achievements of Professor Zunyi Yang

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ABSTRACT: Professor Zunyi Yang is a pioneer paleontologist who established the earliest Paleontological education and research in China, and has contributed his lifetime to promotion of Chinese paleontological education and researches as well as the studies on the Permian-Triassic (P-Tr) mass extinction and its possible causes. Yang has studied six fossil clades and trace fossils, together with his colleagues, he has established 6 new species of cephalopods, 1 new genus and 15 new species of gastropods, 8 new genera and 31 new species of bivalves, 17 new genera and 66 new species of brachiopods, 1 new genus and 4 new species of ophiuroids, 2 new genera and 7 new species of triopsids (Crustacea), and 3 new ichnogenera and 7 new ichnospecies of trace fossils. Yang led the 2nd IGCP working on the P-Tr mass extinction in the world. His group's excellent works on basic stratigraphy and paleontology enable the GSSP of P-Tr boundary (PTB) to be ratified in China. Yang's earlier works on three-episode extinction pattern and volcanism-causing extinction hypothesis are also highlighted here to show how their first-hand data and initiative hypothesis have influenced the current and ongoing debates on the P-Tr crisis and possible causation. Yang school's extinction pattern is reviewed here, and their 2nd phase of extinction is marked by a dramatic loss in biodiversity, pointing to a widely accepted mass extinction. The 3rd extinction is characterized by ecological collapse of ecosystem structures and disappearance of the PTB microbialite ecosystem, while the 1st extinction (also prelude extinction) is indicated by the collapses of deep-water and reef ecosystems. Updated studies show that the volcanic ashes near the PTB originated from silicic, subduction-related igneous activity with little or no basaltic input. This subduction zone activity is related to closure of the Paleo-Tethys Ocean, and the intensity and frequency of the volcanic activity appear to increase near the P-Tr extinction interval. Hg anomalies (Hg/TOC ratios and Hg isotopes) were also detected from the P-Tr extinction interval, and they are interpreted as the results of enhanced volcanic-generated atmospheric mercury, which was injected by the violate eruption of the Siberian traps. Thus, the peak felsic volcanism is coeval with violate eruption of Siberian traps, and the coupled relationship between both types of volcanisms and biotic extinction suggests a causal relationship.

KEY WORDS: Professor Zunyi Yang, IGCP project, Permian-Triassic boundary, mass extinction, South China.

0 INTRODUCTION

IGCP 630 organized its final annual symposium and field excursion in China in 2018. The indoor symposium was held at China University of Geosciences (Wuhan), and this year is the 110th anniversary of late Prof. Zunyi Yang, the leader of the earliest IGCP (formerly International Geological Correlations Program) project in China. A special session celebrating Yang's 110th anniversary was organized joint with the IGCP 630 annual symposium at CUG on 24th of May, 2018. At this special session, most studies focus on the Permian and Triassic worlds, and related extreme climatic, environmental and biotic events. This research area has been a topical subject of interests for nearly five decades since early 1970s. Professor Yang was the worldwide expert on the Permian-Triassic (P-Tr) mass extinction, and his working group has completed tremendous basic paleontological and stratigraphic researches on the Permian and Triassic as well as their system-boundary (Yang et al., 1993, 1987). These original data offered important evidences for developing various hypotheses on extinction patterns and causes during this critical period.

This thematic volume gathers together some of the results presented at this session, and others are collected from recent works by IGCP 630 members. Baud (2018) summarized strati-

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graphical and paleontological features of four important regions where IGCP 572 and 630 organized field workshops to investigate the P-Tr successions and discuss some important issues. Dey and Sen (2018) documented stratigraphical successions of Middle Permian from a marginal Gondwana Basin, India. Nowak et al. (2018) reviewed the global distributions of the Upper Permian to Middle Triassic spore-pollens and recommended the updated palynozones across the P-Tr transition. Lucas (2018) critically reviewed global charophytes across the P-Tr boundary, established several correlative floral zones, and recognized the possible biotic events of this floral group. Huang et al. (2018) reported a new bivalve fauna from the Griesbachian succession of Sidazhai Section, southwest China, and discussed the possible factors controlling the proliferation of bivalve genus *Claraia*. Lyu et al. (2018) re-assessed the taxonomy of conodont *Novispathodus waageni* group and its role in defining the Induan-Olenekian boundary (Lower Triassic). Aljinović et al. (2018) reported the eperic ramp facies Lower Triassic successions exposed in Croatia and also documented variations of several genochemical proxies throughout the section. Zakharov et al. (2018) reported nitrogen and carbon isotope excursions from the Olenekian to Anisian (Middle Triassic) from South Primorye region and correlated those proxies with their counterparts derived from South China. Luo et al. (2018) described new materials of ichnofossil *Sinusichnus sinuosus* from the Middle Triassic of southwestern China, and its paleoecological implications have also been addressed. Smirčić et al. (2018) described the Middle Triassic depositional sequences recorded in Croatia. Stanley (2018) focused on how scleractinian corals survived the end-Triassic mass extinction. This study highlights the importance of assigning simple to advanced paleoecological characters with integration levels, which opens a useful approach to understanding of mass extinction and the dynamics of the recovery. In addition, three studies focusing on the Cambrian to Ordovician microfossils (i.e., radiolarians, and other siliceous microfossils) (Chang et al., 2018; Yi et al., 2018; Zhang et al., 2018) are also collected in this special volume that is dedicated to Prof. Zunyi Yang's 110th anniversary.

In addition, this paper also aims to summarize Yang's achievements in Paleontological education and researches in China as well as his pioneer works on the P-Tr boundary and associated environmental and biotic events. This special issue provides us with an opportunity to acknowledge his substantial and frequently pioneering contributions to the P-Tr studies as well as promotion of Paleontological education and research in China. Here we highlight Yang's earlier works and show how these first-hand data and his initiative hypothesis have influenced the current and ongoing debates on the P-Tr mass extinction and its possible causation.

1 BIOGRAPHY OF PROF. ZUNYI YANG

Professor Zunyi Yang (see his portrait on front page of this volume) was born on Oct. 7, 1908 in Jieyang County, Guangdong Province, China. He obtained Bachelor degree from the Department of Geology, Tsinghua University in 1933, then took a teaching position at the same department of Tsinghua University. In 1936, Zunyi joined the Research School of Yale University with director Prof. Carl Owen Dunbar, as a Ph.D. candidate. He finished his doctorate at Yale University in 1939, and returned to China soon after.

During 1939–1945, Dr. Yang acted as a translator of the ally military delegation and participated the 2nd World War. Meanwhile, Dr. Yang also taught at Zhongshan University, Guangzhou in that time. After the allies won the 2nd World War in 1945, Dr. Yang returned to Tsinghua University and taught there until 1952.

The Beijing College of Geology (now China University of Geosciences) was founded in 1952 with a combination of geoscience faculties/departments from Peking University, Tsinghua University, and others. Professor Yang moved to the newly established BCG, as a founder of this new college, and served there as directors of numerous departments and one of the college top leaders. Since then, Dr. Zunyi Yang has taught at BCG and later CUG. Yang is also notable for his fifty-seven years as a paleontological and stratigraphic professor at BCG/CUG (1952–2009).

Professor Yang was elected to the Paleontological Society of China as Vice Chairman, the sterling member of the Geological Society of China and also director of its sub-committee of Paleontology and Stratigraphy. He was elected as an honorary member of Geological Society of America in 1992. Professor Yang also served as Editor in Chief of *Acta Paleontologica Sinica*. Moreover, Prof. Yang has owned many honoraries and awards. Of these, the Wilbur Cross of Yale University (in 1994), Li Siguang Honorary Award of Geosciences (in 1997), and He-Liang-He-Li Foundation Award for Science and Technology Progress (in 1997) are notable.

2 PALEONTOLOGICAL ACHIEVEMENTS: EDUCATION AND RESEARCH

Professor Yang is the founder of the education on Paleontology and Stratigraphy disciplines in China. He is a pioneer paleontologist and stratigraphier, and, as a great mentor, has trained several generations of paleontologists in China. Yang edited the first text book of Paleontology in Chinese edition in 1956, and firstly opened the major of Paleontology and Stratigraphy at Chinese universities in 1960. Then, he first taught Biostratigraphy and Paleontology, together with other paleontological courses such as Historical Geology, Systematic Paleontology so on, at Chinese Universities in 1962. In 1986, Yang first-authored one comprehensive book on Geology of China (published by Oxford University Press), 47 years after the first copy of Geology of China (English edition) book written by Prof. Siguang Li (J. S. Lee). This book for the first time introduced general overviews on regional geology, stratigraphic correlations, paleobiogeography and tectostratigraphy across the entire China, providing an important geological reference for foreign researchers.

Yang's earliest studies were on taxonomy of various clades. In his paleontological research career, Prof. Yang has studied six fossil groups and ichnofossils. He, together with his co-authors, has described and erected 6 new species of cephalopods, 1 new genus and 15 new species of gastropods, 8 new genera and 31 new species of bivalves, 17 new genera and 66 new species of brachiopods, 1 new genus and 4 new species of ophiuroids, 2 new genera and 7 new species of triopsids (Crustacea), and 3 new ichnogenera and 7 new ichnospecies of trace fossils. Besides, Zunyi, together with his co-authors, has also established 1 new subspecies, 2 new varieties of brachiopods, and 1 new family and 1 new subfamily of triopsids (Crustacea). Most of them are still valid today. All new taxa that Prof. Yang established are listed in Table 1.

Table 1 New taxa (family, subfamily, genus, species, subspecies, variety) established by Prof. Zunyi Yang and his collaborators (Note that some taxa require new revision and updates)

New family, subfamily, genus	
Crustacea	
Xinjiangiopsidae Yang and Hong, 1986	*Brachygastriops* Yang and Hong, 1980
Weichangiopsinae Yang and Hong, 1980	*Weichangiops* Yang and Hong, 1980
Ophiuroidea	
Ophoaulaxoides Yang and Nie, 1982	
Gastropoda	
Trochaliella Yang and Qian, 1988	
Bivalvia	
Carinonychia Pojeta, Zhang and Yang in Pojeta et al., 1986	*Phestioidea* Pojeta, Zhang and Yang in Pojeta et al., 1986
Leiodysodonta Pojeta, Zhang and Yang in Pojeta et al., 1986	*Pseudonuculana* Pojeta, Zhang and Yang in Pojeta et al., 1986
Nodonychia Pojeta, Zhang and Yang in Pojeta et al., 1986	*Rutonia* Yang, Nie and Wu in Yang et al., 1982b
Oxytomoidea Pojeta, Zhang and Yang in Pojeta et al., 1986	*Wuxuanites* Pojeta, Zhang and Yang in Pojeta et al., 1986
Brachiopoda	
Aequspiriferina Yang and Yin, 1962	*Pseudospiriferina* Yang and Xu, 1966
Chilianshania Yang and Ding, 1962	*Qingyenia* Yang and Xu, 1966
Diholkorhynchia Yang and Xu, 1966	*Rhaetinopsis* Yang and Xu, 1966
Leiolepismatina Yang and Xu, 1966	*Sanqiaothyris* Yang and Xu, 1966
Lissorhynchia Yang and Xu, 1966	*Semibrachythyrina* Yang, 1962
Neocyrtina Yang and Xu, 1966	*Septaliphorioidea* Yang and Xu, 1966
Nudirostralina Yang and Xu, 1966	*Sinorhynchia* Yang and Xu, 1966
Nudispiriferina Yang and Xu, 1966	*Thecocyrtelloidea* Yang and Xu, 1966
Paralepismatina Yang and Xu, 1966	
Trace fossil	
Lachrymatichnus Yang and Yin in Yang et al., 1982a	*Multilaqueichnus* Yang and Yin in Yang et al., 1982a
Microspirolithus Yang and Yin in Yang et al., 1982a	*Parascalaritubus* Yang and Yin in Yang et al., 1982a
New species, subspecies, variety	
Crustacea	
Brachygastriops xinboensis Yang and Hong, 1980	*Xinjiangiops hejiafangensis* Yang and Hong, 1986
Weichangiops rotundus Yang and Hong, 1980	*Xinjiangiops planata* Yang and Hong, 1986
Weichangiops triangularis Yang and Hong, 1980	*Xinjiangiops tongchuanensis* Yang and Hong, 1986
Xinjiangiops discreta Yang and Hong, 1986	
Ophiuroidea	
Ophiaulaxoides aliensis Yang and Nie in Yang et al., 1982b	*Ophioderma schistovertebrata* Yang, 1960
Ophiaulaxoides paraliensis Yang and Nie in Yang et al., 1982b	*Ophiolepis shaanxiensis* Yang, 1979
Gastropoda	
Adiozoptyxis cylindrica Yang and Qian, 1988	*Nerinea parahicoriensis* Yang and Qian, 1988
Adiozoptyxis subcylindrica Yang and Qian, 1988	*Nerinea planohercosa* Yang and Qian, 1988
Fibuloptyxis ngariensis Yang and Qian, 1988	*Paracerithiumpentagonum* Yang and Qian, 1988
Itieria (*Brouzetia*) *ellipsoides* Yang and Qian, 1988	*Pileolus circularis* Yang and Qian, 1988
Itieria (*Brouzetia*) *nodosa* Yang and Qian, 1988	*Tomyris quinqueliratus* Yang and Qian, 1988
Itieria (*Brouzetia*) *ovata* Yang and Qian, 1988	*Trochaliella conica* Yang and Qian, 1988
Lesueurilla pentagonum Yang, 1959	*Tropidodiscus gigas* Yang, 1959
Nerinea paradomaensis Yang and Qian, 1988	

Table 1 Continued

New species, subspecies, variety
Cephalopoda
Belemnopsis dingriensis Yang and Wu, 1964
Belemnopsis extenuatus Yang and Wu, 1964
Belemnopsis sinensis Yang and Wu, 1964
Hibolites jiangziensis Yang and Wu, 1964
Hibolites parahastatus Yang and Wu, 1964
Hibolites xizangensis Yang and Wu, 1964
Bivalvia
Actinodesma (*Ectenodesma*) *guangxiensis* Pojeta, Zhang and Yang in Pojeta et al., 1986
Caneyella? *yujiangensis* Pojeta, Zhang and Yang in Pojeta et al., 1986
Carinonychia triangularis Pojeta, Zhang and Yang in Pojeta et al., 1986
Cinitaria sinensis Pojeta, Zhang and Yang in Pojeta et al., 1986
Dysodonta angulata Pojeta, Zhang and Yang in Pojeta et al., 1986
Goniophora (*Cosmogoniophora*) *marija* Pojeta, Zhang and Yang in Pojeta et al., 1986
Leptodesma (*Leptodesma*) *guangxiensis* Pojeta, Zhang and Yang in Pojeta et al., 1986
Lyriopecten ertangensis Pojeta, Zhang and Yang in Pojeta et al., 1986
Modiomorpha harrisae Pojeta, Zhang and Yang in Pojeta et al., 1986
Nodonychia gordia Pojeta, Zhang and Yang in Pojeta et al., 1986
Nuculana? *acutirostra* Pojeta, Zhang and Yang in Pojeta et al., 1986
Nuculana? *planumbona* Pojeta, Zhang and Yang in Pojeta et al., 1986
Nuculoidea minuta Pojeta, Zhang and Yang in Pojeta et al., 1986
Nuculoidea yongfuensis Pojeta, Zhang and Yang in Pojeta et al., 1986
Nuculopsis gibbosa Yang, 1986
Oxytomoidea elegans Pojeta, Zhang and Yang in Pojeta et al., 1986
Parallelodon guangxiensis Pojeta, Zhang and Yang in Pojeta et al., 1986
Phestioidea obtusa Pojeta, Zhang and Yang in Pojeta et al., 1986
Praeradiolites biconvexus Yang, Nie and Wu in Yang et al., 1982b
Praeradiolites ngariensis Yang, Nie and Wu in Yang et al., 1982b
Pseudonuculana zhaoi Pojeta, Zhang and Yang in Pojeta et al., 1986
Pterinopecten (*Pterinopecten*) *wuxuanensis* Pojeta, Zhang and Yang in Pojeta et al., 1986
Ptychopteria (*Actinopteria*) *producta* Pojeta, Zhang and Yang in Pojeta et al., 1986
Rutonia bangonghuensis Yang, Nie and Wu in Yang et al., 1982b
Sanguinolites nagaolingensis Pojeta, Zhang and Yang in Pojeta et al., 1986
Sedgwickia? *yingtangensis* Pojeta, Zhang and Yang in Pojeta et al., 1986
Spathella hepingensis Pojeta, Zhang and Yang in Pojeta et al., 1986
Sphenotus yingtangensis Pojeta, Zhang and Yang in Pojeta et al., 1986
Tusayana? *liujiangensis* Pojeta, Zhang and Yang in Pojeta et al., 1986
Wuxuanites lanceolatus Pojeta, Zhang and Yang in Pojeta et al., 1986
Wuxuanites washingtonensis Pojeta, Zhang and Yang in Pojeta et al., 1986
Brachiopoda
"*Athyris*" *subquadrata* Yang and Xu, 1966
Athyris sulcata Yang, 1948
Athyris sulcata Yang, 1962
"*Athyris*" *sulcata* Yang and Xu, 1966
Adygella elongata Yang and Xu, 1966
Aequspiriferina extraruga Yang and Yin, 1962
Aequspiriferina multiplicata Yang and Yin, 1962
Aequspiriferina obscura Yang and Yin, 1962
Antiptychina arta Yang and Yin, 1962
Antiptychina oblata Yang and Yin, 1962
Antiptychina pentagona Yang and Yin, 1962
Antiptychina robusta Yang and Yin, 1962
Aulacothyris angustaeformis Yang and Xu, 1966
Aulacothyris opima Yang and Yin, 1962
Buxtonia costato-concentrica Yang and Ding, 1962
Cancrinella depressa Yang and Ding, 1962
Chilianshania chilianshanensis Yang and Ding, 1962
Chonetes semicircularis shihchientanensis Yang, 1948
Chonetes transversa Yang and Fan, 1962
Crurirhynchia subfissicostata Yang and Xu, 1966
Derbyia ickbeechesensis Yang and Zhang, 1962
Dielasma curvatum Yang, 1962
Diholkorhynchia sinensis Yang and Xu, 1966
Eomarginifera crenulata Yang and Ding, 1962
Gigantoproductus geniculatus Yang and Ding, 1962
Isogramma asymmetrica Yang and Ding, 1962
Leiolepismatina semiconula Yang and Xu, 1966
Licharewiella noinhoensis Yang and Zhang, 1962
Licharewiella semireticulata Yang and Zhang, 1962
Mentzelia subspherica Yang and Xu, 1966
Neocyrtina mixodeltidiumosa Yang and Xu, 1966
Neoretzia subcircularis Yang and Xu, 1966
Nudirostralina subtrinodosi Yang and Xu, 1966
Nudirostralina subtrinodosi multicostata Yang and Xu, 1966
Nudispiriferina minima Yang and Xu, 1966
Orthotetina sulcata Yang and Zhang, 1962
Paralepismatina semiconica Yang and Xu, 1966
Pseudospiriferina multicostata Yang and Xu, 1966
Pseudospiriferina pinguis Yang and Xu, 1966
Pseudospiriferina variabilis Yang and Xu, 1966
Qingyenia spinosa Yang and Xu, 1966
Rhaetinopsis ovata Yang and Xu, 1966
Sanqiaothyris elliptica Yang and Xu, 1966
Sanqiaothyris subcircularis Yang and Xu, 1966
Semibrachythyrina fasciculata Yang, 1962
Septaliphoria breviplicata Yang and Yin, 1962
Septaliphoria chuntzehoensis Yang and Yin, 1962
Septaliphoria rhomba Yang and Yin, 1962
Septaliphoria sinensis Yang and Xu, 1966
Septaliphoria tienchungensis Yang and Yin, 1962
Septaliphoria xingyiensis Yang and Xu, 1966
Septaliphorioidea paucicostata Yang and Xu, 1966
Sinorhynchia bifaceta Yang and Xu, 1966
Spirifer yuani Yang, 1948
Spiriferina bifurcata Yang and Yin, 1962
Spiriferina cristata sinkiangensis Yang, 1948
Spiriferina lipoldiformis Yang and Yin, 1962
Spiriferina pauciplicata Yang and Yin, 1962

Table 1 Continued

New species, subspecies, variety
Brachiopoda
Linoproductus elongatus Yang and Ding, 1962
Lissorhynchia pygmaea Yang and Xu, 1966
Lissorhynchia triloba Yang and Xu, 1966
Meekella substriatocostata Yang and Zhang, 1962
Mentzelia multicostata Yang and Xu, 1966
Mentzelia paucicostata Yang and Xu, 1966
Spiriferina tsinghaiensis Yang and Yin, 1962
Streptorhynchus cataclinus Yang and Zhang, 1962
Thecocyrtelloidea tubulosa Yang and Xu, 1966
Urushtenia costata Yang and Ding, 1962
Waagenites convexa Yang and Fan, 1962
Trace fossil
Lachrymatichnus maidipingensis Yang and Yin in Yang et al., 1982a
Microspirolithus tianquanensis Yang and Yin in Yang et al., 1982a
Monomorphichnus gaopoensis Yang and Yin in Yang et al., 1982a
Multilaqueichnus ganluoensis Yang and Yin in Yang et al., 1982a
Parascalaritubus emeiensis Yang and Yin in Yang et al., 1982a
Parascalaritubus gaoqiaoensis Yang and Yin in Yang et al., 1982a
Scolicia maidiyanensis Yang and Yin in Yang et al., 1982a

3 IGCP PROJECTS AND PERMIAN-TRIASSICMASS EXTINCTION

IGCP is financially supported by IUGS and UNESCO and aims to organize all experts who have common interests under one umbrella to target a globally concerned geosciences top. As being well-recorded worldwide, the P-Tr mass extinction and recovery has been one of most popular and targeting topics since this IUGS and UNESCO program was found in 1974. This large international collaborative program offers global experts an opportunity to work together, and each IGCP project promotes to approach the answers for many enigmatic questions related to the P-Tr mass extinction and subsequent recovery. The first P-Tr IGCP project concerned geological evolutions during the P-Tr transition led by Russian paleontologist Dr. D. L. Stepanov (Table 2), and Prof. Yang and his Chinese colleagues have been deeply involved in this project. He also acted as the coordinator of Chinese working group. In 1983, Prof. Yang led the 2nd P-Tr IGCP project (IGCP 203: 1983–1987; Table 2) focusing on P-Tr events recorded in the eastern Tethys region and their global correlations. Yang has also co-led the succeeding IGCP 272 (1988–1992), and been involved in the IGCP 359 (1993–1997). In the past 10 years, we have continued, under the IGCP umbrella (IGCP 572 and 630, led by Chen Z.-Q. and others, 2008–2018), to work on P-Tr ecosystems and their responses to extreme climatic and environmental events. Most of new findings and hypotheses, particularly those from China, are built on the global efforts of the earlier IGCP projects and pioneer works led by Yang and his Chinese colleagues.

Yang's earliest studies were on Triassic paleontology and stratigraphy around the entire China, and these allowed him to pioneer the investigation of topics focusing on biotic changeovers across the Permian-Triassic boundary (PTB). Later, Yang was also the first Chinese scientist who led an IGCP project in China, and became a world-leading expert on biotic macroevolution across the P-Tr boundary and possible cause of the PTB mass extinction. After more than a decade efforts, Yang and his school have investigated nearly 60 PTB sections across the entire South China and adjacent regions (i.e., western Qinglin and southern Qilian regions, northwestern China). These original data and their initiative notions on the P-Tr extinction and subsequent recovery were published in two Chinese books (Fig. 1; Yang et al., 1993, 1987) and two English volumes (Fig. 2; Dickins et al., 1992; Sweet et al., 1992). Most of these works have contributed greatly to our understanding of the greatest dying event on Earth and associated severe devastation. In particular, the original data derived from these South Chinese sections are a great treasure for the P-Tr studies and we are still mining these data today.

Of the great achievements that Yang and his school have made after their 1–2 decades' efforts, the following three aspects are notable: (1) establishing highest-resolution biozones across the PTB in the world and finding the most continuous PTB succession in South China; (2) recognition of three episodes of

Table 2 List of all IGCP projects working on the Permian-Triassic transition (some data are after Dong and Yang, 2004)

Project No.	Short title	Leading expert	Project period
IGCP 106	Geological evolutions during the Permian-Triassic transition	D. L. Stepanov	1976–1985
IGCP 203	Permian-Triassic events of eastern Tethys region and intercontinental correlations	Z. Y. Yang	1983–1987
IGCP 272	Late Paleozoic and Early Mesozoic Circum-Pacific Events and Their Global Correlation	J. M. Dickins	1988–1992
IGCP 359	Permian and Triassic correlations cross the Tethys, Circum-Pacific, and Marginal Gondwana	H. F. Yin	1993–1997
IGCP 335	Biotic recoveriesfrom mass extinctions	D. H. Erwin	1998–2002
IGCP 467	Triassic Time and trans-Panthalassan Correlation	M. J. Orchard	2002–2006
IGCP 572	Permian-Triassic ecosystems	Z.-Q. Chen	2008–2013
IGCP 630	Permian-Triassic climatic and environmental extremes, and biotic responses	Z.-Q. Chen	2014–2018

Figure 1. Two Chinese monographs focusing on the Permian-Triassic boundary and biotas and P-Tr environmental and biotic events from South China, respectively written by Z. Y. Yang and coauthors in 1987 and 1993.

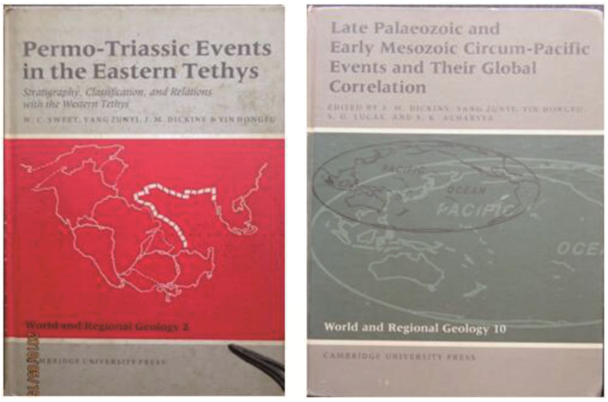

Figure 2. Two English special volumes focusing on the Permian-Triassic stratigraphy, paleontology and geological events from eastern Tethys region and Circum-Pacific regions, respectively collecting research results derived from IGCP 230 and 272 (published by Cambridge University Press in 1992).

biotic death, rather than mono-episode extinction across the PTB, and (3) findings of the widely traceable boundary event clay bed across South China and the notion that volcanism, rather than extraterrestrial impact, may be responsible for biotic mortality in the end of the Permian. The first works (Yin et al., 1996; Yang et al., 1995) are the basis for the later success in ratifying the GSSP of the PTB in the Meishan Section, Changxing County, Zhejiang Province (Yin et al., 2001). The huge amount of the first-hand paleontological and sedimentary data obtained by Yang and his school also allow the recognition of pattern and possible causes of the P-Tr mass extinction in South China. Clearly, the discordant views on the latter two topics still exist, and the debates also continue (see below). However, it is Yang's original data and initiative notions that sparked our current studies and new models.

4 EXTINCTION PATTERNS AND VOLCANISMS

4.1 Three-Phases Extinction Pattern over the P-Tr Transition

The 'abruptness' of the end-Permian mass extinction was highly expected in the 1990s, and later confirmed by the influential paper by Jin et al. (2000). Most studies of the past decades have also considered that the P-Tr mass extinction happened in a relatively much shorter time than other extinctions in term of a geological time scale. However, whether a mono-episode or multi-phase extinction pattern has been extensively debated since early 1990s, and the debate shows no sign of stop. Compiling fossil records from tens of sections, Yang et al. (1993) recognized three episodes of extinction across the PTB in South China. The first extinction is calibrated to the contact between Bed 24d and Bed 24e, and the 2nd and 3rd to the bases of Bed 25 and Bed 28, respectively in the Meishan Section (Fig. 3). It seems a rather non-controversial claim that Yang school's 2nd extinction is the main extinction phase, which is widely accepted by most authors. Later local observations on Meishan Section suggested that the 2nd and 3rd phases of the P-Tr crisis indeed represent two separate extinction events straddling the Permian-Triassic boundary (Chen et al., 2009, 2006, 2005; Song et al., 2009; Yin et al., 2007a, b, 1996; Wignall and Hallam, 1993).

In contrast, after compiling fossil records from a large number of sections from South China, Shen et al. (2011) and Wang et al. (2014) statistically determine the most likely extinction horizon at the base of Bed 25 in Meishan, and thus concluded that the 2nd and 3rd phases of the crisis (or Beds 25–28) represent one single extinction event, with mass extinction starting at the base of Bed 25 and ending in the base of Bed 28. Similarly, Song et al. (2013) also undertook statistic analysis on fossil records from seven well-studied PTB sections in South China and found the P-Tr crisis comprised of two independent extinction events, corresponding to the 2nd and 3rd phases of Yang et al. (1993), respectively. The existence of these two events is also reinforced by ecologic assessments in Meishan (Chen et al., 2015, 2010). Level bottom community structural measures such as Shannon index, dominance, and evenness, all show much severer collapses between Bed 27 and Bed 29 (2nd extinction) than the same proxies across Beds 24–25 boundary (1st extinction) in Meishan (Chen et al., 2010). It is also true that both fossil fragment variations and ichnoecologic measures of ichnofossil assemblages, i.e., ichnodiversity, burrow size, tiering level, and bioturbation levels demonstrate similar pattern to level-bottom communities (Chen et al., 2015). Accordingly, although the notion of the two-phase P-Tr extinction is still contentious, it is clear that the 1st or main extinction (base of Bed 25 in Meishan) is marked by dramatic depletion in biodiversity (Wang et al., 2014; Song et al., 2013; Shen et al., 2011; Jin et al., 2000), and the 2nd extinction associated with Bed 28 is characterized by ecologic collapse of ecosystem (Chen et al., 2015). Thus, the Meishan case indicates that a great biodiversity decline followed by ecosystem's collapse characterizes a major mass extinction event (Chen et al., 2015).

To add new argument for the existence of the 2nd extinction near the PTB (Song et al., 2013; Fig. 3), we found that the microbialite ecosystem structure collapsed during this crisis. In South China, most PTB microbialites disappeared across the boundary between conodont *Isarcicella staeschei* and *I. isarcica* zones (Kershaw et al., 2012; Yang et al., 2011), which coincides with the 2nd extinction calibrated to Bed 28 in Meishan.

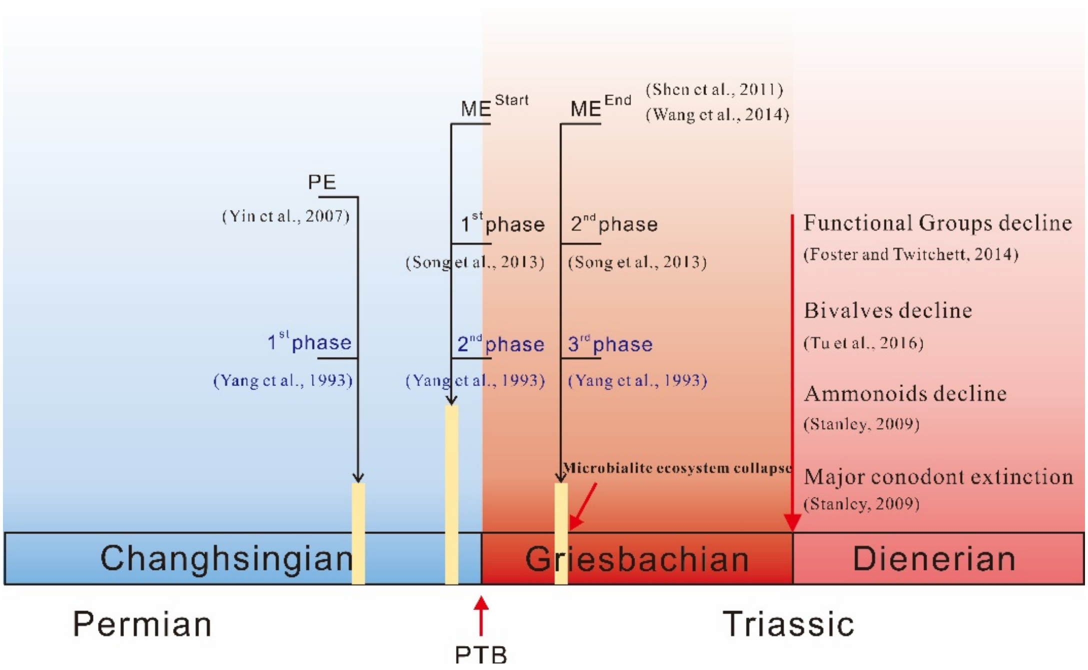

Figure 3. Synthesis of multiple biotic events over the P-Tr transition recorded in South China. PE. Prelude extinction, ME. mass extinction.

Recent studies reveal that the PTB microbialites yield much more abundant and diverse metazoans than previous thought (Foster et al., 2018; Wu et al., 2017; Forel, 2015, 2014; Yang et al., 2015a, b, 2011; Forel et al., 2012). Most metazoans, particularly ostracodes, were extinct after disappearance of the PTB microbialites (Forel, 2015). Moreover, the key components of microbes, i.e., *Gukhumella* and *Renalcis*, characterizing the PTB microbialites never re-occur in the younger Triassic microbialites (Pei et al., 2018; Fang et al., 2017; Wu et al., 2017; Chen and Benton, 2012). Accordingly, microbialite faunas suffered a big loss, and ecosystem compositions and structures underwent major changes during the 2nd extinction in South China (Song et al., 2013).

In addition, new radiometric dates suggest the 60-ka duration for the 1st to 2nd extinction interval (Burgess et al., 2014), which means that the P-Tr mass extinction may have taken place within 60 ka. However, if these two separate extinction events did exist, then each crisis should happen probably only a few thousands of years at most (e.g., Chen et al., 2015; Kaiho et al., 2006).

Compared with those two phases of extinction, the 1st phase crisis of Yang et al. (1993) is more controversial. Yang et al. (1993) calibrated this event to the base of Bed 24e in Meishan, and Yin et al. (2007a, b) also emphasized biotic changes across the Bed 24d–24e boundary. This event, however, was neither demonstrated in statistic analysis of fossil distribution data (Wang et al., 2014; Song et al., 2013, 2009; Shen et al., 2011; Jin et al., 2000) nor reflected in high-resolution fossil fragment assemblage variations (Chen et al., 2015). Nevertheless, it is also true that numerous faunas, including corals, deep-water radiolarians, most fusulinids, and pseudotirolitid ammonoids, and many Permian brachiopods, disappeared prior to the main extinction event in South China (Yin et al., 2007a).

In particular, the well-studied deep-water facies sections (i.e., the Dongpan Section in Guangxi Province, South China) displays clearly that the extinction of radiolarians occurred much earlier than the main extinction (Yin et al., 2007a, b). Similarly, the Changhsingian witnessed the great proliferation of metazoan reefs in South China where at least 15 reefs have been reported (Chen et al., unpublished data), but none of them persist into the main extinction horizon. Instead, they mostly disappeared 1–10 m below the PTB. This means that the latest Permian reef ecosystem collapsed prior to the main extinction event in South China. Thus, this prelude extinction (PE; Yin et al., 2007a; Fig. 3) seems to be characterized by a small to moderate loss of biodiversity and collapses of both deep-water and shallow marine reef ecosystems. However, it is challenge that these biotic events are precisely dated and correlated with one and other, and the PE is anchored to the certain horizon in outcrop sections such as GSSP Meishan. The high-resolution chemo- and magneto-stratigraphy is recommended for the further studies to enable a precise correlation and calibration.

Another major crisis interval is the Griesbachian-Dienerian boundary, which saw major declines of global biodiversity of several clades, such as ammonoids (Stanley, 2009), conodonts (Stanley, 2009), and bivalves (Tu et al., 2016). Global data of functional groups also experienced major decline across this substage boundary (Foster and Twitchett, 2014). Again, it is not easy to calibrate the crisis horizon to a certain horizon at outcrop section.

5.2 Volcanisms and Mass Extinction

The linkage between volcanism and biotic extinction is another important contribution of Yang's school to searching the potential triggers and killers for the P-Tr mass extinction in South China. Yang et al. (1993) documented volcanic ash beds around the PTB in almost all the 50 investigated sections in South China. In particular, the so-called boundary clay bed is traceable 1000 km across the entire South China, and it is associated with biotic extinction in all sections. Thus, they considered that massive volcanisms have resulted in the mass extinction in the end of the Permian (Yang et al., 1993; Yin et al., 1992), counter to the extraterrestrial impact hypothesis (i.e., Kaiho et al., 2001; but see Tohver et al., 2018). However, what they were unsure is whether the widely distributed volcanic ash layers in South China linked to the eruption of Siberian Traps Large Igneous Province (STLIP), and the Siberian traps were also collectively considered as the P-Tr volcanisms that accounted for the biocrisis in that time (Yang et al., 1993).

Recent geochemical data from the ash horizons and sedimentary layers that span the PTB in South China (Fig. 4), including low Nb/Hf and high Th/Nb ratios of zircons, indicate derivation from silicic, subduction-related igneous activity with little or no basaltic input (Wang et al., 2018b; Gao et al., 2015, 2013). This subduction zone activity is related to closure of the Paleo-Tethys Ocean, and the intensity and frequency of the volcanic activity appear to increase near the P-Tr mass extinction interval (Fig. 4; Wang et al., 2018b); for example, three eruptions in Shangsi and Meishan sections, respectively and 5 eruptions in the Daxiakou Section in the P-Tr extinction interval. Volcanic ashes near the PTB cover an area of >1 000 000 km^2 in South China, and an area equivalent to the Siberia Traps (Yin et al., 1992). Furthermore, the subduction-related silicic igneous activity at this time extends beyond the Paleo-Tethys and is widespread around the margins of Pangea, including the 18 000 km long Terra Australis orogen extending from northeastern Australia to northwestern South America (Gao et al., 2015, 2013; Cawood, 2005). Ash beds near the biotic extinction horizoncontain zircons with positive $\varepsilon_{\mathrm{Hf}}(t)$ values indicating input of juvenile mantle with limited interaction between magma and crust, implying rapid transit through the crust (Wang et al., 2018b; Gao et al., 2015, 2013; He et al., 2014). Furthermore, felsic subduction-related volcanism is inherently more violent and explosive than mafic dominated LIP activity due to its higher volatile content, and thus more likely to result in input of gases and particles to the stratosphere resulting in their global distribution (Wang et al., 2018b).

In contrast, LIP eruption never generates such a huge amount of ashes. These P-Tr volcanic ashes were not the products of the Siberian LIP. Instead, both Eu/Eu signals imprinted in conodont bioapatites (i.e., Zhao et al., 2013) and mercury anomalies recorded in the sedimentary strata (Wang et al., 2018a; Grasby et al., 2017) can reflect the signals of the volatile eruption of the Siberian LIP. For instance, Wang et al. (2018a) detected that a pronounced positive Hg/TOC excursion coincides with the extinction interval (Fig. 4). The positive shifts are far greater than modern ocean sediments (maximum value of Hg/TOC ~0.08 innormal sediments of Kagoshima Bay, Japan, Gamboa Ruiz and Tomiyasu, 2015), and highly contaminated sediments from San Francisco Bay (0.2 ppm/wt.%, Conaway et al., 2003). Hg anomalies across the PTB interval therefore were caused by enhanced volcanic generated atmospheric mercury. The limitation of elevated Hg/TOC levels to the P-Tr extinction, yet the presence of felsic ash layers above and below as well as within the extinction interval (Fig. 4) suggest that the South China felsic volcanism was not the cause of the Hg/TOC anomalies. This interpretation is also strengthened by evidence that aquatic sediments do not reliably archive short-term Hg releases associated with sporadic large explosive eruptions (Thibodeau et al., 2016).

Recent high precision geochronology reveals that the sill emplacement of Siberian traps is coeval with biotic extinction in Meishan (Burgess et al., 2017; Burgess and Bowring, 2015). Thus, the PTB Hg anomaly is coeval with sill emplacement of Siberian traps (Wang et al., 2018a). The eruption of the SLIP may have injected a huge amount of Hg, together with CO_2, which lead to loading of the aquatic system to generate the "excess Hg" contents over the extension interval. This would

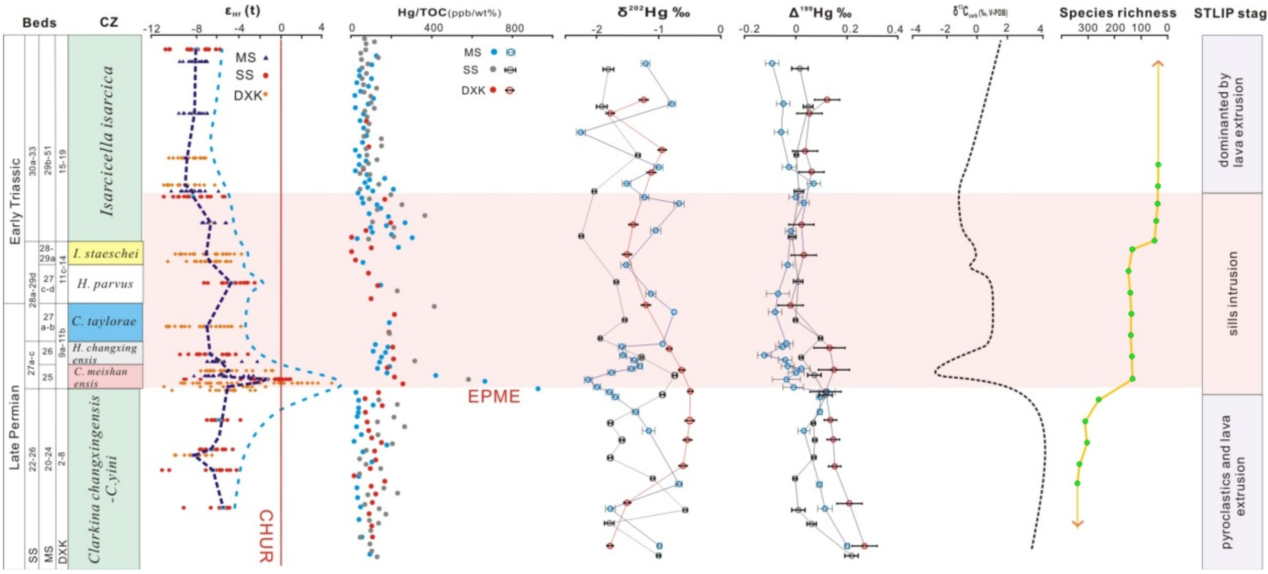

Figure 4. Integrated excursions of zircon Hf isotopes, Hg/TOC ratios, Hg isotopes, $\delta^{13}C$ values, species richness variations, and STLIP stages across the P-Tr interval. MS. Meishan Section, SS. Shangsi Section, DXK. Daxiakou Section. All data of Hf isotopes, Hg/TOC ratios, Hg isotopes are after Wang et al. (2018a, b); Hg isotope compositions of Meishan from Grasby et al. (2017); species richness data from Song et al. (2013); STLIP stage subdivision after Burgess and Bowring (2015) and Burgess et al. (2017).

result in the dramatic build-up of dissolved Hg in ocean water, leading potentially to widespread ocean toxicity (Sanei et al., 2015). The coupled relationship between Hg/TOC and species richness suggests a causal relationship. In summary, the overlap in time of the felsic volcanism, which was associated with subduction zone magmatism, with the Siberian Traps and the peak in felsic activity at this time, likely enhancing the global environmental burden resulting in the P-Tr mass extinction.

6 CONCLUDSIONS

Yang and his collaborators established 129 new species and 29 new genera of six fossil groups as well 3 new ichnogenera and 7 new ichnospecies of trace fossils. Yang is the first expert leading an IGCP project in China and also led the 2nd IGCP working on the P-Tr mass extinction. His group's excellent works on basic stratigraphy and paleontology enable the GSSP of PTB to be ratified in the Meishan Section, South China. Yang's earlier works on multi-episode extinction patterns and volcanism-causing extinction hypothesis are also highlighted here to show how their first-hand data and initiative hypothesis have influenced the current and ongoing debates on the P-Tr mass extinction and possible causation. Updated review shows that a dramatic loss in biodiversity characterizes Yang's 2nd phase of extinction (also termed main extinction), equating the widely accepted mass extinction. The 3rd extinction is marked by ecosystem ecological collapse and disappearance of the PTB microbialite ecosystem, while the 1st extinction (also prelude extinction) is indicated by the collapses of deep-water and reef ecosystems. Updated studies show that the volcanic ashes near the PTB originated from silicic, subduction-related igneous activity with little or no basaltic input. This subduction zone activity is related to closure of the Paleo-Tethys Ocean, and the intensity and frequency of the volcanic activity appear to increase near the P-Tr mass extinction interval. Hg anomalies (Hg/TOC ratios and Hg isotopes) are also detected from the P-Tr extinction interval, and they are interpreted as the results of enhanced volcanic generated atmospheric mercury. The latter was injected by the violate eruption of the Siberian traps. Thus, both violate eruptions of felsic volcanism and Siberian traps may have resulted in biotic morality during the P-Tr great dying.

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REFERENCES CITED

Aljinović, D., Horacek, M., Krystyn, L., et al., 2018. Western Tethyan Epeiric Ramp Setting in the Early Triassic: An Example from the Central Dinarides (Croatia). *Journal of Earth Science*, 29(3): 806–823. https://doi.org/10.1007/s12583-018-0787-3

Baud, A., 2018. Final Results and Recommendations of the Last 10 Years IGCP 572 and 630 Field Workshops in South Turkey, Oman, India (Kashmir) and Armenia. *Journal of Earth Science*, 29(4): 733–744. https://doi.org/10.1007/s12583-018-0796-2

Burgess, S. D., Bowring, S. A., 2015. High-Precision Geochronology Confirms Voluminous Magmatism before, during, and after Earth's most Severe Extinction. *Science Advances*, 1(7): e1500470–e1500470. https://doi.org/10.1126/sciadv.1500470

Burgess, S. D., Bowring, S. A., Shen, S. Z., 2014. High-Precision Timeline for Earth's most Severe Extinction. *Proceedings of the National Academy of Sciences, USA*, 111(9): 3316–3321. https://doi.org/10.1073/pnas.1317692111

Burgess, S. D., Muirhead, J. D., Bowring, S. A., 2017. Initial Pulse of Siberian Traps Sills as the Trigger of the End-Permian Mass Extinction. *Nature Communications*, 8(1): 164e. https://doi.org/10.1038/s41467-017-00083-9

Cawood, P. A., 2005. Terra Australis Orogen: Rodinia Breakup and Development of the Pacific and Iapetus Margins of Gondwana during the Neoproterozoic and Paleozoic. *Earth-Science Reviews*, 69(3/4): 249–279. https://doi.org/10.1016/j.earscirev.2004.09.001

Chang, S., Feng, Q. L., Zhang, L., 2018. New Siliceous Microfossils from the Terreneuvian (Cambrian) Yanjiahe Formation, South China: The Possible Earliest Radiolarian Fossil Record. *Journal of Earth Science*, 29(4): 912–919. https://doi.org/10.1007/s12583-017-0960-0

Chen, Z. Q., Yang, H., Luo, M., et al., 2015. Complete Biotic and Sedimentary Records of the Permian-Triassic Transition from Meishan Section, South China: Ecologically Assessing Mass Extinction and Its Aftermath. *Earth-Science Reviews*, 149: 67–107. https://doi.org/10.13039/501100002338

Chen, Z.-Q., Benton, M. J., 2012. The Timing and Pattern of Biotic Recovery Following the End-Permian Mass Extinction. *Nature Geoscience*, 5(6): 375–383. https://doi.org/10.1038/ngeo1475

Chen, Z.-Q., Kaiho, K., George, A. D., 2005. Survival Strategies of Brachiopod Faunas from the End-Permian Mass Extinction. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 224(1/2/3): 232–269. https://doi.org/10.1016/j.palaeo.2005.04.014

Chen, Z.-Q., Kaiho, K., George, A. D., et al., 2006. Survival Brachiopod Faunas of the End-Permian Mass Extinction from the Southern Alps (Italy) and South China. *Geological Magazine*, 143(3): 301–327. https://doi.org/10.1017/s0016756806001993

Chen, Z.-Q., Tong, J. N., Liao, Z. T., et al., 2010. Structural Changes of Marine Communities over the Permian-Triassic Transition: Ecologically Assessing the End-Permian Mass Extinction and Its Aftermath. *Global and Planetary Change*, 73(1/2): 123–140. https://doi.org/10.1016/j.gloplacha.2010.03.011

Chen, Z.-Q., Tong, J. N., Zhang, K. X., et al., 2009. Environmental and Biotic Turnover Across the Permian-Triassic Boundary on a Shallow Carbonate Platform in Western Zhejiang, South China. *Australian Journal of Earth Sciences*, 56(6): 775–797. https://doi.org/10.1080/08120090903002607

Conaway, C. H., Squire, S., Mason, R. P., et al., 2003. Mercury Speciation in the San Francisco Bay Estuary. *Marine Chemistry*, 80(2/3): 199–225. https://doi.org/10.1016/s0304-4203(02)00135-4

Dey, J., Sen, S., 2018. Sequence Stratigraphic Model of Middle Permian Barakar Formation from a Marginal Gondwana Basin, India. *Journal of Earth Science*, 29(4): 745–754. https://doi.org/10.1007/s12583-018-0791-7

Dickins, M. J., Yang, Z. Y., Yin, H. F., et al., eds., 1992. Late Palaeozoic and Early Mesozoic Circum-Pacific Events and Their Global Correlation. World and Regional Geology 10. Cambridge University Press, Cambridge

Dong, S. W., Yang, Z. Y., 2004. Three Decades of IGCP in China. *Episodes*, 27(1): 56–58

Fang, Y. H., Chen, Z.-Q., Kershaw, S., et al., 2017. Permian-Triassic Boundary Microbialites at Zuodeng Section, Guangxi Province, South China: Geobiology and Palaeoceanographic Implications. *Global and Planetary Change*, 152: 115–128. https://doi.org/10.13039/501100001809

Forel, M. B., 2014. Heterochronic Growth of Ostracods (Crustacea) from Microbial Deposits in the Aftermath of the End-Permian Extinction. *Journal of Systematic Palaeontology*, 13(4): 315–349. https://doi.org/10.1080/14772019.2014.902400

Forel, M. B., 2015. Heterochronic Growth of Ostracods (Crustacea) from Microbial Deposits in the Aftermath of the End-Permian Extinction. *Journal of Systematic Palaeontology*, 13(4): 315–349. https://doi.org/10.1080/14772019.2014.902400

Forel, M. B., Crasquin, S., Kershaw, S., et al., 2012. In the Aftermath of the End-Permian Extinction: The Microbialite Refuge?. *Terra Nova*, 25(2): 137–143. https://doi.org/10.1111/ter.12017

Foster, W. J., Lehrmann, D. J., Yu, M., et al., 2018. Persistent Environmental Stress Delayed the Recovery of Marine Communities in the Aftermath of the Latest Permian Mass Extinction. *Paleoceanography and Paleoclimatology*, 33(4): 338–353. https://doi.org/10.1002/2018pa003328

Foster, W. J., Twitchett, R. J., 2014. Functional Diversity of Marine Ecosystems after the Late Permian Mass Extinction Event. *Nature Geoscience*, 7(3): 233–238. https://doi.org/10.1038/ngeo2079

Gamboa Ruiz, W. L., Tomiyasu, T., 2015. Distribution of Mercury in Sediments from Kagoshima Bay, Japan, and its Relationship with Physical and Chemical Factors. *Environmental Earth Sciences*, 74(2): 1175–1188. https://doi.org/10.1007/s12665-015-4104-5

Gao, Q. L., Chen, Z. Q., Zhang, N., et al., 2015. Ages, Trace Elements and Hf-Isotopic Compositions of Zircons from Claystones around the Permian-Triassic Boundary in the Zunyi Section, South China: Implications for Nature and Tectonic Setting of the Volcanism. *Journal of Earth Science*, 26(6): 872–882. https://doi.org/10.1007/s12583-015-0589-9

Gao, Q. L., Zhang, N., Xia, W. C., et al., 2013. Origin of Volcanic Ash Beds across the Permian-Triassic Boundary, Daxiakou, South China: Petrology and U-Pb Age, Trace Elements and Hf-Isotope Composition of Zircon. *Chemical Geology*, 360/361: 41–53. https://doi.org/10.1016/j.chemgeo.2013.09.020

Grasby, S. E., Shen, W. J., Yin, R. S., et al., 2017. Isotopic Signatures of Mercury Contamination in Latest Permian Oceans. *Geology*, 45(1): 55–58. https://doi.org/10.1130/g38487.1

He, B., Zhong, Y. T., Xu, Y. G., et al., 2014. Triggers of Permo-Triassic Boundary Mass Extinction in South China: The Siberian Traps or Paleo-Tethys Ignimbrite Flare-Up?. *Lithos*, 204: 258–267. https://doi.org/10.13039/501100001809

Huang, Y. F., Tong, J. N., Fraiser, M. L., 2018. A Griesbachian (Early Triassic) Mollusc Fauna from the Sidazhai Section, Southwest China, with Paleoecological Insights on the Proliferation of Genus Claraia (Bivalvia). *Journal of Earth Science*, 29(3): 794–805. https://doi.org/10.1007/s12583-017-0966-7

Jin, Y. G., Wang, Y., Wang, W., et al., 2000. Pattern of Marine Mass Extinction near the Permian-Triassic Boundary in South China. *Science*, 289(5478): 432–436. https://doi.org/10.1126/science.289.5478.432

Kaiho, K., Chen, Z. Q., Kawahata, H., et al., 2006. Close-up of the End-Permian Mass Extinction Horizon Recorded in the Meishan Section, South China: Sedimentary, Elemental, and Biotic Characterization and a Negative Shift of Sulfate Sulfur Isotope Ratio. *Palaeogeography*, *Palaeoclimatology*, *Palaeoecology*, 239(3/4): 396–405. https://doi.org/10.1016/j.palaeo.2006.02.011

Kaiho, K., Kajiwara, Y., Nakano, T., et al., 2001. End-Permian Catastrophe by a Bolide Impact: Evidence of a Gigantic Release of Sulfur from the Mantle. *Geology*, 29(9): 815–818. https://doi.org/10.1130/0091-7613(2001)029<0815:epcbab>2.0.co;2

Kershaw, S., Crasquin, S., Li, Y., et al., 2012. Microbialites and Global Environmental Change Across the Permian-Triassic Boundary: A Synthesis. *Geobiology*, 10(1): 25–47. https://doi.org/10.1111/j.1472-4669.2011.00302.x

Lucas, S. G., 2018. Permian-Triassic Charophytes: Distribution, Biostratigraphy and Biotic Events. *Journal of Earth Science*, 29(4): 778–793. https://doi.org/10.1007/s12583-018-0786-4

Luo, M., Gong, Y.-M., Shi, G. R., et al., 2018. Palaeoecological Analysis of Trace Fossil *Sinusichnus sinuosus* from the Middle Triassic Guanling Formationin Southwestern China. *Journal of Earth Science*, 29(4): 854–863. https://doi.org/10.1007/s12583-018-0794-4

Lyu, Z. Y., Orchard, M. J., Chen, Z.-Q., et al., 2018. A Taxonomic Re-Assessment of the *Novispathodus waageni* Group and Its Role in Defining the Base of the Olenekian (Lower Triassic). *Journal of Earth Science*, 29(4): 824–836. https://doi.org/10.1007/s12583-018-0795-3

Nowak, H., Schneebeli-Hermann, E., Kustatscher, E., 2018. Correlation of Lopingian to Middle Triassic Palynozones. *Journal of Earth Science*, 29(4): 755–777. https://doi.org/10.1007/s12583-018-0790-8

Pei, Y., Chen, Z. Q., Fang, Y. H., et al., 2018. Volcanism, Redox Conditions, and Microbialite Growth Linked with the End-Permian Mass Extinction: Evidence from the Xiajiacao Section (western Hubei Province), South China. *Palaeogeography*, *Palaeoclimatology*, *Palaeoecology*. https://doi.org/10.13039/501100001809

Pojeta, J., Zhang, R. J., Yang, Z. Y., 1986. Systematic Paleontology of Devonian Pelecypods of Guangxi and Michigan. *Professional Paper of the United States Geological Survey*, 1394: 57–108.

Sanei, H., Grasby, S. E., Beauchamp, B., 2015. Contaminants in Marine Sedimentary Deposits from Coal Fly Ash during the Latest Permian Extinction. *Environmental Contaminants*, *Developments in Paleoenvironmental Research* I, 18: 89–99

Shen, S. Z., Crowley, J. L., Wang, Y., et al., 2011. Calibrating the End-Permian Mass Extinction. *Science*, 334(6061): 1367–1372. https://doi.org/10.1126/science.1213454

Smirčić, D., Kolar-Jurkovšek, T., Aljinović, D., et al., 2018. Stratigraphic Definition and Correlation of Middle Triassic Volcaniclastic Facies in the External Dinarides: Croatia and Bosnia and Herzegovina. *Journal of Earth Science*, 29(4): 864–878. https://doi.org/10.1007/s12583-018-0789-1

Song, H. J., Wignall, P. B., Tong, J. N., et al., 2013. Two Pulses of Extinction during the Permian-Triassic Crisis. *Nature Geoscience*, 6(1): 52–56. https://doi.org/10.1038/ngeo1649

Song, H., Tong, J., Chen, Z.-Q., 2009. Two Episodes of Foraminiferal

Extinction near the Permian-Triassic Boundary at the Meishan Section, South China. *Australian Journal of Earth Sciences*, 56(6): 765–773. https://doi.org/10.1080/08120090903002599

Stanley, G. D. Jr., 2018. Paleoecological Response of Corals to the End-Triassic Mass Extinction: An Integrational Analysis. *Journal of Earth Science*, 29(4): 879–885. https://doi.org/10.1007/s12583-018-0793-5

Stanley, S. M., 2009. Evidence from Ammonoids and Conodonts for Multiple Early Triassic Mass Extinctions. *Proceedings of the National Academy of Sciences*, *USA*, 106(36): 15264–15267. https://doi.org/10.1073/pnas.0907992106

Sweet, W. C., Yang, Z. Y., Dickins, J. M., Yin, H. F., eds., 1992. Permo-Triassic Events in the Eastern Tethys: Stratigraphy Classification and Relations with the Western Tethys. World and Regional Geology 2. Cambridge University Press, Cambridge

Thibodeau, A. M., Ritterbush, K., Yager, J. A., et al., 2016. Mercury Anomalies and the Timing of Biotic Recovery Following the End-Triassic Mass Extinction. *Nature Communications*, 7: 11147e. https://doi.org/10.1038/ncomms11147

Tohver, E., Schmieder, M., Lana, C., et al., 2018. End-Permian Impactogenic Earthquake and Tsunami Deposits in the Intracratonic Paraná Basin of Brazil. *GSA Bulletin*, 130(7/8): 1099–1120. https://doi.org/10.1130/b31626.1

Tu, C. Y., Chen, Z.-Q., Harper, D. A. T., 2016. Permian-Triassic Evolution of the Bivalvia: Extinction-Recovery Patterns Linked to Ecologic and Taxonomic Selectivity. *Palaeogeography*, *Palaeoclimatology*, *Palaeoecology*, 459: 53–62. https://doi.org/10.13039/501100002338

Wang, X. D., Cawood, P. A., Zhao, H., et al., 2018a. Mercury Anomalies across the End Permian Mass Extinction in South China from Shallow and Deep Water Depositional Environments. *Earth and Planetary Science Letters*, 496: 159–167. https://doi.org/10.13039/501100001809

Wang, X. D., Cawood, P. A., Zhao, L. S., et al., 2018b. Convergent Continental Margin Volcanic Source for Ash Beds at the Permian-Triassic Boundary, South China: Constraints from Trace Elements and Hf-Isotopes. *Palaeogeography*, *Palaeoclimatology*, *Palaeoecology*. https://doi.org/10.13039/501100001809

Wang, Y., Sadler, P. M., Shen, S. Z., et al., 2014. Quantifying the Process and Abruptness of the End-Permian Mass Extinction. *Paleobiology*, 40(1): 113–129. https://doi.org/10.1666/13022

Wignall, P. B., Hallam, A., 1993. Griesbachian (Earliest Triassic) Palaeoenvironmental Changes in the Salt Range, Pakistan and Southeast China and their Bearing on the Permo-Triassic Mass Extinction. *Palaeogeography*, *Palaeoclimatology*, *Palaeoecology*, 102(3/4): 215–237. https://doi.org/10.1016/0031-0182(93)90068-t

Wu, S. Q., Chen, Z.-Q., Fang, Y. H., et al., 2017. A Permian-Triassic Boundary Microbialite Deposit from the Eastern Yangtze Platform (Jiangxi Province, South China): Geobiologic Features, Ecosystem Composition and Redox Conditions. *Palaeogeography*, *Palaeoclimatology*, *Palaeoecology*, 486: 58–73. https://doi.org/10.13039/501100001809

Yang, H., Chen, Z.-Q., Ou, W. Q., 2015a. Microconchids from Microbialites near the Permian-Triassic Boundary in the Zuodeng Section, Baise Area, Guangxi Zhuang Autonomous Region, South China and Their Paleoenvironmental Implications. *Journal of Earth Science*, 26(2): 157–165. https://doi.org/10.1007/s12583-015-0554-7

Yang, H., Chen, Z.-Q., Wang, Y. B., et al., 2015b. Palaeoecology of Microconchids from Microbialites near the Permian-Triassic Boundary in South China. *Lethaia*, 48(4): 497–508. https://doi.org/10.1111/let.12122

Yang, H., Chen, Z.-Q., Wang, Y. B., et al., 2011. Composition and Structure of Microbialite Ecosystems Following the End-Permian Mass Extinction in South China. *Palaeogeography*, *Palaeoclimatology*, *Palaeoecology*, 308(1/2): 111–128. https://doi.org/10.1016/j.palaeo.2010.05.029

Yang, Z. Y., 1948. Permo-Carboniferous Brachiopods of Shihchientan Formation, Shihchientan, Northeastern Sinkiang. *Science Reports of the National Tsinghua University*, *Series C*: *Geological*, *Geographical and Meteorological Sciences*, 1: 196–214

Yang, Z. Y., 1959. Middle Ordovician Mulluscs from the Paiyangho Region, Chilienshan ("Nanshan"). *Acta Palaeontologica Sinica*, 7: 484–498

Yang, Z. Y., 1960. On the Discovery of a Scythic Ophiuroid from Kueichou, China. *Acta Palaeontologica Sinica*, 8: 159–163

Yang, Z. Y., Ding, P. Z., Yin, H. F., et al., 1962. The Brachiopod Fauna of Carboniferous, Permian and Triassic in the Qilianshan Region. In: Institute of Geology and Palaeontology, Chinese Academy of Sciences, Institute of Geology, et al., eds., Monograph on the Geology of the Qilian Mountains, 4(4). Science Press, Beijing. 1–134

Yang, Z. Y., Hong, Y. C., 1980. Discovery of Fresh-Water Triopsids from the Upper Jurassic Dabeigou Formation of Weichang, Hebei, China and Its Bearing on the Classification of the Family Triopsidae Martalent. *Acta Palaeontologica Sinica*, 19: 91–98

Yang, Z. Y., Hong, Y. C., 1986. Fossil Fresh-Water Triopsids, a New Family Xinjiangiopsidae Fam. Nov.. *Bulletin of the Chinese Academy of Geological Sciences*, 12: 85–91

Yang, Z. Y., Nie, Z. T., 1982. New Jurassic Ophiuroids from the Ngari Area of Xizang (Tibet), China. *Acta Palaeontologica Sinica*, 21: 83–86

Yang, Z. Y., Qian, J. X., 1988. Fossil Gastropods from Ngari, Xizang (Tibet). *Earth Science-Journal of China University of Geosciences*, 13: 457–471

Yang, Z. Y., Sheng, J. Z., Yin, H. F., 1995. The Permian-Triassic Boundary—The Global Stratotype Section and Point (GSSP). *Episodes*, 18(1/2): 49–53

Yang, Z. Y., Wu, S. B., 1964. Late Jurassic-Early Cretaceous Belemnites from Southern Tibet, China. *Acta Palaeontologica Sinica*, 12: 187–216

Yang, Z. Y., Wu, S. B., Yin, H. F., et al., 1993. Permo-Triassic Events of South China. Geological Publishing House, Beijing. 1–153

Yang, Z. Y., Xu, G. R., 1966. Triassic Brachiopods of Central Gueizhou (Kueichow) Province, China. China Industry Publishing House, Beijing. 151

Yang, Z. Y., Yin, H. F., Lin, H. M., 1979. Marine Triassic Faunas from Shihchienfeng Group in the Northern Weihe River Basin, Shannxi Province. *Acta Palaeontologica Sinica*, 18: 465–474

Yang, Z. Y., Yin, H. F., Wu, S. B., et al., 1987. Permian-Triassic Boundary Stratigraphy and Fauna of South China. Geological Publishing House, Beijing. 1–379

Yang, Z. Y., Yin, J. C., He, T. G., 1982a. Early Cambrian Trace Fossils from the Emei-Ganluo Region, Sichuan, and Other Localities. *Geological Review*, 28: 291–298

Yang, Z. Y., Nie, Z. T., Wu, S. B., et al., 1982b. Cretaceous Rudists from Ngari, Xizang (Tibet), Autonomous Region, China and Their Geologic Significance. *Acta Geologica Sinica*, 56: 293–303

Yi, Y. H., Yuan, A. H., Aitchison, J. C., et al., 2018. Upper Darriwilian (Middle Ordovician) Radiolarians and Ostracods from the Hulo Formation, Zhejiang Provicnce, South China. *Journal of Earth Science*, 29(4): 886–899. https://doi.org/10.1007/s12583-017-0951-6

Yin, H. F., Feng, Q. L., Baud, A., et al., 2007a. The Prelude of the End-Permian Mass Extinction Predates a Postulated Bolide Impact. *In-*

ternational Journal of Earth Sciences, 96(5): 903–909. https://doi.org/10.1007/s00531-006-0135-1

Yin, H. F., Feng, Q. L., Lai, X. L., et al., 2007b. The Protracted Permo-Triassic Crisis and Multi-Episode Extinction around the Permian-Triassic Boundary. *Global and Planetary Change*, 55(1/2/3): 1–20. https://doi.org/10.1016/j.gloplacha.2006.06.005

Yin, H. F., Huang, S. J., Zhang, K. X., et al., 1992. The Effects of Volcanism on the Permo-Triassic Mass Extinction in South China. In: Sweet, W. C., Yang, Z. Y., Dickins, J. M., et al., eds., Permo-Triassic Events in the Eastern Tethys. Cambridge University Press, Cambridge. 169–174

Yin, H. F., Sweet, W. C., Glenister, B. F., et al., 1996. Recommendation of the Meishan Section as Global Stratotype Section and Point for Basal Boundary of Triassic System. *Newsletters on Stratigraphy*, 34(2): 81–108. https://doi.org/10.1127/nos/34/1996/81

Yin, H. F., Zhang, K. X., Tong, J. N., et al., 2001. The Global Stratotype Section and Point (GSSP) of the Permian-Triassic Boundary. *Episodes*, 24 (2): 102–114

Zakharov, Y. D., Horacek, M., Popov, A. M., et al., 2018. Nitrogen and Carbon Isotope Data of Olenekian to Anisian Deposits from Kamenushka/South Primorye, Far-Eastern Russia and Their Palaeoenvironmental Significance. *Journal of Earth Science*, 29(4): 837–853. https://doi.org/10.1007/s12583-018-0792-6

Zhang, K., Yuan, A. H., Feng, Q. L., 2018. The Upper Ordovician Microfossil Assemblages from the Pagoda Formation in Zigui, Hubei Province. *Journal of Earth Science*, 29(4): 900–911. https://doi.org/10.1007/s12583-017-0958-7

Zhao, L. S., Chen, Z.-Q., Algeo, T. J., et al., 2013. Rare-Earth Element Patterns in Conodont Albid Crowns: Evidence for Massive Inputs of Volcanic Ash during the Latest Permian Biocrisis?. *Global and Planetary Change*, 105: 135–151. https://doi.org/10.1016/j.gloplacha.2012.09.001