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The terrestrial end-Permian mass extinction in South China

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ABSTRACT

The end-Permian mass extinction reflects the most severe life crisis during the Phanerozoic and was associated with major global environmental changes. However, the consistency of the time and pattern of the terrestrial and marine extinctions remains controversial. In this paper, we presented detailed analyses of the high-resolution biostratigraphical and geochemical data from terrestrial sections in South China. Our analyses show that the transitional Kayitou Formation actually recorded the process of terrestrial mass extinction as evidenced by the mass disappearance of the *Gigantopteris* megaflora in the lower part, the dramatic reduction in abundance of palynomorphs in the middle, and the last occurrences of plant remains and abundant charcoal fossils in the uppermost part. It is associated with a distinct negative shift of $\delta^{13}C_{org}$, beginning in the middle part of the formation, which is correlative with that in the top of Bed 26 at the marine Meishan section. In addition, the Kayitou Formation is characterized by a distinct shift of lithofacies of fresh lake-swamp or river flat environment from olive/grey/black mudstone, siltstone, fine to coarse sandstone in the lower part to gradually increasing maroon rocks, to purely maroon mudrocks with poorly-sorted breccia, calcic palaeosols and calcareous nodules in the lowest part of the Dongchuan Formation, which indicates a dramatic collapse of soil system associated with rapid deforestation and climatic warming and drying. In the coastal area, the Kayitou Formation contains marine beds with the typical Permian–Triassic mixed faunas and floras which are correlative with the latest Changhsingian marine mixed fauna 1 at Meishan. The Kayitou Formation also recorded a distinct transgression that began in the latest Changhsingian. All above phenomena suggest that the Kayitou Formation is actually the witness of the terrestrial end-Permian mass extinction; and it is mostly or entirely of latest Changhsingian (Permian), rather than Triassic age.

1. Introduction

The end-Permian life crisis reflects the most profound crisis in the marine biosphere of all time, and it has been extensively studied in the marine ecosystem. The marine extinction has been recently well calibrated within a very short interval bracketed by two ash beds respectively at Bed 25 and 28 (61 ± 48 kyr) at Meishan, South China (Burgess et al., 2014). Biostratigraphically, it spans from the base of the conodont *Clarkina meishanensis* Zone to the base of the *Isarcicella isarcica* Zone (Jiang et al., 2007; Yuan et al., 2014). Associated with the marine mass extinction, a number of major environmental perturbations have been well documented. These include globally recognizable negative excursions of both $\delta^{13}C_{carb}$ and $\delta^{13}C_{org}$ within the extinction interval (Cao et al., 2002, 2009; Xie et al., 2007; Korte and Kozur, 2010; Hermann et al., 2011; S.Z. Shen et al., 2011; Shen et al., 2012, 2013); distinct sea level changes (Wu et al., 2006; Payne et al., 2007; Yin et al., 2014); a rapid temperature rise of ~8 °C in the extinction interval based on oxygen isotopes of conodont apatite (Joachimski et al., 2012; Chen et al., 2013) and brachiopods (Brand et al., 2013); evidence for widespread wildfires (Shen et al., 2006a; S.Z. Shen et al., 2011; W.J. Shen et al., 2011); and cyanobacteria and microbialite blooms (Kershaw et al., 2002, 2012; Wang et al., 2005; Xie et al., 2010; Mata and Bottjer, 2012; Wu et al., 2014); marine anoxia and euxinia (Isozaki, 1997; Grice et al., 2005; Cao et al., 2009; Y. Shen et al., 2011); and burst of monotonous Triassic-type taxa, which indicates profound environmental deterioration in the extinction interval and its aftermath (Rodland and Bottjer, 2001; Peng et al., 2007; Huang and Tong, 2014).

All those phenomena suggest that the extinction was associated with a major perturbation in global scale and the most popular scenario is that it is likely caused by the massive release of greenhouse gases during the magnetism and eruptions of Siberian Traps (Svensen et al., 2009;

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Cui et al., 2013) and/or volcanism in China (He et al., 2014). Therefore, it should be reflected in the terrestrial ecosystem as well (Algeo et al., 2011; S.Z. Shen et al., 2011). However, it remains controversial whether or not the terrestrial extinction is synchronous with the marine extinction (Yu et al., 2007, 2008, 2010; Peng and Shi, 2008; S.Z. Shen et al., 2011; W.J. Shen et al., 2011; Y. Shen et al., 2011; Bercovici et al., 2015). Precise correlation between the terrestrial and marine PTB is difficult due to the absence of the marine conodont index fossils in the terrestrial sections. The end-Permian terrestrial extinction has been considered equally devastating for plants and animals on land in different regions (Visscher et al., 1996; Retallack, 1999, 2013; Looy et al., 2001; Twitchett et al., 2001; Ward et al., 2005; Algeo et al., 2011; S.Z. Shen et al., 2011). However, it has also been documented that the terrestrial extinction predated the marine extinction in a horizon equivalent to the marine *Clarkina changxingensis*–*Clarkina deflecta* Zone of late Changhsingian age (Kozur and Weems, 2011), and postdated the PTB in the terrestrial sections and its marine counterpart based on the sections in southwestern China (Yu et al., 2007, 2008, 2010; Peng and Shi, 2008; Bercovici et al., 2015).

South China has been universally depicted as an isolated island in the eastern Tethyan gape in the tropical zone during the Permian–Triassic transition in terms of palaeogeographical reconstruction maps. There have been preserved the most complete Permian–Triassic marine sequences when most parts of the Pangea emerged. It is probably due to this unique palaeogeographical position that South China contains the most complete and abundant palaeontological data to unravel the end-Permian mass extinction and recovery patterns; notably the Meishan sections at Changxing, Zhejiang Province has become the most extensively-studied sections in terms of the end-Permian mass extinction and PTB. However, relatively less has been studied for the complete terrestrial alluvial and transitional coastal Permian–Triassic sections in South China, which contain important clues to understand the links and correlation between oceanic and terrestrial ecosystems. Although terrestrial sections recording the extinction have been increasingly documented recently, the timing and pattern of the extinction are interpreted in different ways (Yu et al., 2007, 2008, 2010; Peng and Shi, 2008; S.Z. Shen et al., 2011; Bercovici et al., 2015). A general conclusion showing the marine and terrestrial extinctions in South China has been briefly presented by S.Z. Shen et al. (2011). In this report we present a more detailed analysis of the terrestrial extinction on the basis of previous and recent new chemostratigraphical, biostratigraphical, geochronologic, and lithological data from terrestrial sections in South China. We provide a different interpretation of the terrestrial extinction in terms of timing and patterns in South China.

2. Geological setting

Recent palaeogeographical reconstruction of South China reveals a variety of palaeogeographical environments (Wang and Jin, 2000). The Yangtze Platform and the Jiangnan Basin were bracketed by the Kangdian High in the west and the Cathaysian High in the east. The eruption of the Emeishan basalt in the Late Guadalupian (Middle Permian) resulted in the formation of a large (about 300,000 km^2) coal-bearing depositional system during the Late Permian along the eastern margin of this volcanic plateau and accommodation of terrestrial alluvial and transitional coastal deposits in their peripheral areas (Feng et al., 1994). We measured four Permian–Triassic sections located in the eastern margin of the Kangdian High (Fig. 1). In addition, tens of other sections in the study area were previously studied mainly for biostratigraphical, palaeontological, and coal resource purposes (Yao et al., 1980; Ouyang, 1986; Wang and Yin, 2001; Peng et al., 2005; Yu et al., 2008, 2010; S.Z. Shen et al., 2011). We also review the data from those sections and provide our interpretation. Among the sections investigated, the Guanbachong, Longmendong, Lubei, and Chahe sections represent terrestrial alluvial deposits, and the Mide section represents the transitional coastal sequences on the eastern margin of the Kangdian High.

3. Lithostratigraphy and biostratigraphy of the studied sections

3.1. Lithostratigraphy

The Lopingian (Late Permian) Series in the eastern margin of the Kangdian High are all characterized by the coal-bearing sequences which are composed mainly of olive, grey or multicolored sandstone and mudstone. Among the sections studied in this paper, the Permian–Triassic sequences at the Guanbachong, Longmendong, Lubei, Chahe, and Mide sections consist of the Xuanwei, Kayitou, and Dongchuan formations in ascending order (Fig. 2), of which the Chahe section has been most studied (Wang and Yin, 2001; Peng et al., 2005; Yu et al., 2007; Peng and Shi, 2008; S.Z. Shen et al., 2011; Bercovici et al., 2015). The Xuanwei Formation unconformably overlies the Middle Permian (Maokouan, Late Guadalupian) Emeishan basalt at all terrestrial sections in the study area. It is composed of the alluvial and occasionally marine/non-marine transitional deposits, and contains the highly diverse Cathaysian *Gigantopteris* flora and a few productive coal seams (Yao et al., 1980; Wang and Yin, 2001; Peng et al., 2005). This formation is constrained by the last appearance of coal seam at the top (Fig. 3). It is 90 m thick at the Guanbachong section, 85.1 m thick at the Chahe section (Wang and Yin, 2001; Peng et al., 2005; Yu et al., 2007; Bercovici et al., 2015), and 34.8 m thick at the Longmendong section (S.Z. Shen et al., 2011). It is characterized by conglomerates in the lower part and multicolored siltstone and mudstone with productive coal seams in the middle and upper parts at the Guanbachong section. The conglomerates in the lower part of the Xuanwei Formation at the Guanbachong section are missing at Longmendong, Lubei, and Chahe sections. The whole formation at the Longmendong section contains more coarse- and medium-grained olive sandstone.

The Xuanwei Formation is overlain by the Permian or Permian–Triassic transitional Kayitou Formation in the four terrestrial sections (Guanbachong, Chahe, Longmendong and Lubei) in the study area (Wang and Lu, 1937). This formation is defined by the last appearance of coal seam at the base (Wang and Lu, 1937; Wang, 2001) and last appearance of olive/grey rock at the top in South China (Fig. 3). Therefore, there is no coal in this formation. Lithologically, it is characterized by the olive/brownish/maroon alternative sandstone and mudstone, and maroon beds increase upwards in abundance until the disappearance of olive bed at the top. Poorly-sorted breccia and palaeosol with calcareous nodules occur in the upper part of the formation (Fig. 4) and such kind of rocks has been reported from the PTB intervals in Antarctic, Australia and South Africa (Retallack, 2005). It is 10.1 m thick at the Guanbachong section, 24.5 m thick at the Chahe section, 9.4 m at the Lubei section, and 6.4 m thick at the Longmendong section based on this definition, and they are all marked by a coal seam at the base (Fig. 3). Specifically, the topmost part of the Kayitou Formation at the Guanbachong section is marked by a 1.6-m-thick coarse volcanogenic sandstone with calcareous sandy nodules, abundant charcoal fossils, and malachite spots on the bedding plane (Fig. 4G). It is marked by a poorly-sorted lacustrine breccia with conchostracans, charcoal fossils, and malachite spots at the Longmendong section (Fig. 4F, H). The boundary between the Kayitou and the Dongchuan formations at the Chahe and Lubei sections is transitional, syngeneric calcareous sandstone nodules begin to occur in the upper part of the Kayitou Formation, and numerous calcareous nodules occur in the basal part of the Dongchuan Formation (Fig. 4A, B).

The overlying Early Triassic Dongchuan Formation is characterized by uniformly maroon fine to medium sandstone, siltstone, and mudstone with trough cross-bedding, parallel bedding, and scour structures. The scour is commonly filled by the same maroon angular sandstone/