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Astronomical tuning of the end-Permian extinction and the Early Triassic Epoch of South China and Germany

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ABSTRACT

The timing of the end-Permian mass extinction and subsequent prolonged recovery during the Early Triassic Epoch can be established from astronomically controlled climate cycles recorded in continuous marine sedimentary sections. Astronomical-cycle tuning of spectral gamma-ray logs from biostratigraphically-constrained cyclic stratigraphy through marine sections at Meishan, Chaohu, Daxiakou and Guandao in South China yields an integrated time scale for the Early Triassic, which is consistent with scaling of magnetostratigraphy from climatic cycles in continental deposits of the Germanic Basin. The main marine mass extinction interval at Meishan is constrained to less than 40% of a 100-kyr (kilo-year) cycle (i.e., <40 kyr) and the sharp negative excursion in $\delta^{13}C$ is estimated to have lasted <6 kyr. The sharp positive shift in $\delta^{13}C$ from −2‰ to 4‰ across the Smithian–Spathian boundary at Chaohu was completed in 50 kyr. The earliest marine reptiles in the Mesozoic at Chaohu that are considered to represent a significant recovery of marine ecosystems did not appear until 4.7 myr (million years) after the end-Permian extinction. The durations of the Griesbachian, Dienerian, Smithian and Spathian substages, including the uncertainty in placement of widely used conodont biostratigraphic datums for their boundaries, are 1.4 ± 0.1, 0.6 ± 0.1, 1.7 ± 0.1 and 1.4 ± 0.1 myr, implying a total span for the Early Triassic of 5.1 ± 0.1 myr. Therefore, relative to an assigned 251.902 ± 0.024 Ma for the Permian–Triassic boundary from the Meishan GSSP, the ages for these substage boundaries are 250.5 ± 0.1 Ma for base Dienerian, 249.9 ± 0.1 Ma for base Smithian (base of Olenekian stage), 248.2 ± 0.1 Ma for base Spathian, and 246.8 ± 0.1 Ma for the base of the Anisian Stage. This astronomical-calibrated timescale provides rates for the recurrent carbon isotope excursions and for trends in sedimentation accumulation through the Early Triassic of studied sections in South China.

1. Introduction

Life was nearly annihilated during the end-Permian mass extinction (EPME) 252 million years ago (Ma). A prolonged and unstable biotic recovery through the Early Triassic was punctuated by recurrent anomalously hot climate episodes, carbon-cycle perturbations and global ocean anoxia (e.g., Burgess et al., 2014; Chen and Benton, 2012; Payne et al., 2004; Sun et al., 2012; Wignall, 2015). The causes, timing and rates of the EPME and these repeated environmental disruptions have yet to be explained, partly because age models for the Early Triassic are highly disputed (Burgess et al., 2014; Galfetti et al., 2007; Ogg, 2012; Szurlies, 2007; Wu et al., 2012).

A reliable chronology is the requirement for calibrating the rates of these dramatic Early Triassic events. Radio-isotopic dating of Late Permian–Early Triassic had produced contradictory ages for the same events due to application of different methods or standards by different laboratories (e.g., Bowring et al., 1998; Burgess et al., 2014; Mundil et al., 2004; Shen et al., 2011). The revised EARTHTIME tracer solutions (e.g., Burgess et al., 2014) do not

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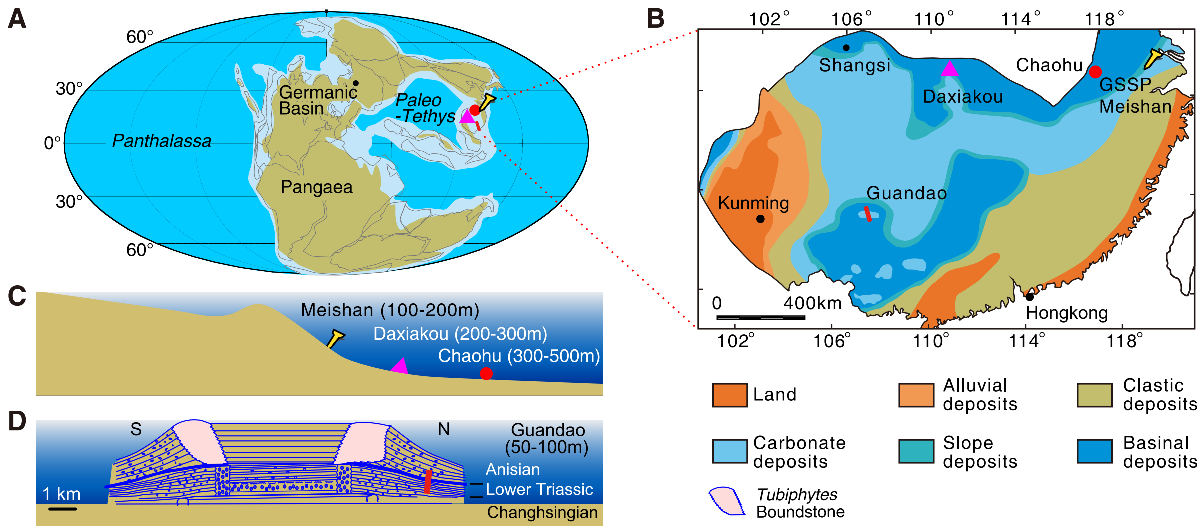

Fig. 1. Paleogeography maps. **A**. Early Triassic global paleogeographic map (modified from http://www.scotese.com). **B**. Early Triassic paleography of South China (modified from Feng et al., 1997). **C**. Sketch of paleo-depths of the studied Meishan, Chaohu and Daxiakou sections (Song et al., 2013a). **D**. Schematic cross section of the depositional setting for the Changhsingian to Anisian strata of the Great Bank of Guizhou in the Nanpanjiang Basin of South China (Lehrmann et al., 1998) with paleo-depth of Guandao section according to Song et al. (2013a).

allow a linear transformation of dates from previously measured zircons; therefore, estimating the Early Triassic stages/substages durations by combination/comparison of published zircon dates cannot be undertaken until zircons from those volcanic ash layers are remeasured using the new tracers and protocols. Another complication is that some zircon populations appear to be clustered at ages that are older than the volcanic ash bed or yield artifacts of younger ages due to lead-loss that can not be entirely removed by standard laboratory methods. An excellent example of such complications is the apparently non-sequential U–Pb dates derived from several volcanic ash beds that bracket the Olenekian/Anisian stage boundary at the Monggan/Wantou section in South China (Ovtcharova et al., 2015).

The Milankovitch concept is that quasi-periodic oscillations in the Earth's tilt and its orbit around the Sun induce prominent 10^4–10^6 yr variations in the Earth's seasonal contrasts, and that these climatic oscillations are recorded in the stratigraphic record (e.g., Hays et al., 1976; Hinnov, 2013). When combined with other stratigraphic methods, such as biostratigraphy, magnetostratigraphy and radio-isotopic dating, the analysis and interpretation of astronomically-modulated climatic signals derived from proxies in sedimentary rocks yield a high-resolution astronomical time scale (ATS) (Hinnov and Hilgen, 2012). However, compiling a reliable ATS requires (1) high-resolution climate proxy records from continuous successions, (2) confirmation that detected sedimentation cycles have an origin from astronomical-climate cycles, and (3) verified assignment of detected cycles to specified astronomical parameters. Efforts to apply cyclostratigraphy method to the Early Triassic epoch have yielded conflicting interpretations, partly because recognized sedimentation wavelengths were assigned to an astronomical parameter (precession, obliquity, eccentricity) based mainly on their presumed consistency with selected radio-isotopic dates. For example, the duration of the Griesbachian substage using interpreted short-eccentricity (∼100 kyr) tuning is ca. 1.3 myr in Germany (Kozur and Weems, 2011), but only 0.73 myr at the West Pingdingshan section (Guo et al., 2008) and a brief 0.49 myr at the Daxiakou section (Wu et al., 2012).

We applied cyclostratigraphic analysis to spectral gamma-ray logs of multiple Permian–Triassic conodont-zoned marine sections on the South China carbonate platform to compile an integrated 5.1-myr-long ATS for the entire Early Triassic Epoch. The magnetostratigraphy of this cycle-tuned composite from South China correlates well to the independent studies of cycle-tuned magnetostratigraphy from continental successions in the Germanic basin (Kozur and Bachmann, 2008; Menning and Käding, 2014; Szurlies, 2004, 2007). This inter-regional ATS provides a high-resolution integrated time scale for the end-Permian through Early Triassic record of climate change and evolution.

2. Materials and methods

2.1. Yangtze Platform sections

During the Early Triassic, the South China Plate was located at the eastern part of the Paleo-Tethys Ocean and isolated from the Pangaea supercontinent (Fig. 1). The well-preserved Upper Permian through Lower Triassic marine successions have been extensively studied. Three sections from the northern margin of the Yangtze Platform and one section from the Great Bank of Guizhou in the northern portion of the Nanpanjiang Basin were used to establish the Early Triassic timescale.

The Meishan section in Zhejiang Province contains the Global Boundary Stratotype Section and Point (GSSP) for the Permian–Triassic boundary (PTB) (Yin et al., 2001), and the Chaohu section is a candidate for the GSSP of the Induan–Olenekian boundary of the Lower Triassic (Tong et al., 2003). The Guandao section on the northern margin of the Great Bank of Guizhou is a significant section for the Olenekian–Anisian boundary (OAB) because it contains both the proposed conodont markers and magnetic-reversal marker, and it has dated volcanic ash beds that bracket for the OAB (Lehrmann et al., 2006, 2015).

The GSSP for the PTB (base of Griesbachian substage) is defined at the first appearance datum (FAD) of conodont *Hindeodus parvus* at Meishan (Yin et al., 2001), and this FAD is also recorded at Daxiakou (Zhao et al., 2013). The base of the Dienerian has been placed at the base of the conodont *Sweetospathodus kummeli* Zone at Chaohu (Zhao et al., 2007) and Daxiakou (Zhao et al., 2013). The proposed GSSP candidate level at Chaohu for the base-Olenekian is at the FAD of the conodont *Novispathodus waageni eowaageni*, which is immediately below the base of the ammonoid *Flemingites–Euflemingites* Zone (Tong et al., 2003). The Smithian–Spathian substage boundary in these sections is assigned to the base of the conodont *Novispathodus pingdingshanensis* Zone, which is accompanied by a sharp positive shift in $\delta^{13}C$ that serves as a