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Early Triassic estuarine depauperate *Cruziana* Ichnofacies from the Sichuan area of South China and its implications for the biotic recovery in brackish-water settings after the end-Permian mass extinction

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ABSTRACT

New ichnological data from the Lower Triassic (Induan) Dongchuan Formation (Longmendong, South China) record the recovery interval of marginal-marine communities following the end-Permian mass extinction. Here, we document six ichnogenera from the upper part of the Dongchuan Formation of Dienerian (Early Triassic) age in the Longmendong area, Sichuan Province, South China. These are *Cylindrichnus*, *Diplocraterion*, *Palaeophycus*, *Planolites*, *Siphonichnus*, and *Teichichnus*, illustrating a depauperate *Cruziana* Ichnofacies. Facies analysis suggests that the depauperate *Cruziana* Ichnofacies is present in deposits recording the transition from fluvial to tide-dominated estuarine settings. Compilation of worldwide brackish-water ichnofaunas from Permian (average alpha ichnodiversity = 6.2) to Triassic (average alpha ichnodiversity = 5.5) suggests that no significant ichnodiversity decrease took place in these settings as a result of the mass extinction and further implies that the impact of the mass extinction may have been less severe in marginal-marine settings. Ichnofaunas in pre- and post-extinction marginal-marine environments are remarkably similar and tend to be dominated by facies-crossing ichnotaxa (e.g., *Diplocraterion*, *Palaeophycus*, *Planolites*) produced by opportunistic faunas.

1. Introduction

The end-Permian mass extinction has been considered as the biggest mass extinction event in Earth history, due to the disappearance of 81% of marine species, approximately 80% of terrestrial vertebrate species and drastic re-structuring of marine and continental ecosystems (McGhee et al., 2004; Erwin, 2006; Stanley, 2016). Numerous studies have focused on biotic recovery in recent years, essentially concluding that the marine ecosystem was not fully recovered until the early Middle Triassic (e.g., Erwin, 2006; Chen and Benton, 2012). The Early Triassic is characterized by continuous low biodiversity (Erwin, 1993), reduction in the size of metazoans (Twitchett, 2007) and protozoans (Song et al., 2011), the absence of metazoan reefs and calcareous algae, and blooms of opportunistic and disaster taxa (Bottjer et al., 2008). Geochemical data show that Early Triassic stressed marine environments were accompanied by a long standing hot climate (Sun et al., 2012) and several oceanic anoxic events (Song et al., 2014). Ichnological data also suggest that the loss of the mixed layer was an important factor controlling the seawater and sediment chemistry, further constraining ecosystem recovery during the Early Triassic (Hofmann et al., 2015).

Recently, the study of trace fossils started to play a major role to reveal the tempo and pattern of ecological recovery following the end-Permian mass extinction (Pruss and Bottjer, 2004; Twitchett and Barras, 2004; Barras and Twitchett, 2007; Beatty et al., 2008; Zhao and Tong, 2010; Zonneveld et al., 2010a, 2010b; Chen et al., 2011, 2012; Hofmann et al., 2013, 2015, Hofmann, 2016; Baucon et al., 2014; Shi et al., 2015; Zhao et al., 2015; Luo et al., 2016). Trace fossils record organism-substrate interactions, and represent the activities of both skeletonized and soft-bodied organisms. Furthermore, trace fossils are the only biotic evidence of recovery in otherwise unfossiliferous strata. Also, ichnological data have suggested that recovery was faster in high paleolatitude areas (Twitchett and Barras, 2004; Wetzel et al., 2007; Beatty et al., 2008; Zonneveld et al., 2010a). However, most ichnological research was done in fully marine successions and marginal-marine ecosystems have not been analyzed to the same degree. The environmental factors that control the temporal and spatial patterns of Early Triassic trace fossils are still unclear and there is a need for more quantitative studies (Chen and Benton, 2012).

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The Lower Triassic Dongchuan Formation (Induan) in the Longmendong section (central-south Sichuan Province, South China) reveals an abundant and well-preserved trace-fossil association. Here we document this ichnofauna and associated sedimentary facies, including description of the ichnotaxa, their stratigraphic distribution and interpretation of associated depositional settings, therefore providing new evidence on the timing of colonization and ecological recovery in Early Triassic marginal-marine environments.

2. Geological setting and methods

The study area is located in the western part of the Upper Yangtze sedimentary province (Fig. 1) (Tong and Yin, 2002), and belongs to the west part of the Chengdu-Chongqing Basin (Li et al., 1991). The Longmendong section in Sichuan Province of South China provides excellent outcrops of Permian-Triassic strata. The upper Permian in the area is represented by the Kayitou Formation (Fig. 2), which is characterized by interbedded olive/brown/purple-red medium- and fine-grained sandstone and mudstone (FA1 and FA2). Purple-red beds increase in abundance upwards parallel to a decrease in the abundance of olive-color beds. Poorly sorted breccia and paleosols with calcareous nodules occur in the upper part of the formation. At the Longmendong section, breccia contains lacustrine fossils (conchostracans) as well as charcoal and malachite mottles (Lin et al., 1982; Zhang et al., 2016). The Kayitou Formation is considered latest Permian in age based on the most negative $\delta^{13}C_{org}$ value, abundant conchostracans such as *Euestheria* and *Palaeolimnadia*, and radiometric dating data near the base of this unit (252.30 ± 0.07 Ma) (Zhang et al., 2016).

Triassic strata are exposed along the Longmen River on a ca. 5 km long section. The Lower Triassic strata in this section record a transition from sandstone facies to mixed sandstone and carbonate facies (FA3–6). In the Longmendong section, the Lower Triassic strata are up to 500 m thick and comprise the Dongchuan, Feixiangguan and Jialingjiang formations. The Lower Triassic successions in the study area include diverse clastic and carbonate sedimentary facies interpreted to represent fluvial to marginal- and shallow-marine shelfal and basinal settings (Fig. 1).

The Dongchuan Formation is characterized by uniformly purple-red fine- to medium-grained sandstone, siltstone, and mudstone with trough cross bedding, tabular cross bedding, parallel lamination, current

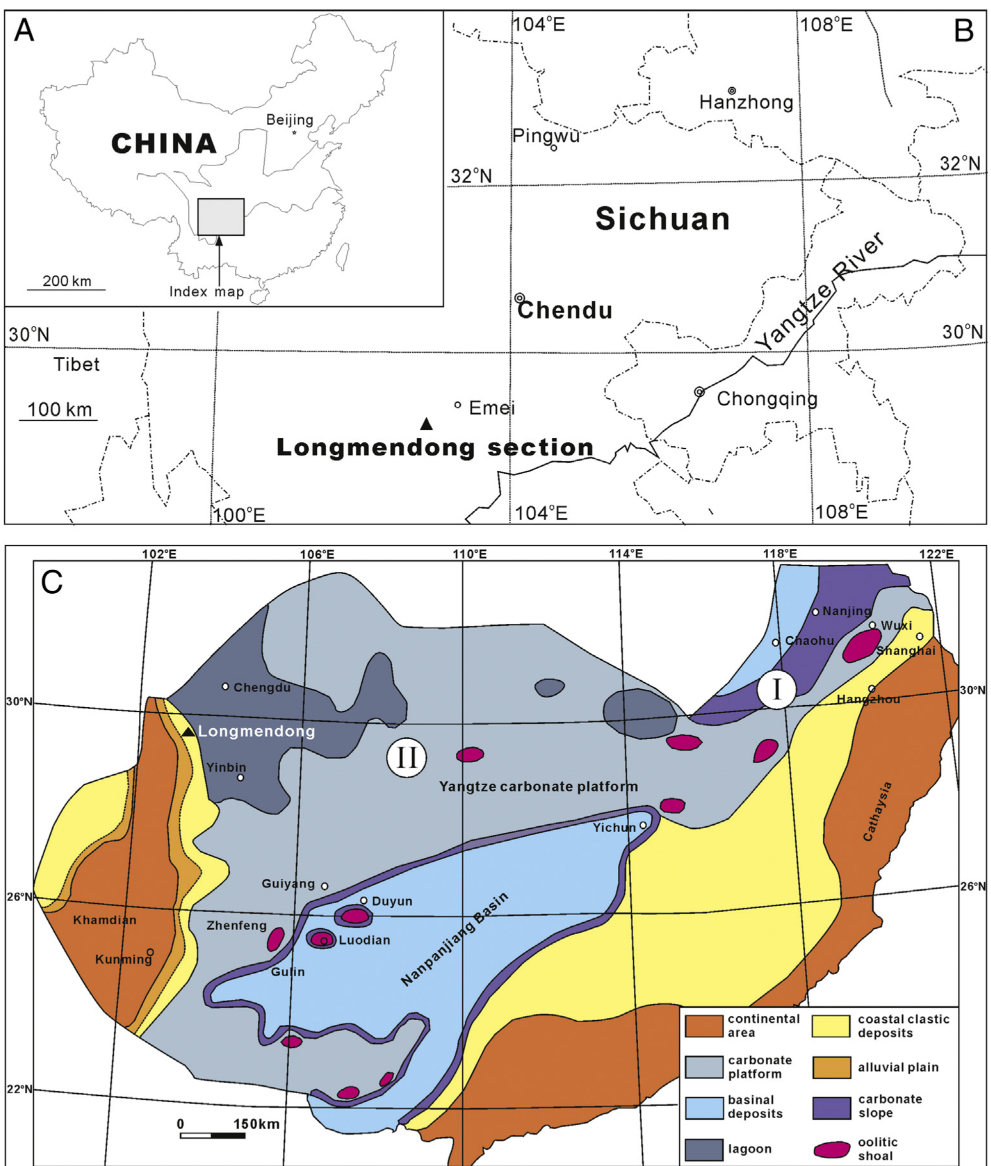

Fig. 1. Location maps and paleogeography of the Longmendong section in the Sichuan Province of South China. A, B. Location of the studied section. C. Early Triassic paleogeographic map of South China (modified from Feng et al., 1997). I: Lower Yangtze sedimentary province, II: Upper Yangtze sedimentary province.

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