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Editorial

The Permian–Triassic boundary crisis and Early Triassic biotic recovery

1. Introduction

This issue of *Palaeogeography Palaeoclimatology Palaeoecology* is devoted to papers on the Permian–Triassic boundary crisis and Early Triassic biotic recovery. It is an outgrowth of the Symposium on Early Triassic Chronostratigraphy and Biotic Recovery that was held in Chaohu, China, on May 21st–23rd, 2005 under the auspices of IGCP Project 467 and attended by about 200 Earth scientists with a global representation. The 26 manuscripts contained in this issue provide a state-of-the-art survey of Permian–Triassic boundary (PTB) research in diverse disciplines, including biostratigraphy, paleontology, sedimentology, stratigraphy, and geochemistry.

1.1. Geographic distribution of studies

The studies in this issue have a global distribution, although Chinese boundary sections are heavily represented among the field-based projects, especially the Global Stratotype Section and Point (GSSP) at Meishan in Zhejiang Province and a newly excavated boundary section near the conference site at Chaohu in Anhui Province:

Meishan, China: Chen et al.; Wang and Visscher; Zhang et al.
Chaohu, China: Li et al.; Zhao et al.
South/southwest China: He et al.; Lehrmann et al.; Metcalfe and Nicoll
West/northwest China: Isozaki et al.; Ji et al.; Yang et al., Yao et al.
Vietnam: Algeo et al. (a)
Kashmir: Algeo et al. (b)
Iran: Horacek et al. (a)
Caucasus: Vuks
Germany: Weidlich
Austria: Horacek et al. (b)
Slovenia: Kolar-Jurkovšek and Jurkovšek
Oman: Bernecker
South Africa: Tabor et al.
North America: Fraiser and Bottjer, Woods et al.

Although most of these studies are marine-based, changes in terrestrial environments and climate are considered in Tabor et al. and Yang et al. Also included in this issue are global syntheses on conodonts by Orchard, brachiopods by Peng et al., and molluscs by Twitchett.

1.2. Advances in biostratigraphy and paleontology

The biostratigraphic framework of the PTB continues to be refined, especially through conodont studies, providing an improved temporal yardstick against which contemporaneous events and processes can be better understood. Data from Chinese sections figure prominently: Zhang et al. present a revised conodont (and palynomorph) zonation from Meishan, the location of the basal Triassic GSSP; Zhao et al. present a conodont zonation, including new taxa, for a proposed basal Olenekian GSSP at Chaohu; Ji et al. describe a relatively expanded PTB succession in a deep basinal setting in northern Sichuan; and Metcalfe and Nicoll augment conodont work with paleomagnetic and C-isotopic data in locating the PTB in transitional marine-to-nonmarine facies in western Guizhou. Yao et al. investigate the palynology of relatively unstudied Permian sections in Xinjiang Province. Further afield, Kolar-Jurkovšek and Jurkovšek report the first occurrence of the key *Hindeodus–Isarcicella* population in Slovenia, and Vuks shows the intercalibration of foraminifers with other index fossils of the Olenekian

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in the Black-Caspian seas region, where a late Olenekian transgression provided conditions for migration between paleobasins.

The impact of sea-level changes and opportunistic expansion are themes explored by Orchard, who presents a comprehensive study of latest Permian and Early Triassic conodont evolution from a unique 'multielement' perspective. Rather than emphasizing the PTB extinction, this study recognizes a gradual decline of conodont families and genera through the Changhsingian and Griesbachian, followed by a faunal turnover and major radiation in apparatuses during the Dienerian, an explosive radiation in the early-middle Smithian, and a major extinction in the late Smithian; this in turn is followed by a major radiation early in the Spathian, and a general decline in the late Spathian.

The effects of changes in trophic systems and reduced environmental oxygen levels are considered in several studies. Isozaki et al. document complete disappearance of radiolarians at Chaotian in South China, indicating that the PTB crisis struck at the base of the marine trophic system, and that reduced energy flows may have been an important factor in addition to other environmental stresses. Peng et al. show that the Lingulidae brachiopods, a group that survived the PTB mass extinction and thrived in the Early Triassic marine realm, occupied vacated ecological space through adaptations recorded in short-term changes in shell size, shape, and thickness and longer-term changes in shell composition. These changes are interpreted as reflecting food shortage, more efficient adaptation to a burrowing habitat, and increased efficiency of oxygen exchange. Twitchett discusses the diminished size, or Lilliput effect, that characterizes Lower Triassic biotas in more general terms. Miniaturization of body and trace fossils in both the marine and terrestrial realms is shown to reverse from the mid-Induan, but pre-extinction sizes are not common again until the Middle Triassic. A combination of factors is invoked, including marine anoxia, low atmospheric concentrations of oxygen, sluggish ocean circulation in a greenhouse world, and food shortage.

1.3. Advances in sedimentology and stratigraphy

Strong stratigraphic condensation of many PTB sections including the Meishan GSSP can make determination of the sequence of closely spaced boundary events difficult. Event sequencing requires stratigraphically expanded sections, such as those studied by Isozaki et al. at Chaotian, China, and by Algeo et al. (a,b) at Nhi Tao, Vietnam and Guryul Ravine, India. One issue that such sections can address is the relative sequence of the PTB crises in the marine and terrestrial realms: Wang and Visscher provide evidence that the terrestrial crisis occurred first, whereas Algeo et al. (a) conclude that the crises were probably synchronous. Obviously, the relative timing of events around the PTB is not yet completely understood, and event sequencing is likely to remain an important area of research in the future. Sedimentologic research remains important to an understanding of Permo-Triassic climate and eustasy. Yang et al. investigate the sedimentologic record of Late Permian climate change in terrestrial facies of northwest China, and Li et al. study the Early Triassic eustatic record in marine facies at Chaohu. The marine versus non-marine character of some Lower Triassic deposits remains uncertain: Weidlich presents a case that the Untere Bundsandstein Group of central Europe has been incorrectly interpreted in the past as a non-marine facies owing to its impoverished biota.

1.4. Advances in geochemistry

Geochemical studies have become increasingly important in advancing our understanding of events and processes associated with the PTB. Algeo et al. (a) generate a high-resolution chemostratigraphic record of the PTB from Nhi Tao, Vietnam that documents a series of C-isotopic excursions and correlative pyritic horizons, providing evidence of repeated upwelling of sulfidic, ^{13}C-depleted deep-ocean waters at short (~20 ky) intervals. Horacek et al. (a,b) generate some of the most detailed C-isotope records for the full Lower Triassic interval yet reported from sections in Italy and Iran, providing evidence of multiple large perturbations to the global carbon cycle. Woods et al. provide evidence of concurrent perturbations of seawater chemistry in their study of Lower Triassic synsedimentary seafloor cements in western North America. Wang and Visscher identify aromatic biomarkers (dibenzofuran homologues) in the Meishan GSSP that have been linked elsewhere to massive soil erosion following the destruction of terrestrial vegetation during the end-Permian crisis. Tabor et al. conclude from a study of Permo-Triassic paleosols that C-isotope records from poorly drained soils may not be faithful recorders of atmospheric $p\mathrm{CO}_2$.

1.5. Major themes

Although the end-Permian mass extinction represents the acme of the biotic crisis in both the marine and terrestrial realms, environmental deterioration appears to have begun earlier in the Late Permian, possibly contributing to biotic changes such as the reduction in average radiolarian size documented by Isozaki et al.

and to a minor biotic crisis at the Wuchiapingian–Changhsingian substage boundary (~2.5 My prior to the PTB). Infra-Late Permian environmental changes in marine facies are investigated at Meishan by Wang and Visscher and in southwest China by Isozaki et al., and coeval environmental changes in terrestrial facies from northwest China are examined by Yang et al.

The ultimate cause of the Permian–Triassic boundary is still uncertain, although the age of the boundary is now known to be coeval with the onset of Siberian Traps flood-basalt volcanism, within the uncertainty limits of radiometric dating. Although commonly invoked as a potential trigger for the PTB event, it is unclear whether flood basalt volcanism—even at a massive scale—can produce the kinds of climatic and environmental changes observed at the PTB. Isozaki et al. contend that coeval large-scale rhyodacitic volcanism may have been more important in causing environmental perturbations at the PTB. On the other hand, Algeo et al. (a) argue that oceanic processes appear to have played a major role at the PTB. A question that requires further investigation is the nature of the links between PTB volcanism and concurrent oceanographic changes. The hypothesis advanced by Algeo et al. (a) is that volcanically induced climate cooling triggered renewed oceanic overturn following a protracted interval of oceanic stagnation during the Late Permian. Noteworthy is that none of the contributions to this issue (nor any of the presentations at the Chaohu symposium) provide any evidence in support of an extraterrestrial impact model. Although it may be premature to reject any hypothesis, it is nonetheless the consensus of a large part of the PTB research community that the existing evidence for a bolide impact at the PTB is weak, and that events before, during, and after the PTB are better explained through a combination of intrinsic processes.

A major focus of the Chaohu conference was the delayed recovery of the marine ecosystem following the end-Permian mass extinction. Marine biotas in general and benthic populations in particular were characterized by low diversity, reduced body size, and high proportions of "disaster taxa" throughout the ~6 million years of the Early Triassic, as shown by Chen et al., Fraiser and Bottjer, He et al., and Twitchett. Conodonts appear to have been an exception, as noted by Orchard, achieving an acme of Triassic diversity by the early Olenekian only to succumb to a major extinction in the middle part of that stage (end Smithian); this pattern also appears true of the pelagic ammonoids. However, some manifestations of the biotic recovery, such as the development of high-relief, reef-rimmed carbonate platforms, were delayed until the Middle or Late Triassic, as discussed by Bernecker and Lehrmann et al. The unusually long delay in biotic recovery following the PTB mass extinction has contributed to the view, expressed by Chen et al., Fraiser and Bottjer, Twitchett, and Woods et al., that conditions in marine environments generally remained inhospitable to metazoans for most or all of the Early Triassic.

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