



Editorial

Permian–Triassic paleoceanography

1. Introduction

This theme issue of *Global and Planetary Change* is devoted to studies of “Permian–Triassic paleoceanography.” It consists of 14 papers that advance our understanding of marine environmental conditions during the Permian–Triassic boundary (PTB) crisis and its aftermath (Table 1).

The end-Permian mass extinction (EPME) at 252.28 Ma (Shen et al., 2011) was the largest biotic catastrophe of the Phanerozoic, resulting in the disappearance of ~90% of skeletonized marine species (Erwin, 1994; Bambach et al., 2004; Alroy et al., 2008; Clapham et al., 2009) and a transition from the ‘Paleozoic Fauna’ to the ‘Modern Fauna’ (Sepkoski, 1982, 2002). The biocrisis was broad, resulting in major losses of diversity among radiolarians (Feng et al., 2007), foraminifera (Groves and Altiner, 2005), corals (Flügel, 2002), brachiopods (Chen et al., 2005a,b), bryozoans (Powers and Pachut, 2008), echinoderms (Twitchett and Oji, 2005; Chen and McNamara, 2006), conodonts (Orchard, 2007; Stanley, 2009), and ammonoids (McGowan, 2004; Brayard et al., 2006, 2009; Stanley, 2009), among other clades. Early Triassic marine communities were characterized by (1) a lack of metazoan reefs, creating a ‘reef gap’ until the Middle Triassic (Flügel, 2002; Pruss and Bottjer, 2005; Marengo et al., 2012); (2) small size (‘Lilliput effect’) among benthic invertebrates (Fraiser and Bottjer, 2004; Payne, 2005; Twitchett, 2007; Metcalfe et al., 2011), and (3) reduced ecological complexity, as seen in limited tiering, empty megaguilds, and dominance of a few taxa (Fraiser and Bottjer, 2005; Bottjer et al., 2008). Although some nektic groups recovered rapidly (Hallam and Wignall, 1997; Brayard et al., 2009; Stanley, 2009), biodiversity remained low in most clades during the Early Triassic, and the general recovery of benthic marine ecosystems was delayed by ~5 Myr (Erwin, 1994; Schubert and Bottjer, 1995; Fraiser and Bottjer, 2004, 2007). The papers in this theme issue explore changes in paleoceanographic conditions during and following the end-Permian crisis, their significance for the mass extinction event and the subsequent delay in recovery of marine ecosystems, and their relationship to contemporaneous global climate change.

2. Permian–Triassic paleoceanographic changes

One of the most important recent discoveries in the field of Permian–Triassic paleoceanography is an extreme rise in tropical sea-surface temperatures (SSTs) during the latest Permian to Early Triassic, with peak temperatures up to 40 °C, or >15 °C above pre-crisis SSTs (Joachimski et al., 2012; Romano et al., 2012; Sun et al., 2012). Such extreme warming is likely to have been the primary cause of contemporaneous oceanographic changes, including intensified stratification of the

oceanic water column and a sharp reduction in global overturning circulation (Horacek et al., 2007; Algeo et al., 2010, 2011a; Winguth and Winguth, 2012). Song et al. (2013–this volume) have developed an innovative method of quantifying the degree of oceanic stratification during the PTB crisis interval. They analyzed vertical gradients in marine carbonate $\delta^{13}\text{C}$ ($\Delta\delta^{13}\text{C}$) in a series of carbonate sections from South China representing water depths ranging from <50 m to ~500 m. This analysis revealed that $\Delta\delta^{13}\text{C}$ increased from 2‰ in the Late Permian to a maximum of 8.5‰ in the earliest Triassic, fluctuated between 3.5‰ and 7.2‰ during the mid-Griesbachian to Smithian, and then declined rapidly back to ~2‰ during the Spathian. Whereas pre- and post-crisis vertical $\delta^{13}\text{C}$ gradients are similar to those for the modern ocean (0–3‰; Kroopnick, 1985), gradients >3‰ are found today only in strongly stratified restricted marine basins such as the Black Sea and Framvaren Fjord. The Song et al. study concluded that stratification within the Early Triassic oceanic thermocline was roughly as intense as that within the modern Black Sea (i.e., with a vertical density gradient of at least $4\sigma_t$). Although modeling studies have argued that prolonged stagnation of deep-ocean circulation is not possible (e.g., Hotinski et al., 2001; Kiehl and Shields, 2005), it is possible that these studies have not yet considered sufficiently extreme climatic changes to induce intense stagnation.

Extreme warming and oceanic stratification during the PTB crisis had other important oceanographic consequences, including probable changes in marine redox conditions and productivity, the global carbon cycle, and the seawater sulfur cycle. Oceanic anoxia is thought to have increased greatly during the latest Permian to Early Triassic (Wignall and Twitchett, 1996, 2002; Isozaki, 1997) with expansion concentrated at intermediate water depths, i.e., within the oxygen-minimum zone (Algeo et al., 2010, 2011a; Winguth and Winguth, 2012). Upward movement of the chemocline (i.e., the top of the oxygen-minimum zone) was not geologically instantaneous but progressed over an interval of ~100 kyr during the latest Permian, decimating deepwater radiolarian and sponge faunas in advance of the main end-Permian extinction event (Wignall and Newton, 2003; Algeo et al., 2012; Feng and Algeo, 2012; Shen et al., 2012a). However, environmental changes within Late Permian oxygen-minimum zones were complex, as shown by an analysis of an upwelling system along the northwestern Pangean margin (Opal Creek, Alberta, western Canada) by Schoepfer et al. (2013–this volume). This upwelling system was stable and highly productive during the Middle and Late Permian but experienced a rapid expansion of anoxia during the EPME, after which upwelling was largely terminated and productivity fell to low levels. This pattern is consistent with the results of a recent study of uranium isotopes, a proxy for global marine redox conditions, that showed that a ~6× expansion of anoxic sinks for uranium at the time of the

Table 1
Articles in the “Permian–Triassic paleoceanography” theme issue.

Article	Location	Age range	Type of study
1 Song et al.	South China	Chang–Scythian	C-isotope chemostratigraphy
2 Schoepfer et al.	Western Canada	Induan	Inorganic chemostratigraphy
3 Luo et al.	South China	Chang–Griesbach	Organic geochemistry
4 Algeo et al.	Global	Chang–Griesbach	Organic carbon fluxes
5 Takahashi et al.	Japan	Chang–Scythian	Inorganic chemostratigraphy
6 Heydari et al.	Iran	Wujiaping–Induan	Carbonate sedimentology
7 Woods	Western U.S.A.	Olenekian	Carbonate sedimentology
8 Li et al.	South China	Chang–Induan	Carbonate sedimentology
9 Shen et al.	South China	Chang–Griesbach	Inorganic chemostratigraphy
10 Zhao et al.	South China	Chang–Griesbach	Inorganic chemostratigraphy
11 Saito et al.	South China	Scythian	Organic geochemistry
12 Winguth and Winguth	Global	Chang–Griesbach	Paleoclimate modeling
13 Osen et al.	Global	Changhsingian	Paleoclimate modeling
14 Saitoh et al.	South China	Guad–Wujiaping	Carbonate sediments, paleoecology

EPME (Brenneka et al., 2011). Both results are consistent with strong sea-surface warming and intensified oceanic stratification during the end-Permian crisis.

Changes in oceanic circulation and redox conditions are likely to have had major consequences for Early Triassic marine plankton communities and primary productivity (Payne and van de Schootbrugge, 2007). Luo et al. (2013–submitted for publication) showed that changes in vertical gradients in organic $\delta^{13}\text{C}$ in Early Triassic seas were related to a shift in dominance from eukaryotic marine algae to bacteria, e.g., green sulfur bacteria in deepwater environments (Grice et al., 2005; Hays et al., 2007; Cao et al., 2009) and diazotrophic cyanobacteria in shallow-water environments (Xie et al., 2005, 2007; Luo et al., 2011). Biomarker studies were used to evaluate changes in shallow-marine algal–microbial communities (Chen et al., 2011), and this approach has been applied to the Cili section (Hubei Province, South China) in the contribution of Luo et al. (2013–this volume). The latter study revealed a complex post-disaster community in latest Permian microbialite beds consisting, in addition to cyanobacteria, of anaerobic bacteria, archaea, and/or acritarchs. The transformative changes in planktic and benthic algal–microbial communities documented in these studies suggest that major changes in marine productivity may have occurred during the PTB crisis. Such productivity changes were investigated by Algeo et al. (2013–this volume), who developed a series of transfer functions to back-calculate the sinking flux of organic carbon to the sediment–water interface and, more tentatively, to primary production in the ocean–surface layer. These calculations suggest that marine productivity did not vary in any systematic manner globally, but that certain regions were subject to major changes during the crisis—most notably, a crash of marine productivity across the South China craton that persisted for at least ~100 kyr into the Early Triassic.

Changes in oceanic circulation and redox conditions during the crisis interval influenced the global carbon and seawater sulfur cycles. At the EPME, marine carbonate $\delta^{13}\text{C}$ profiles exhibit a pronounced 2 to 8‰ negative shift, the source of which has been attributed to inputs of isotopically light carbon from volcanic CO_2 (Payne and Kump, 2007), seafloor or coalfield methane (Krull et al., 2004; Retallack and Jahren, 2008; Shen et al., 2012b), or soil organic matter (Algeo et al., 2011b). This C-isotopic shift was accompanied by a sharp shift toward more negative pyrite $\delta^{34}\text{S}$ values in Panthalassic deep-sea sediments, as documented by Takahashi et al. (2013–this volume). The latter shift reflects

an increased sinking flux of framboidal pyrite from the oceanic oxygen–minimum zone (Algeo et al., 2010, 2011a), as pyrite that is ‘syngenetic’ (i.e., formed within the water column) exhibits greater S-isotopic fractionation as a consequence of bacterial sulfate reduction within a sulfate–unlimited system (i.e., seawater; Wilkin et al., 1996, 1997). During the Early Triassic, both the carbon and sulfur cycles were strongly perturbed, as shown by large fluctuations (>10‰) in the marine carbonate $\delta^{13}\text{C}$ and seawater sulfate $\delta^{34}\text{S}$ records (Newton et al., 2004; Payne et al., 2004; Tong et al., 2007). A recent study (Song et al., in review) demonstrates positive and nearly synchronous excursions in the carbonate $\delta^{13}\text{C}$ and carbonate-associated sulfate (CAS) $\delta^{34}\text{S}$ records at this time, a pattern reflecting coordinated changes in rates of marine productivity, organic carbon sinking, and pyrite burial. Variation in these oceanic proxies was probably driven by sea-surface temperature changes: warming episodes led to a weakening of overturning circulation, reducing upwelling of nutrients to the ocean–surface layer and limiting primary productivity. Lower productivity led in turn to smaller organic carbon sinking fluxes, reduced rates of bacterial sulfate reduction and pyrite formation, and an isotopically lighter seawater sulfate pool. The oceanic C and S cycles remained closely coupled in this manner throughout the Early Triassic, a pattern that broke down only during the Spathian (Song et al., in review).

Latest Permian to Early Triassic shallow-marine facies are characterized by a variety of unusual carbonate deposits. Features that have been documented include seafloor crystal fans, subtidal stromatolite bioherms, and wrinkle structures (Schubert and Bottjer, 1992; Baud et al., 1997; Kershaw et al., 1999; Woods et al., 1999, 2007; Pruss and Bottjer, 2004; Pruss et al., 2006; Woods and Baud, 2008; Mata and Bottjer, 2009). Collectively, these features have been characterized as ‘anachronistic facies’ because their previous period of abundant occurrence was during the Late Proterozoic, about 300 Myr prior to the PTB (Sepkoski et al., 1991; Baud et al., 2007). Several studies in the present volume provide documentation of features of this type. Heydari et al. (2013–this volume) note the presence of large seafloor crystal fans in the PTB section at Shareza, Iran, which they link to major changes in the chemistry of tropical seawater and the mineralogy of marine carbonate precipitates in response to contemporaneous climate change. Woods (2013–this volume) describes micritic ooids and cortoids (grains with constructive micritic envelopes) in the Spathian Virgin Limestone from Nevada (western U.S.A.), and Li et al. (2013–this volume) document giant ooids of Induan age from Moyang (Guizhou Province, South China) that are of fully marine origin despite their large size (2–12 mm diameter). In both studies, ooid growth is thought to have been mediated by an abundance of surficial microbes resulting from high seawater nutrient concentrations. For the Moyang ooids, evidence of microbial influence is provided by the presence of tiny carbonate fluorapatite (CFA) crystals along cortical laminae, which are inferred to represent microbially adsorbed P. The Li et al. paper also includes a tabulation of global occurrences of giant ooids during the Early Triassic, the prevalence of which is consistent with contemporaneous global warming (Joachimski et al., 2012; Romano et al., 2012; Sun et al., 2012) and a consequent increase in the carbonate saturation levels of global seawater (Zeebe and Wolf-Gladrow, 2001).

The cause of extreme warming during the Early Triassic is thought to be the eruption of the Siberian Traps (Wignall, 2007), e.g., emissions of volcanic CO_2 and/or thermogenic methane from magmatic intrusions into the West Siberian Coal Basin (Payne and Kump, 2007; Retallack and Jahren, 2008). Although radiometric ages for the Siberian Traps (~252–250 Ma; Campbell et al., 1992; Renne et al., 1995; Reichow et al., 2009) are effectively coeval with the end-Permian crisis within present dating uncertainties (Mundil et al., 2010), few if any studies have presented evidence of a direct link between these eruptions and coeval biotic or climate change. Two studies in the present volume attempt to address this deficiency. Shen et al. (2013–this volume) investigated the relationship of volcanic ash

layers to marine environmental changes in the deepwater Xinmin section (Guizhou Province, South China). They determined that recurrent episodes of volcanic ash deposition during the pre-crisis Late Permian had harmful effects on the local marine environment, and that a massive increase in the flux of volcanic ash coincided with the EPME. In another study, Shen et al. (in review) demonstrate a link between volcanic ash deposition and concurrent changes in the composition of the marine microplankton community, especially acritarchs and radiolarians, in two South China PTB sections (Xinmin and Shangsi). Zhao et al. (2013–this volume) demonstrated a strong volcanic influence on shallow-marine PTB sections at Meishan D (Zhejiang Province) and Daxiakou (Hubei Province) through another approach—analysis of rare earth elements (REEs) in conodont apatite. Although they sought to recover a seawater REE signal, a careful analysis of elemental patterns revealed that the bulk of the REEs in all samples were derived from terrigenous material, probably the clay minerals that are present in low concentrations in both sections. REE profiles revealed a large compositional shift at the level of the EPME, with post-boundary samples showing substantially elevated total REE concentrations, low Eu/Eu* and La/Yb ratios, and high Th/La ratios. These characteristics are consistent with a significant volcanic component in the clay fraction (cf. Shen et al., 2012a, 2012b, 2013a), suggesting that volcanic ashfall (or erosion of ash deposits from land areas) markedly influenced the composition of marine sediments for an extended ($> 10^5$ -yr) interval following the EPME. Although these studies provide evidence of volcanic influences on latest Permian marine biotas and environments, it is not yet known conclusively whether the ash layers found in Upper Permian–Lower Triassic strata in the South China region were sourced from the Siberian Traps, as hypothesized by Shen et al. (2012b, 2013a–this volume).

The full recovery of marine ecosystems following the PTB crisis was remarkably slow, extending over the ~5-Myr duration of the Early Triassic (Bottjer et al., 2008; Song et al., 2011). One factor contributing to the slowness of recovery may have been the magnitude of the mass extinction, necessitating an unusually long post-crisis interval for the evolution of new taxa and reintegration of the marine ecosystem (Erwin, 2001, 2007; Chen and Benton, 2012). Another factor may have been repeated environmental perturbations during the Early Triassic (Xie et al., 2005, 2007; Retallack et al., 2011; Yin et al., 2012), possibly linked to multiple eruptive phases of the Siberian Traps (Song et al., in review). However, it is now clear that Early Triassic marine environments were subject to persistently extreme conditions, especially strongly elevated sea-surface temperatures, from the Griesbachian through the Smithian (Romano et al., 2012; Sun et al., 2012). Significant seawater cooling began only in the Early Spathian, leading to a reduction in the intensity of oceanic stratification (Song et al., 2013–this volume), enhanced overturning circulation and nutrient upwelling, and a final, brief episode of productivity-driven marine anoxia (Galfetti et al., 2007, 2008; Song et al., in review). Following the earliest Spathian cooling event, both the global carbon and seawater sulfur cycles stabilized (Payne et al., 2004; Tong et al., 2007; Song et al., in review). A general amelioration of marine environmental conditions led to a strong recovery among many clades of marine invertebrates during the remainder of the Spathian (Brayard et al., 2006, 2009; Bottjer et al., 2008; Chen and Benton, 2012). Recovery of terrestrial ecosystems was under way during the same interval as herbaceous lycopsids and bryophytes that had dominated terrestrial floras since the EPME were replaced by woody gymnosperms (Looy et al., 1999; Herrman et al., 2011). The article by Saito et al. (2013–this volume) documents the same general pattern of terrestrial floral change for South China as previously reported from Greenland and Pakistan, providing further evidence that such changes were of global extent.

Several articles in this theme issue explore Permian–Triassic paleoceanographic conditions on the basis of climate model simulations. The study by Winguth and Winguth (2013–this volume)

reveals a high variability in monsoonal precipitation and associated fluctuations in river runoff and equatorial upwelling in response to precessional extremes, leading to significant variations in the export of carbon from the euphotic zone and hence reduction in dissolved oxygen concentrations in subsurface layers. These findings are in agreement with the decimation of the radiolarian zooplankton community, potentially in the oxygen minimum zone, as inferred from the Chinese and Japanese marine sections (Isozaki, 1997; Algeo et al., 2010, 2011a; Shen et al., 2012a; Feng and Algeo, 2012). Strong changes in river run-off linked to precipitation oscillations possibly led to a high variability in the nutrient supply to the Tethys Ocean, thus affecting regional productivity and oxygen distribution. The presence of a mid-ocean ridge in the Panthalassa enhanced vertical mixing and topographic steering of currents near the ridge axis, as shown by Osen et al. (2013–this volume). The oxygen contrast between deep-sea basins that are separated by mid-ocean ridge appears small due to enhanced vertical mixing. Changes in sill height between the deep Paleo-Tethys and Panthalassa during the Late Permian to Early Triassic could have led to environmental changes within the Paleo-Tethys. A rise in sill height would have led to enhanced stratification, and the associated reduced dissolved oxygen concentration of the water masses to dysoxic or near-anoxic conditions below 1800 m, thereby contributing to the regional extinction of species at the EPME.

In summary, the scientific contributions to the present theme issue provide new insights regarding paleoceanographic changes during the end-Permian mass extinction and its aftermath. Collectively, these studies provide additional support for Siberian Trap magmatism as both the trigger for the EPME and the main cause of extreme environmental conditions that persisted for ~2 Myr thereafter and that significantly delayed recovery of marine ecosystems. Although a largely coherent picture of the PTB crisis has begun to emerge from these diverse studies, it should be noted that some findings remain 'discordant' and difficult to accommodate within this picture. First, the EPME was preceded by a second-order mass extinction within the Middle Permian (Stanley and Yang, 1994; Isozaki, 2009; Stanley, 2009; Bond et al., 2010), probably in response to the eruption of the Emeishan Large Igneous Province in southwestern China (Zhou et al., 2002). This event may have had oceanographic effects that were similar to, albeit less intense than, those at the PTB (Saito et al., 2013–this volume). The significance of this event as a precursor to the EPME, possibly 'setting the stage' for the end-Permian biocrisis, requires further investigation. Second, recent reports from the Guryul Ravine PTB section of northern India of a possible extraterrestrial sediment fraction (Brookfield et al., 2010) and of seismite and tsunamite beds (Brookfield et al., in revision) will need careful assessment. Earlier reports of chondritic meteorite materials linked to an extraterrestrial impact (Becker et al., 2001, 2004; Basu et al., 2003) were largely discredited (Farley et al., 2005; Müller et al., 2005), but it is not impossible that a bolide impact around the time of the EPME had regional effects on the northern Gondwanan margin. However, the timing of such an event in relation to the EPME would represent a major coincidence, unless the eruption of the Siberian Traps themselves or the carbon release from West Siberian coal beds was triggered by the impact. These and similar issues will require further investigations.

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