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Paleoceanographic and paleoclimatic context of Early Triassic time

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Abstract

The Early Triassic interval is dominated by unusual oceanic and climatic conditions that are perhaps unique to the Phanerozoic. Early Triassic oceans were likely anoxic and possibly alkaline while climate during the period was dominated by the expansion of deserts and the migration of warm, moist conditions to high Southern Hemisphere latitudes. Atmospheric O_2 levels apparently decreased during the period while CO_2 levels increased. The unusual and severe nature of many aspects of Early Triassic oceans and climate likely played a role in determining the timing and shape of the biotic recovery from the Permian–Triassic mass extinction. ***To cite this article: A.D. Woods, C. R. Palevol 4 (2005)***.

Résumé

Contexte paléocéanographique et paléoclimatique du début du Trias. Le contexte océanique et climatique du début du Trias s'avère exceptionnel, voire unique, dans l'histoire du Phanérozoïque. Les océans étaient vraisemblablement anoxiques et alcalins, tandis que, durant le même intervalle de temps, s'accroissait l'extension des déserts et qu'un régime climatique chaud et humide gagnait les hautes latitudes de l'hémisphère sud. Simultanément, les teneurs en oxygène de l'atmosphère semblent apparemment diminuer et, en revanche, celles du CO_2 augmenter. Les conditions anormales et rigoureuses qui affectèrent, à l'orée du Trias, maints paramètres des océans et des climats jouèrent sans doute un rôle déterminant dans le rythme et dans les modalités de la restauration de la biosphère qui succéda aux extinctions massives du Permo-Trias. ***Pour citer cet article : A.D. Woods, C. R. Palevol 4 (2005)***.

Keywords: Early Triassic; Paleoceanography; Paleoclimate; Anoxia; Biotic Recovery

Mots clés : Trias inférieur ; Paléocéanographie ; Paléoclimat ; Anoxie ; Reconquête biologique

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1. Introduction

Much effort has been focused in recent years on events surrounding the Permian–Triassic mass extinction. While most scientific interest has concentrated on the cause of the mass extinction and the role oceanic and climatic perturbations may have played in the event, far less energy has been directed towards the period following the mass extinction. Oceanic and climatic conditions during the Early Triassic were probably some of the most unusual and severe of the Phanerozoic and likely had at least some effect on the timing and shape of the biotic recovery from the Permian–Triassic mass extinction. Indeed, recent work on oxygenated sedimentary rocks from the Central Oman Mountains shows that the biotic recovery began much earlier under fully oxygenated conditions than in other regions where anoxic conditions were present [45,80]. Therefore, it is not enough to only document trends in how and when organisms recover; instead, recovery trends must be considered in light of environmental conditions.

Declines in the abundance of chert [3,38,60] and phosphorite [78] in the marine record, and coal in the terrestrial record [64] attest to the grim environmental conditions that were likely present during the Early Triassic. Evidence from deep sea cherts suggest that the deep oceans were probably anoxic throughout the entire Early Triassic [35], and those waters likely impinged on the continental shelves during the Griesbachian [87], and, to a lesser extent, during the Smithian-Spathian interval (refer to Fig. 1 for Early Triassic stratigraphic nomenclature). The widespread occurrence of inorganic calcite precipitates on the seafloor and large microbial bioherms in Lower Triassic rocks (e.g., [2,29,37,49,67,90]) are indicative oceanic conditions that may be more similar to the Proterozoic, when such features were last common to the rock record. Global warming and drying climates appear to have pushed deciduous forests, typically associated with warm climates, to the polar regions in the Southern Hemisphere [76,77], caused desert belts to expand to between 15° and 45°, and perhaps extend as high as 60° latitude [39], and led to the deposition of extensive evaporites [24]. Finally, the reduction of atmospheric O_2 during the span of the Early Triassic [6] would have acted as another source of environmental stress for both terrestrial and marine organisms that had adapted to the higher atmospheric O_2 levels of the Permo-Carboniferous [82].

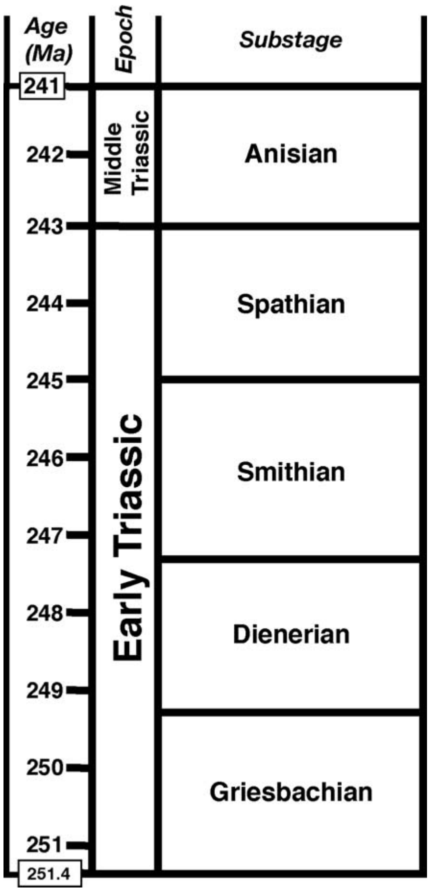

Fig. 1. Early to early Middle Triassic stratigraphic divisions and ages. Absolute ages are the top of the Anisian [11] and the base of the Triassic [10]. Other ages interpolated by Erwin et al. [20]. Modified from Erwin et al. [20].

Fig. 1. Subdivisions stratigraphiques et âges du Trias inférieur et du début du Trias moyen. Les datations absolues concernent le sommet de l'Anisien [11] et la base du Trias [10]. D'autres âges sont interpolés d'après Erwin et al. [20]. Modifié d'après Erwin et al. [20].

2. Early Triassic Paleoceanography

The collision of Gondwana and Laurasia in the Late Paleozoic resulted in the creation of a single large continent, Pangaea, an immense ocean, the Panthalassic Ocean, and a smaller ocean, the Tethys Sea. Study of Early Triassic paleoceanography is difficult due to nearly complete loss of Lower Triassic seafloor via subduction. Some windows into this period of Earth history exist in the form of allochthonous terranes (e.g., [35,75]), and provide tantalizing glimpses of oceans during this time, however, most inferences of Early Triassic oceanography come from modeling studies or analyses of sedimentary rock deposited along the continental margins.

2.1. Surface and deep ocean circulation

Surface currents were probably fairly simple during the Early Triassic. Modeling studies suggest that the supercontinent/superocean paleogeographic configuration resulted in the establishment of a simple 2-gyre system in the Panthalassic Ocean with a strong, westward-flowing equatorial current, and weaker return flow located around 60° paleolatitude [48] (Fig. 2). The Tethys Sea may have exhibited a similar 2-gyre current system centered on the equator [39]. Palaeogeographic reconstructions [69] suggest that the Neotethys likely had an open connection to the Panthalassic Ocean while the Paleotethys may have been more restricted.

The emergence of evidence indicative of anoxic waters in the global ocean during the Early Triassic [34,35] has compelled ocean modelers to develop models that satisfactorily explain the conditions necessary for widespread anoxia to be established in the deep ocean. Sluggish oceanic circulation, perhaps related to a decrease in the pole-to-equator temperature gradient, has been evoked as a cause for Early Triassic anoxia by many authors (e.g., [35,84,86]), and modeling studies

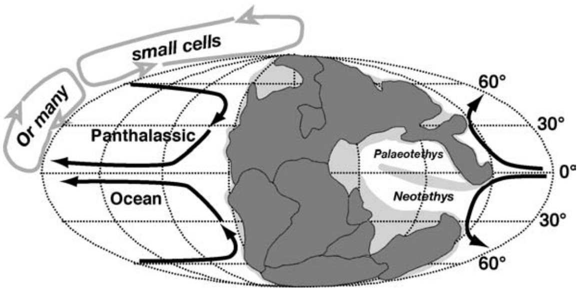

Fig. 2. Early Triassic paleogeography including surface ocean circulation (black arrows) and atmospheric circulation (gray arrows). Atmospheric circulation may have existed as a two-cell system, or may have been comprised of many small cells [39]. Currents in Panthalassic Ocean from Kutzbach [48]; atmospheric circulation from Kidder and Worsely [39]. Base map from Scotese [69].

Fig. 2. Paléogéographie du début du Trias incluant les circulations océanographiques des eaux de surface (flèches noires) et les circulations atmosphériques (flèches grises). La circulation atmosphérique pouvait comporter un système à deux cellules, ou être composée de nombreuses petites cellules [39]. Courants dans la Panthalassa d'après Kutzbach [48] ; circulations atmosphériques selon Kidder et Worsely [39]. Carte des continents et des océans selon Scotese [69].

support or marginally support this scenario [32,33,91]. Kidder and Worsley [39] further modified the sluggish ocean model in order to account for evidence of persistent Permo-Triassic warmth at the poles (e.g., [76,77]) by suggesting that the locus of deep water formation shifted from the poles to the subtropics during the Late Permian. According to their model, warm saline bottom water (WSBW) was produced in evaporative marginal seas, traveled through the deep ocean, and upwelled in polar regions [39]. WSBW would also be more likely to become anoxic due to the inverse relationship between O_2 solubility and water temperature and salinity, together with the anti-estuarine circulation that was likely present within WSBW source areas [12,32,39].

The development and perpetuation of anoxic conditions in the global ocean during the Early Triassic may have also been made more likely as the amount of O_2 in the atmosphere was significantly lower in the Early Triassic than the Permian (see below) [4,5,7,25,71]. Reduced atmospheric O_2 levels would have resulted in Early Triassic surface waters containing as little as two-thirds as much O_2 as Permian waters [32], allowing widespread anoxia to develop more readily.

2.2. Oceanic anoxia

The study of pelagic cherts from allochthonous terranes in Japan and British Columbia provide strong evidence that bottom-water anoxia was present in the Panthalassic Ocean from the middle Late Permian through the earliest Middle Triassic [34,35]. Red cherts from the Waipapa Terrane of New Zealand suggest that local, well-oxygenated areas may have existed in the Panthalassic Ocean [75].

Many studies have attempted to document the incursion of low-O_2 waters onto the continental shelves and into shallow water environments (e.g., [79,85,86]), and Wignall and Twitchett [87] produced a series of paleogeographic maps summarizing the extent of anoxic waters from the Permian–Triassic boundary through the mid-Dienerian. In general, widespread anoxic and euxinic conditions were present in the deep ocean throughout the period. Anoxic and suboxic waters expanded into shallow environments near the Permian–Triassic boundary, with the notable exception of the southern edge of the Neotethys where oxygenated conditions persisted until anoxic conditions apparently reached their maximum extent, during the Late Griesbachian [45,80,87]. Poorly-oxygenated waters retreated from the continental shelves by the mid-Dienerian [87]. Anoxic conditions apparently strengthened again during the Smithian-Spathian in the Panthalassic Ocean, but did not return to the Tethys Sea [87]. Smithian-Spathian anoxia has been documented in the outer shelf facies equivalent of the Moenkopi Formation, the Union Wash Formation of east-central California, U.S.A. [89,90], from basinal facies of the Thaynes Formation of the Phosphoria Basin (Idaho, Wyoming, Montana, Nevada and Utah, U.S.A.) [41,46], and from deeper water facies of the Western Canada Sedimentary Basin (western Alberta and eastern British Columbia) [14,15].

2.3. Anomalous carbonates

The Early Triassic period is characterized by a 'reef gap', or absence of large metazoan reefs [21]. Instead, shallow carbonate shelves commonly exhibit large microbial build-ups, and/or inorganic calcite seafloor precipitates in the form of fans and crusts (e.g., [2,29,51]; for a review of microbialite localities refer to p. 400 of Flügel [22]). Most Lower Triassic microbialites and inorganic calcite precipitates are found near the Permian–Triassic boundary; however, they have also been documented from the Smithian-Spathian interval. Nearshore facies of the upper Lower Triassic Moenkopi Formation of the southwest US contain m-scale microbial build-ups [58,59,67], while the correlative deep-water facies (outer shelf to slope) of the Union Wash Formation contain inorganic calcite fans and crusts [58,89,90]. In addition, similar-age microbial buildups have also been noted from the Nanpanjiang basin of south China [49]. Oolites also seem to be a common feature of Permian–Triassic boundary sections (e.g., [30,51]), and may share a common origin with microbialites and other inorganic precipitates that occur during the period.

The widespread resurgence of microbialites near the Permian–Triassic boundary and later in the Early Triassic may be due to their expansion into devastated, post-extinction environments as 'disaster forms' [67,68]. Similar trends in microbialites following mass extinctions have been noted elsewhere, including following the Late Ordovician [70] and Frasnian–Famennian [72,73] mass extinctions, however, the large size (meters to tens of meters high) of many Lower Triassic microbial bioherms implies that environmental conditions may also have played a role in their resurgence (see below).

Knoll et al. [40] hypothesized that anaerobic decay within a stratified ocean might lead to the buildup of CO_2 and H_2S beneath the redoxocline. Oceanic overturn would have resulted in rapid mixing of the Panthalassic Ocean and the release of large volumes of CO_2, which may have caused the Permian–Triassic mass extinction via hypercapnia (CO_2-poisoning) [27,40]. While this hypothesis did not garner much support as a kill mechanism for the mass extinction, one hypothesized effect of mixing of deep, anoxic, alkaline waters with well-oxygenated surface waters is the deposition of anomalous inorganic and microbial carbonates. Woods et al. [90] and Woods and Bottjer [89] modified the Grotzinger and Knoll [27] hypothesis to explain the presence of sea floor fans and crusts within the Union Wash Formation of east-central California by suggesting inorganic calcite precipitation took place as the result of localized upwelling of anoxic, alkaline waters. The occurrence of large microbial mounds during the period may also be the result of unusual seawater chemistry. Grotzinger [26] suggested that increased seawater alkalinity during the Proterozoic may have aided in the growth of large microbial mounds, and the possible establishment of analogous conditions during the Early Triassic may have had similar consequences [27,57,59]. Recent modeling studies have questioned whether such conditions could have developed in the global ocean during this time [8,33], but the feasibility of the Grotzinger and Knoll [27] model or its application to local or regional anomalous carbonate accumulations could not be definitely proved or disproved [8,33].

2.4. Early Triassic marine productivity

Long-terms declines in the depositional rates of chert [3,38,60] and phosphorite [78] have been documented during the Early Triassic interval. Kidder and Worsley [39] suggest that a dip in chert deposition and phosphorite formation might imply a reduction in the amount of nutrients available to the oceans. A smaller pole-to-equator thermal gradient would have reduced global wind velocities, causing an ebbing in upwelling intensity, and a drop in the amount of nutrients supplied to surface waters from the deep sea [38,39]. Kidder and Erwin [38] and Kidder and Worsley [38,39] further suggest that the expansion of dry climates during the period would have resulted in a decline in the rate of chemical weathering and a waning in the flux of terrestrial-derived nutrients to the ocean, however, a rise in strontium isotopic values during the Early Triassic period is indicative of increased continental erosion [42], and argues against a decrease in nutrient flux from the continents. The presence of chert in Lower Triassic sediments from the Waipapa Terrane of New Zealand [75] and black, organic-rich shales from accreted Japanese terranes [74] suggest enclaves of productive waters were present in the open ocean, while the occurrence of low-grade phosphorite deposits at high latitudes during the Early Triassic [78] may imply an overall shift in oceanic productivity from lower latitudes to higher latitudes during the period, however, the non-economic nature of these deposits attest to the low level of oceanic productivity during this time.

3. Early Triassic paleoclimatology

The vast area of the Pangaean supercontinent, as well as its north-south orientation, stretching nearly from pole to pole, had a profound effect on terrestrial climate during the period. Strong seasonality characterized the supercontinent [55], which was likely quite dry [16,56]. Increased levels of CO_2 in the atmosphere [4,5,7,25,71] led to global warming, resulting in an expansion of arid climates into high latitudes in the Northern Hemisphere [3,18,39,53,81,92], and the shift of deciduous forests to Southern Hemisphere polar regions [76,77].

3.1. Atmospheric composition

Modeling studies suggest that atmospheric O_2 levels decreased during the Early Triassic while atmospheric CO_2 levels increased [4,5,7,25,71]. O_2 levels dropped steadily during the Triassic after reaching maximum values (up to 35% of atmospheric volume) around the Permian-Carboniferous boundary, and bottomed out near 10% of atmospheric volume close to the Triassic-Jurassic boundary [7]. Atmospheric CO_2 levels underwent a substantial increase during the Permian–Triassic interval and remained high through the Triassic period [9]. A shift in the locus of organic carbon burial from terrestrial to marine settings [8,13], a decrease in the drawdown of CO_2 via photosynthesis due to dwindling global forest coverage and waning oceanic productivity [39], and a decline in the rate of silicate weathering caused by curtailed orogenesis during the terminal formation of Pangaea [39] have been proposed as drivers for long-term increases in atmospheric CO_2 during the Permian–Triassic interval. Additional sources of CO_2 to the atmosphere on shorter timescales include: 1) CO_2 release via eruption of the Siberian Traps around the Permian–Triassic boundary [61]; 2) decay of large amounts of biomass annihilated by the mass extinction [8]; 3) buildup of CO_2 in deep anoxic waters of a stratified ocean followed by overturn and CO_2 degassing [40]; and 4) release of CH_4 from methane hydrates in marine sediments and subsequent oxidation of CH_4 to CO_2 [19,43,44,50].

Modeling studies suggest that the consequence of increasing CO_2 during the Permian–Triassic interval was a rise in global temperatures on the order of 6–8 °C [66]. Evidence of global warming during the period can be seen within isotopic records for the period (e.g., [31,54]), as well as the presence of high-latitude deciduous forests in the Southern Hemisphere [76,77], shifts in the distribution of temperate paleosols to higher latitudes [62,63], and an expansion of dry climates [39,53,81,92,93] into high latitudes [3,18].

A decrease in atmospheric O_2 is supported by the presence of berthierine in Earliest Triassic paleosols [71]. In addition, low atmospheric O_2 levels during the Early Triassic may be responsible for adaptations in terrestrial vertebrates that allow greater uptake of O_2 such as large, barrel chests in *Lystrosaurus* and *Proterosuchus* [65] or the evolution of complex and efficient respiratory systems in birds [82].

3.2. Atmospheric circulation

Evidence for warm, moist polar climates (e.g., [63,76]) during the Early Triassic implies major atmospheric reorganization during this time [39]. Modern polar climates are dry as sinking air of the Polar Cell leads to high pressure and clear skies [83]. Kidder and Worsely [39] propose that the Polar Cell either weakened or disappeared altogether, allowing deciduous forests [76,77] and temperate paleosols [62,63] to develop at high latitudes. As a result, the modern 3 convection cell system in each hemisphere (Hadley, Ferrel, and Polar [83]) either broke down into a more chaotic configuration, or converted to a 2-cell system in each hemisphere (Fig. 2). Kidder and Worsley [39] also suggest that the region of sinking air, high pressure, and dry climates located between the Hadley Cell and Ferrel Cell in the modern atmosphere (between about 25° to 35° latitude [83]), may have expanded to between 15° and 45° latitude, and perhaps to latitudes as high as 60°. This hypothesis is based on paleophytogeography from the Permian–Triassic interval that implies growth of desert belts during this time [53,81,92,93]. The expansion of dry climates also led to widespread deposition of evaporates [24], and marginal evaporative basins may have served as source areas for deep ocean waters (WSBW) [39].

3.3. Cloud cover

If sinking air and high pressure at the poles were replaced during the Permian–Triassic interval by rising air, low pressure, and warm climates, the result would be an increase in clouds over the poles, as suggested by Kidder and Worsley [39]. Cloud cover is fed with moisture from warm ocean waters, and further insulates the poles by trapping warmth. Tropical regions would also experience greater cloud cover than today as global temperatures increased; however, thick clouds would likely prevent temperatures from becoming too extreme in the tropics [39]. This model is in contrast with paleophytogeographic evidence presented by Ziegler et al. [92], which suggests that the tropics may have become too dry to support any plant life during this time. This dichotomy may be the result of the extremely seasonal conditions brought about by the Pangaean megamonsoon (see below).

3.4. Pangaean Megamonsoon

Climate models suggest that Pangaea was dominated by strongly seasonal rainfall patterns [23,47,88] that were the result of the development of the Pangaean 'megamonsoon' [47,55]. Monsoonal conditions developed because Pangaea was nearly symmetrical around the equator, and the almost pole-to-pole distribution of the supercontinent likely caused a breakdown in zonal circulation (Fig. 2) [47,55]. Seasonal contrasts in temperature between hemispheres created a pressure gradient that led to cross equatorial air flow [47,55]. As air was passing from one hemisphere to the other it passed over the Tethys Sea, which would have provided moisture to the air mass as well as latent heat [47,55]. The result would have been strongly seasonal rainfall where climates were dominated by wet summers and dry winters, similar to conditions in south Asia today [83]. The development of the Pangaean megamonsoon is reflected in the widespread deposition of red beds, which are thought to be deposited in areas of strongly seasonal rainfall [55].

3.5. Storms

Global warming during the Early Triassic likely resulted in an increase in the intensity and frequency of hurricanes as well as winter storms [1,17,36,39,52]. An increase in the wavelength of hummocky cross-stratification over the Permian–Triassic interval supports this hypothesis [36]. Kidder and Worsely [39] suggest that warm waters both at the surface and at depth in the Late Permian and Early Triassic seas might have allowed hurricanes to reach sizes much greater than today and allowed those hurricanes to exist for longer periods of time provided they did not make landfall.

4. Summary and conclusions

Study of Early Triassic sedimentary rocks and fossils, as well as climate and ocean modeling reveal several aspects of Early Triassic oceans and climate:

- Early Triassic oceans were likely anoxic and euxinic [35], and those anoxic waters impinged into shallow environments during the Griesbachian [e.g.,87], and perhaps again in the Smithian–Spathian interval [89];
- oceanic anoxia was probably brought about by sluggish ocean circulation [32,33,91], perhaps coupled with a shift in the locus of deep water formation from the poles to the dry subtropics [39];
- the oceans may have been alkaline as well as anoxic, suggesting oceanic conditions during the Early Triassic may have been more similar to those of the Proterozoic than the Phanerozoic [27,40,90];
- atmospheric levels of O_2 decreased while levels of CO_2 increased [4,5,7,25,71];
- global warming led to temperate conditions in the polar regions [62,63,76,77], an expansion of desert belts [39,92,93], and a large-scale reorganization of atmospheric circulation [39];

- climate was dominated by monsoonal conditions [47,55] and storms with increased intensity and duration [1,17,36,39,52].

Recent studies (e.g., [80]) have noted the apparently complex nature of the biotic recovery from the Permian–Triassic mass extinction and suggest that the timing and shape of the recovery was likely strongly affected by environmental conditions. While the catastrophic nature of the mass extinction most certainly played a role in shaping the recovery [19], the widespread occurrence of deleterious conditions on land and in the seas suggests environmental factors were also important in determining the tempo and direction of recovery [28].

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