Changes in productivity and oxygenation during the Permian-Triassic transition

Arne M.E. Winguth
University of Texas Arlington, Department of Earth and Environmental Sciences, 500 Yates St., Arlington, Texas 76019, USA

The causes of the transition from an Early Permian cold house into an Early Triassic hothouse world have been of great interest, because this time encompasses the greatest extinction of species in Earth’s history. Common hypotheses for the causes of this transition include the massive volcanic eruptions of the Siberian Traps (e.g., Renne et al., 1995), and thermogenic methane emission from magmatic intrusions into the West Siberian Coal Basin (Retallack and Jahren, 2008; Svensen et al., 2009) as supported by coal fly ash deposits in lake deposits (Grasby et al., 2011). Alternative hypotheses favored a massive bolide impact, or a combination of impact and volcanism (e.g., Basu et al., 2003). The transition into a Triassic hothouse could also have been stimulated by a long-term reorganization of the carbon cycle (Berner, 2002) and associated biophysical-climate feedbacks (e.g., Beerling et al., 2007). For example, these feedbacks could consist of nitrous oxide release from microbial activities; emissions of volatile organic compounds (VOCs) such as isoprene from plants that can affect ozone, lifetime of methane and aerosol concentration; dimethyl sulfide (DMS) emission from marine plankton and its flux from the sea to the atmosphere where it is oxidized to a variety of compounds, including sulfate aerosols, which interact with sunlight to form cloud condensation nuclei that affect optical depth and albedo (Kump and Pollard, 2008).

The Permian-Triassic Boundary (PTB), ca.252 Ma, was characterized by a severe mass extinction (referred to as the latest Permian mass extinction, LPME) with the disappearance of >90% of marine species and a major macroevolutionary change (e.g., Erwin, 1994; Raup and Sepkoski, 1982). Potential causes for the marine extinction are controversial and include a lethal hothouse climate with tropical ocean water temperatures in the Tethys Ocean exceeding 40 °C (Sun et al., 2012). Increased ocean stratification and lower oxygen solubility induced by global warming could have contributed to a widespread decline in marine dissolved oxygen concentration, resulting in widespread shallow marine euxinic conditions, expansion of the oxygen minimum zone, and global deep-sea anoxia (e.g., Isozaki, 1997; Knoll et al., 1996). The ocean anoxia could have contributed to the release of H₂S to the atmosphere, as presently occasionally occurring in upwelling regions, the Gulf of Mexico, or the Black Sea. Mixing of sulfidic intermediate or deep waters to the surface and associated massive H₂S fluxes to the atmosphere could have led to a destruction of the oxygenate reservoirs, harmful ultraviolet exposure, and an increase in methane-induced global warming (Kump et al., 2005). In addition, the massive volcanic eruption of the Siberian Traps likely emitted highly acidic halogenes that could have led to a global depletion of the ozone concentration by up to 70% and massive ocean acidification (Black et al., 2014) which could have been enhanced by a substantial volcanic-induced carbon dioxide sequestration into the ocean (e.g., Clarkson et al., 2015).

One challenge is to estimate the global temperature for the Early Triassic to constrain environmental changes. Oxygen isotope measurements in conodonts and brachiopods are sparse and samples are potentially diagenetically altered (Joachimski et al., 2012). Hothouse worlds, like the Early Triassic are generally characterized by lower-than-present pole-to-equator surface temperature gradients, but climate models have generally underestimated polar temperatures for the PTB, and overestimated the pole-to-equator gradient (e.g., Kiehl and Shields, 2005). If global surface temperatures at the PTB rose by 10 °C or more (Retallack et al., 2011; Sun et al., 2012) and a typical climate sensitivity of 3 °C for the doubling of the preindustrial atmospheric CO₂ concentration is assumed (Knutti and Hegerl, 2008), then the atmospheric pCO₂ (or equivalent greenhouse house gases) must have risen by at least 10x pre-industrial levels, or 5600 PgC (1 Pg = 10¹⁵ g). These estimates appear reasonable, based on the CO₂ estimates from stomatal indices (Retallack et al., 2011), but even higher values may have been possible based on gas venting rates from metamorphism of organic matter in the Tunguska Basin in eastern Siberia (Svensen et al., 2009). Note that the consideration of biophysical and long-term geological climate feedbacks could have led to higher climate sensitivities (Kump and Pollard, 2008). Another challenge is to estimate how dissolved oxygen concentration were altered in the aftermath of the LPME by biological processes and by temperature- and salinity-dependent solubility of oxygen in seawater. The biological pump, or biological sequestration of carbon, may have been influenced by an increase in nutrient input into the ocean due to physical and chemical weathering changes by increases in atmospheric CO₂ concentration, warming, and acid rain, and by and alterations in landscape stability (Algeo and Twitchett, 2010). The transport of organic material into the deep sea could have led to an expansion of the oxygen minimum zone and anoxia (Meyer et al., 2008; Winguth and Winguth, 2012). Alternatively, primary productivity in the aftermath of the LPME may have declined (Shen et al., 2015) as indicated by substantially declined fossil abundance and reductions in body size (the “Lilliput effect”; Twitchett, 2007). Another alternative scenario in support of the diminished marine productivity would be a decline in wind-stress induced upwelling (Winguth et al., 2015). Thus, vertical organic carbon flux and the expansion of the oxygen minimum zone could have been reduced.

In this issue of Geology, Grasby et al. (2016, p. 779 ) report on newly gathered nitrogen isotope data from an Early Triassic (early Smithian) marine section at the Pacific Northwest (USA) and suggest that the increasing nutrient stress inferred from δ¹⁵N and N/P ratios and a decline in productivity inferred from metal proxies correspond with a substantial decrease in total organic carbon production. The authors imply that a transition to more negative δ¹⁵N may also be linked to higher rates of nitrogen fixation from atmospheric N₂ (Karl et al., 1997) and that deoxygenation could have occurred under conditions of a hot haline-mode ocean circulation, reduced upwelling with increased vertical stratification (Winguth et al., 2015), and a potential deepening and expansion of the thermocline. Eventually during the middle Triassic, when ocean temperature decreased and ventilation increased, renewed upwelling and nutrient supply to the euphotic zone, and a rise in organic-rich deposits occurred in the coastal region near northwest Pangea.

The study of Grasby et al. will certainly stimulate more research into Early Triassic environmental changes and their impact on regional and
global oxygenation. New insights on a biological pump mechanism under the hot, euxinic, and acidic conditions during the early Triassic may be developed. There is a need for a better understanding of the surface productivity changes under hothouse conditions and the associated development of euxinia in the oxygen minimum zone. For example, the microbial loop is expected to be intensified in a hothouse climate (e.g., Taucher and Oschlies, 2011) which could lead to reduced carbon export into the deep sea despite higher surface productivity.

The environmental changes in the aftermath of the LPME are of great importance for a better understanding of future climate change as indicated by the recent rise in global temperature (Hansen et al., 2010) and its environmental impact, such as an increase in marine productivity (Behrenfeld et al., 2006), and ocean deoxygenation (Long et al., 2016). More geochemical and stratigraphic analyses of available sections that consist of well-preserved records need to be completed to constrain the global change in temperature, productivity, and particle flux. These new data sets in conjunction with Earth system modeling that considers a variety of biophysical feedbacks promise to provide more insights in ecosystem changes during a transition to an extreme hothouse climate.

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