Lessons from Earth's deep past: Climate change and ocean acidification 200 million years ago

József Pálfy, Ádám T. Kocsis, Zsófia Kovács and Szabina Karancz

Abstract Major advances have been made recently in understanding of ongoing climate change and predicting its trajectory into the near future. However, only knowledge of past climate change events in the deep history of Earth can inform us about the possible extremes of greenhouse conditions, rates and magnitude of long-term climate change, and their consequences to the ocean and the biosphere. The end of the Triassic period was a time of major greenhouse warming, driven by volcanic emission of CO_2 and other gases from eruptions in the Central Atlantic Magmatic Province, one of the largest known igneous provinces. The end-Triassic mass extinction, one of the five most severe crises of the biosphere in the Phanerozoic, is best regarded as the biotic response to a cascade of rapid environmental changes triggered by volcanism. Ocean acidification was likely a major factor driving the selective extinction of calcifying marine organisms. Research in Triassic-Jurassic boundary sections in Hungary has helped elucidate changes in the carbon cycle as recorded in carbon isotope excursions, ocean acidification reflected in changes in carbonate sedimentation, and crises in both marine and terrestrial ecosystems. As anthropogenic increase of atmospheric CO_2 is the key forcing mechanism of ongoing climate change, further research into natural high-CO_2 events in Earth history, such as at the end-Triassic, will provide valuable insights for climate evolution scenarios.

$.1 Past and present climate change, ocean acidification and biodiversity crises

The Earth system is composed of four major interconnected subsystems, the lithosphere, hydrosphere, atmosphere and biosphere. Geologists use the rock record to understand processes and past changes in climate and environment, both on land and in the ocean, whereas paleontologists study the fossil record to reveal the history

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and past diversity of life on Earth.

The Holocene, when our geologically recent past merges with human history, is a more than 10,000-year-long epoch with relatively stable interglacial climate which was an important natural background for development of human societies. The climate record of the past millennium reveals that this stability was terminated by a rapid rise in temperature since the 20^{th} century.

Ongoing global warming is primarily driven by the anthropogenic increase of atmospheric CO_2, mainly from fossil fuel burning. Adverse effects of global warming are exacerbated by increasing uptake of CO_2 by the ocean which in itself restrains temperature increase, but leads to a decrease of seawater pH, known as ocean acidification. This process is detrimental to corals and other marine organisms which secrete calcium-carbonate skeleton, endangering reef ecosystems and driving many species to extinction.

Such changes unfolding in our human time scale are not unprecedented in Earth history. Five major mass extinctions punctuate the history of life on Earth, including the one at the Triassic-Jurassic boundary ~200 million years ago. The modern rate of species loss is comparable with or exceeds of those measured at the “Big Five” events (Raup & Sepkoski 1982), suggesting that mankind is unintentionally triggering the Sixth Extinction. Geological evidence is mounting to show that drivers of past biotic crises include rapid climatic and environmental changes, with many natural parallels to the modern world. The end-Triassic event has been subject to both detailed studies and recent reviews (Hesselbo et al. 2007, Pálfy & Kocsis 2014) and offers a prominent case of Earth system’s response to perturbation in deep time.

$.2 The Earth 200 million years ago

Planet Earth looked substantially different 200 million years ago. All landmasses formed the supercontinent Pangea which then started to break up by voluminous volcanism of the giant Central Atlantic Magmatic Province (CAMP) (Fig. 1). Carbon-dioxide emission and other consequences of CAMP volcanism are key in driving environmental change at the end of the Triassic period.

Radiometric dating of zircon crystals in volcanic ashes from marine sedimentary rocks in western Canada and Peru allows to pinpoint the age of the Triassic-Jurassic boundary at ~201 Ma. Dating of volcanic rocks from CAMP yielded the same dates, proving the synchrony of large-scale volcanism and extinction, helping to establish their cause-and-effect relationship.

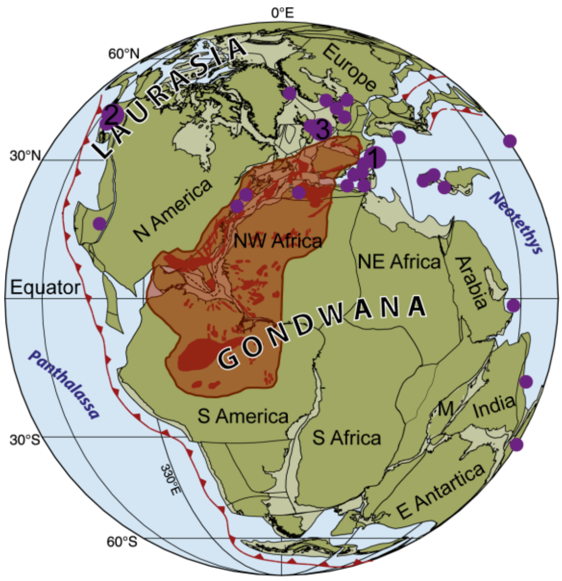


Fig. $.1 Paleogeographic map showing key stratigraphic sections with $\delta^{13}C$ data across the Triassic-Jurassic boundary. 1–Csővár, Hungary; 2–Kennecott Point, Canada; 3–St. Audrie's Bay, UK. (Modified from Pálfy & Kocsis 2014)

$.2.1 Biodiversity crisis and global warming at the Triassic-Jurassic boundary

Dramatic extinctions of marine organisms happened at the Triassic-Jurassic boundary. For instance, assemblages of radiolarians, marine siliceous microfossils, are markedly different across the Triassic-Jurassic boundary, but are remarkably similar on both sides of the vast Panthalassa superocean, now preserved in western Canada and Japan. This fossil group clearly shows the severe extinction at the end of Triassic, coeval with the CAMP volcanism. Although previous analyses or radiolarian turnover rates indicated otherwise, our new global analyses at higher stratigraphic resolution indicated that radiolarians were just as affected as bivalves, corals, or brachiopods (Kocsis et al. 2014). This indicates that both global warming and ocean acidification were important extinction agents. Few proxies are available to reconstruct the concentration of atmospheric CO_2 in the deep geological past. Leaves of fossil plants offer valuable clues as the density of their stomata, allowing the gas exchange, is proportional to pCO_2. Paleobotanical data from different localities indicate a massive increase in the CO_2 level at the Triassic-Jurassic boundary, leading to a major episode of global warming (Steinthorsdottir et al. 2011).

$.2.2 Carbon cycle perturbation at the Triassic-Jurassic boundary

If CO_2 were a key factor of climate and environmental change, then a perturbation of the global carbon cycle could be expected. Our best means to trace changes in the carbon cycle in the geological record is to measure the carbon isotopic ratios preserved in carbonate or organic carbon. So far nearly 50 Triassic-Jurassic boundary sections have been studied for stable isotope geochemistry worldwide. The first three of them, from Hungary (Pálfy et al. 2001), Canada (Ward et al. 2001) and England (Hesselbo et al. 2002), recognized a negative carbon isotope excursion in both organic matter and carbonate, before the first appearance of the earliest Jurassic ammonite genus *Psiloceras*. Possible causes of the sharp 2–4‰ excursion include CO_2 emission from CAMP volcanism, followed by methane release from gas hydrate dissociation. The latter process could be induced by gradual warming and in turn may have led to runaway greenhouse conditions. The best estimate for the duration of the excursion, based on cyclostratigraphy, is 20–40,000 years (Ruhl et al. 2010).

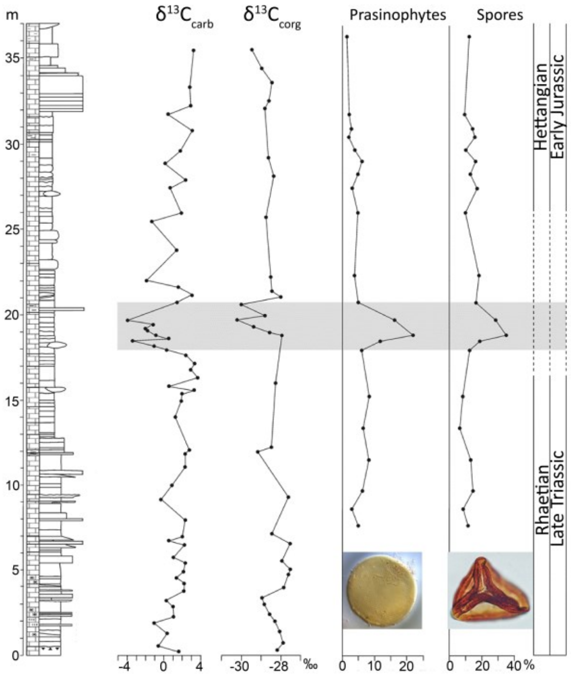
$.2.3 Ocean acidification at the Triassic-Jurassic boundary

As a corollary of the rise of atmospheric CO_2 which drove high global temperatures, changes in ocean chemistry also characterized the Earth ~200 million years ago. Carbon dioxide dissolved in seawater produce carbonic acid which dissociates to bicarbonate and hydrogen ion thus decreasing the seawater pH. The hydrogen ion reacts with the carbonate, and when the dissolved carbonate ion content of the water is depleted, more carbonate ions are supplied from carbonate rocks and shells or skeletons of marine organisms through dissolution, which leaves a signature in the stratigraphic record.

The Triassic-Jurassic transition shows a distinctive, nearly global interruption of carbonate sedimentation that hints to ocean acidification (Greene et al. 2012), which also had a severe effect on the marine biota. The end-Triassic extinction severely affected the carbonate secreting groups. Among these, corals are the best known, and represent one of the most ecologically sensitive groups, which suffered a major extinction at the end-Triassic, resulting in a reef gap in the earliest Jurassic.

Past global warming and acidification events are analogous in many ways to the ongoing global change. Even though the source of the CO_2 is different, the alteration of the atmospheric composition and ocean chemistry is comparable. The continuous uptake of CO_2 by the oceans results in increasing acidification. The ocean pH has already dropped 0.1 unit since the industrial revolution, and a further 0.3-0.4 unit fall is expected in the next century (Orr et al. 2005).

Fig. $.2 Carbon isotope excursion and synchronous spikes in abundance of fern spores and prasinophyte algae mark synchronous changes in both terrestrial and marine ecosystems and perturbation of the carbon cycle at the Triassic-Jurassic boundary in the Csővár section, Hungary. (After Götz et al. 2009)



$.3 The Triassic-Jurassic boundary in Hungary

Sedimentary strata spanning the Triassic-Jurassic boundary crop out in different parts of Hungary and were deposited in different environments. Marine rocks occur in the Transdanubian Range, whereas a coal-bearing terrestrial sequence is known from the Mecsek Mountains. A globally significant, continuous marine sedimentary section across the Triassic-Jurassic boundary is exposed near the village Csővár. Simultaneously with the worldwide documented excursion in the carbon isotope record, the marine and the terrestrial palynomorph assemblages also show spikes in their abundance (Fig. $.2). The proliferation of stress-tolerant green algae, the prasinophytes, point to the disturbance of the marine ecosystem, and is interpreted as a response to changes of ocean chemistry and temperature (Götz et al. 2009).

An abandoned quarry at the Kálvária Hill in Tata provides a spectacular exposure of the Triassic-Jurassic boundary developed in shallow marine environment (Fig. $.3). Here, as in several sections elsewhere in the Transdanubian Range, light grey platform limestone layers are abruptly terminated and are overlain by pink lowermost Jurassic limestone. The gap separating the two formations represents the boundary and is likely related to the cumulative effects of ocean acidification and extinction of marine organisms.

Studies of Triassic-Jurassic boundary sections in Hungary in the past 15 years has provided much new data and significant new insights. Ongoing research continues to focus on the paleontological, sedimentological and geochemical record to advance our understanding of the boundary events.

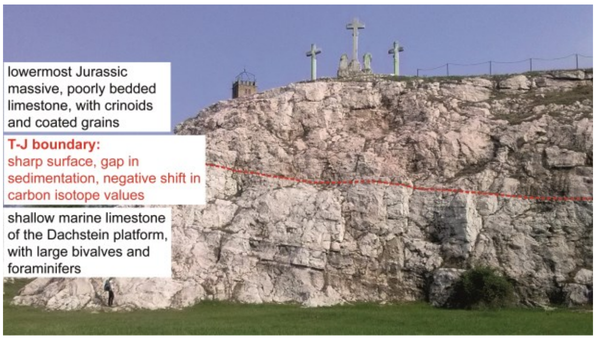


Fig. $.3 The Triassic-Jurassic boundary, marked by an abrupt change in sedimentation, in the abandoned quarry at Tata, Hungary

$.4 Conclusions

At the Triassic-Jurassic boundary, global warming and ocean acidification, with attendant geochemical and sedimentological signatures were part of a cascade of environmental changes that lead to a major mass extinction event (Fig. $.4). Triggered by volcanic eruptions and CO_2 emission of the Central Atlantic Magmatic Province, this crisis some 200 million years ago offers valuable lessons for understanding human-induced changes of today. The modern, anthropogenic surge in greenhouse gas emission has natural analogs in Earth's deep past. The many

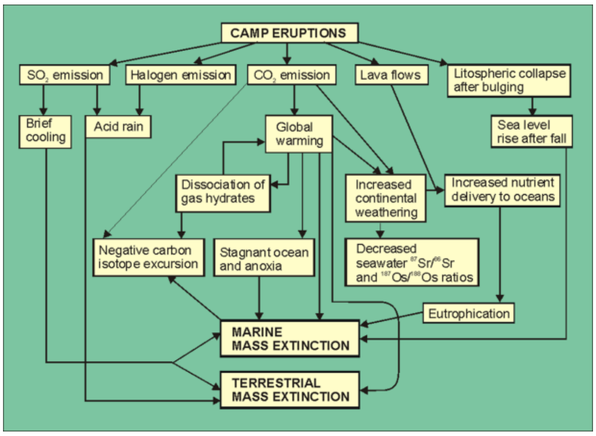


Fig. $.4 Schematic diagram summarizing the cause-and-effect relationship of various events taking part in the global change at the Triassic-Jurassic boundary. (Adapted from Wignall 2001)

similarities make reconstruction of past environmental and biotic crises, such as that at the end of the Triassic, a crucial step in understanding Earth system processes at times of extreme change. The Triassic-Jurassic boundary sections in Hungary preserve important records of these changes.

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