The Toarcian Oceanic Anoxic Event: where do we stand?

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Abstract: The study of past climate changes is pivotal for understanding the complex biogeochemical interactions through time between the geosphere, atmosphere, hydrosphere and biosphere, which are critical for predicting future global changes. The Toarcian Oceanic Anoxic Event, also known as the Jenkyns Event, was a hyperthermal episode that occurred during the early Toarcian (c. 183 Ma; Early Jurassic) and resulted in numerous collateral effects including global warming, enhanced weathering, sea-level change, carbonate crisis, marine anoxia–dysoxia and biotic crisis. The IGCP-655 project of the IUGS–UNESCO has constituted an international network of researchers with different disciplinary skills who have collaborated and shared conceptual advances on uncovering drivers of the environmental changes and ecosystem responses. This volume, Carbon Cycle and Ecosystem Response to the Jenkyns Event in the Early Toarcian (Jurassic), presents 16 works that investigate the early Toarcian environmental changes related to the global warming, sea-level rise, carbon cycle perturbation and second-order mass extinction through biostratigraphy, micropalaeontology, palaeontology, ichnology, palaeoecology, sedimentology, integrated stratigraphy, inorganic, organic and isotopic geochemistry, and cyclostratigraphy.

The study of oceanic anoxic events (OAEs) that affected past marine ecosystems provides the chance to place the ongoing environmental global changes in a geological, long-term perspective and to comprehend the future evolution of habitats and ecosystems. The Toarcian Oceanic Anoxic Event (T-OAE), also named the Jenkyns Event, during the Early Jurassic (c. 183 Ma), is a potential analogue for the ongoing global warming and biotic crisis. The study of this event constituted the subject of the IGCP-655 project entitled Toarcian Oceanic Anoxic Event Impact on Marine Carbon Cycle and Ecosystems (2017-20). The T-OAE was accompanied by global warming (García Joral et al. 2011; Korte and Hesselbo 2011; Suan et al. 2011; Them et al. 2017a; Ruebsam et al. 2020a, b) that altered marine ecosystems diversity (e.g. Jenkyns 1988; Jenkyns and Clayton 1997; Hesselbo et al. 2007) and led to sea-level changes (Hallam 1987; de Graciansky et al. 1998; Pittet et al. 2014; Haq 2018) and widespread deposition of black shales in various epicontinental basins (Jenkyns 1988). Both marine and terrestrial organic matter and marine carbonates record a negative carbon isotopic excursion (CIE) that documents a perturbation of the carbon cycle, coeval to this event (e.g. Jenkyns and Clayton 1986; Hesselbo et al. 2000, 2007; Schouten et al. 2000; Kemp et al. 2005; Suan et al. 2010; Caruthers et al. 2011; Izumi et al. 2012; Reolid 2014; Rodrigues et al. 2019; Ruebsam et al. 2019, 2020a).

Environmental perturbation was accompanied by a major biotic crisis that manifested in a second-order mass extinction, affecting marine invertebrates (Little and Benton 1995; Aberhan and Fürsich 2000; Cecca and Macchiioni 2004; Wignall et al. 2005; Gómez and Goy 2011; Danise et al. 2013, 2015; Caruthers et al. 2014; Rita et al. 2016), but also terrestrial tetrapods (Pol et al. 2020), while marine primary producers, such as nannoplankton and dinoflagellates experienced a temporary blackout (Bucel- falo Palliani et al. 2002; Mattioli et al. 2004; van de Schootbrugge et al. 2013; Correia et al. 2017).
A broad term for the early Toarcian climate perturbations: the Jenkyns Event

Over five decades, the global effects of the Toarcian environmental perturbations have been recognized from sediment archives around the globe. In particular, the global occurrence of black shales, formed under oxygen-deficient conditions, is a hallmark of the Jenkyns Event (e.g. Jenkyns and Clayton 1986; Jenkyns 1988). The deposition of organic carbon-rich sediments was associated with a long-lasting positive CIE, which was interrupted by the above-mentioned negative CIE (e.g. Hesselbo et al. 2000, 2007). Whereas the black shale record is strongly variable according to the palaeogeographic context (Wignall et al. 2005; McArthur 2019), the negative CIE is, however, a common feature of sedimentary rocks in most of the studied basins. While carbon cycle perturbations, associated with the T-OAE, affected marine and continental areas, black shale deposition was limited to basins that were prone to developing oxygen-deficient conditions. In this sense, T-OAE sensu stricto is not a term that is representative of the global change occurring during the early Toarcian and has to be used to indicate the effects of global perturbations in marine environments submitted to oxygen depletion.

Müller et al. (2017) proposed the ‘Jenkyns Event’ to more properly name the T-OAE, in honour of the early contributions on the early Toarcian environments by Professor Hugh Jenkyns. Reolid et al. (2020a) proposed using T-OAE when studying marine deposits with evidence of oxygen-depleted conditions, and the term Jenkyns Event in a wider sense for the global changes that occurred during the early Toarcian. According to these suggestions the Jenkyns Event includes:

1. The carbon cycle perturbation indicated by the prominent negative CIE affecting the marine environment (e.g. Saelen et al. 1996; Reolid 2014; Baghli et al. 2020) and land ecosystems (as shown by land plant organic matter, e.g. Hesselbo et al. 2007; Pieńkowski et al. 2020; Ruebsam et al. 2020a).

2. The oxygen-depleted conditions in marine ecosystems, in some areas reaching generalized anoxia and euxinia (e.g. Gill et al. 2011; Fonseca et al. 2018; Izumi et al. 2018; Ruebsam et al. 2018; Suan et al. 2018), but not affecting all basins and palaeomargins (e.g. Boomer et al. 2009; Reolid et al. 2014a, 2015; Miguez-Salas et al. 2017; McArthur 2019; Rodrigues et al. 2020).

3. An enhanced organic carbon accumulation during the negative CIE, but to a variable extent depending on latitude and local environmental conditions (e.g. Wignall et al. 2005), with the most typical facies being black shales in central and north Europe (e.g. Jenkyns and Clayton 1986; Bellanca et al. 1999; Röhl et al. 2001; Fonseca et al. 2018; McArthur 2019), but also in the Western Panthalassa Palaeomargin (e.g. Caruthers et al. 2011; Them et al. 2017b; Kemp et al. 2019).

4. A climatic change including a global warming (e.g. Gómez et al. 2008; Korte and Hesselbo 2011; Danise et al. 2013; Slater et al. 2019; Baghli et al. 2020; Ruebsam et al. 2020b; Ulmann et al. 2020), increased weathering (e.g. Brazier et al. 2015; Montero-Serrano et al. 2015; Fu et al. 2017), variations in detrital and nutrients input to marine basins (e.g. Rodríguez-Tovar and Reolid 2013; Danise et al. 2015; Fantasia et al. 2019; Kemp et al. 2019; Reolid et al. 2020b) and changes in marine productivity and a sea-level rise (e.g. Hallam 1987; Röhl and Schmid-Röhl 2005; Wignall et al. 2005; Mattioli et al. 2008, 2009) and acidification (e.g. Treballi et al. 2012; Müller et al. 2020; Ettinger et al. 2021).

5. A biotic crisis recorded with different manifestations in marine ecosystems (e.g. Little and Benton 1995; Bucefalo Palliani et al. 2002; Mattioli et al. 2008, 2009; Caswell et al. 2009; Gómez and Goy 2011; Danise et al. 2015; Caswell and Frid 2017; Reolid et al. 2019), but also recorded in terrestrial ecosystems by changes in diversity and composition in land plants (e.g. Mander and McElwain 2019; Slater et al. 2019) and herbivorous dinosaurs (Pol et al. 2020) with the intensification of wildfires in some areas during the end of the event (Baker et al. 2017). The biotic crisis includes extinctions, temporary disappearance (blackout) of taxa, and reduction in body size, as observed for calcareous nanofossils (Mattioli et al. 2004; Suan et al. 2010; Reolid et al. 2014a; Clémence et al. 2015; Ferreira et al. 2017), benthic foraminifera (Reolid et al. 2014b; Rita et al. 2016), ostracods (Cabral et al. 2020) and macroinvertebrates (brachiopods, García Joral et al. 2018; Piazza et al. 2019; bivalves, Ros-Franch et al. 2019; ammonites, Morton and Twichett 2009; and belemnites, Rita et al. 2019).

Future research topics

The Jenkyns Event is actually well established as a time of large-magnitude global palaeoenvironmental change, and may be the largest such event in the Mesozoic (Jenkyns 1985, 1988, 2010). In addition, early studies recognized the interest in this event concerning the origin of major oil and gas source
rocks (e.g. Barnard and Cooper 1981; Fleet et al. 1987). However, the growing sedimentological, palaeontological, and geochemical datasets generated for early Toarcian strata in a wide variety of settings have led to a number of controversies. Currently, there is no general consensus about the causes of the Jenkyns Event, which could include: (a) volcanic CO$_2$ and thermogenic CH$_4$ related to the emplacement of the Karoo–Ferrar Large Igneous Province that broadly coincides with late Pliensbachian–early Toarcian (McElwain et al. 2005; Hesselbo et al. 2007; Moulin et al. 2017; Fantasia et al. 2019); (b) destabilization of marine methane hydrates (Hesselbo et al. 2000; Kemp et al. 2005); and (c) increased rates of wetland methanogenesis (Them et al. 2017b) and deterioration of climate-sensitive reservoir permafrost areas during global warming (Ruebsam et al. 2019, 2020a, c).

Further uncertainty regarding the duration of the event arises from different cyclostratigraphically based timescales, in which well-characterized cyclic signals in lithological, micropalaeontological and geochemical proxies were interpreted as precession, obliquity or eccentricity cycles. The different assignments of sedimentary cycles with Milankovitch frequencies result in duration estimates that differ by an order of magnitude (e.g. Hinov and Park 1999; Kemp et al. 2005; Suan et al. 2008; Bouilila et al. 2014; Huang and Hesselbo 2014; Ruebsam et al. 2019). The generation of cyclostratigraphic records from a wide variety of biostatigraphically and chemostatigraphically constrained successions should eventually lead to a more stable cyclostratigraphic age model.

Also related to the role of volcanism in driving environmental changes, elemental mercury anomalies have been reported that may derive directly from volcanic input or indirectly from emerged land provenance (Percival et al. 2015; Them et al. 2019). The $\text{^{98/99}Mo}$ has been analysed to interpret the incidence of euxinic conditions and water renewal during the Jenkyns Event (Dickson et al. 2017). Other geochemical anomalies continue to be confirmed and refined, for example, Os isotopes ($\text{^{187}Os/^{188}Os}$; Cohen et al. 2004; Percival et al. 2016; Them et al. 2017b) and Ca isotopes ($\delta^{44/40}\text{Ca}$; Brazier et al. 2015), which were previously suspected to be proxies from water mass restriction (McArthur et al. 2008) but might indicate continental weathering. These results support the hypothesis that the Jenkyns Event included enhanced weathering associated with concentrated atmospheric greenhouse gases and a consequent flux of freshwater and nutrients to shallow shelves and oceans (Them et al. 2017b).

Despite the enhanced nutrient availability across vast shelf areas, marine primary producers, such as dinoflagellates and calcareous nanoplankton, experienced a major crisis during the Jenkyns Event (Bucefalo Palliani et al. 2002; Mattioli et al. 2004, 2008, 2009). Biological activity was probably also affected by the lowering of salinity in surface waters of epicontinental basins, prolonged surface water stratification preventing the mixing of nutrients in surface water and sea-water deoxygenation in a context of climate warming (e.g. Mattioli et al. 2009). High organic matter accumulation seems to be related to a combination of low accumulation rate during the Jenkyns Event and enhanced preservation of the organic matter, rather than enhanced biomass production (Mattioli et al. 2004, 2009).

Finally, Ruebsam et al. (2020a) inferred that the early Toarcian warming was paralleled by an increase in atmospheric CO$_2$ levels from c. 500 to c. 1000 ppmv. All of these records require confirmation or discussion in a wide variety of different settings from many locations away from NW Europe, where most studies have been conducted. Studies of parallel palaeoenvironmental changes in non-marine environments are still quite rare (e.g. Baker et al. 2017; Xu et al. 2017; Jin et al. 2020; Pol et al. 2020).

A dramatic decrease in calcareous nanoplankton production (Mattioli et al. 2009) and the coeval demise of carbonate platform production (Dromart et al. 1996; Mattioli et al. 2004) during the early Toarcian have been interpreted as evidence of a biocalcification crisis related to high $p$CO$_2$ levels in the atmosphere/hydrosphere system. In fact, high $p$CO$_2$ levels may have lowered the carbonate saturation state of Early Jurassic oceans, and finally, hampered biocalcification in shallow-platform and pelagic environments. However, the effects of enhanced CO$_2$ might have been indirect, affecting pelagic producers via changes in climate and sea-level. Indeed, precipitation/evaporation budgets and continental runoff-controlled nutrient levels and salinity in surface oceanic waters also are major factors impacting on pelagic biocalcifiers (Mattioli et al. 2009; Suan et al. 2010).

Several environmental changes have been proposed for explaining the mass extinction event in marine environments, such as marine deoxygenation affecting platforms and oceanic deep environments, a rapid greenhouse warming event and sea-level changes (e.g. Hallam 1987; Röhl et al. 2001; Bailey et al. 2003; Jenkyns 2003; Wignall et al. 2005; Gómez and Guy 2011; Reolid et al. 2012, 2019; Caruthers et al. 2014; Ria et al. 2016; Caswell and Frid 2017; Them et al. 2018).

Finally, a limited number of works documented the incidence of the Jenkyns Event in areas located in the Southern Hemisphere or in the eastern Tethys (e.g. Fu et al. 2017; Them et al. 2017b; Fantasia et al. 2018). Detailed correlation between different depositional environments will be critical to the
successful application of new palaeoenvironmental proxies, but will also be critical to the wider confirmation or rejection of hypotheses currently built on relatively small and palaeogeographically limited datasets.

The contributions of this volume

The contributions in this volume investigate climatic changes related to the sea-level rise, carbon cycle perturbation, global warming and second-order mass extinction through detailed studies of upper Pliensbachian to middle Toarcian biostratigraphy, micropalaeontology, palaeontology, ichnology, palaeoecology, sedimentology, integrated stratigraphy, inorganic, organic and isotopic geochemistry and cyclostratigraphy.

The paper by Correia et al. (2021) is a review of the Early Jurassic dinoflagellate cysts of the Lusitanian Basin, with particular emphasis on the effects of the Jenkyns Event on the evolution of this planktic group. The work shows the late Pliensbachian radiation of dinoflagellate cysts and the highly productive pre-Jenkyns Event interval characterized by maximum abundance and richness values. The Jenkyns Event severely affected the evolution of this group for the remainder of the Early Jurassic with an earlier recovery at northern latitudes than in southern Europe basins.

Fraguas et al. (2021) present a quantitative analysis performed on latest Pliensbachian–early Toarcian calcareous nanofossil assemblages from the Camino section (Basque Cantabrian Basin) and describe their response to the environmental changes recorded during this time interval. Coinciding with the warmer and probably wetter conditions, recorded shortly before the Jenkyns Event, the mesotropical taxa were dominant. During the event, nanofossil assemblages were dominated by opportunistic taxa.

Menini et al. (2021) present new quantification data for fluxes and sizes of calcareous nanofossils and discuss primary v. carbonate production across the Jenkyns Event in the Mochras borehole (Cardigan Bay Basin, UK). That work clearly illustrates that relatively high nannoplankton production occurred prior to the event, and was followed by a blackout and a size decrease at the core of the event. Such new data open up the debate on the fate of organic and mineral carbon production and their export to the sedimentary reservoir in times of intense palaeoenvironmental perturbations.

Thuy and Nemberger-Thuy (2021) describe ophiuroid remains retrieved from Dudelange drill core (Luxembourg), spanning from the top of the Pliensbachian to the onset of the Jenkyns Event, and report a total of 21 species, including several new taxa. According to these authors the highest diversities are recorded just below the black shales corresponding to the onset of the Jenkyns Event.

As far as marine vertebrates are concerned, Bomou et al. (2021) present a palaeoenvironmental study of a Pliensbachian–Toarcian interval section from the Grands Causses Basin, where exceptionally well-preserved marine vertebrates have recently been excavated. This study sheds light on some of the key requirements that led to the preservation of marine vertebrates during and after the Toarcian Oceanic Anoxic Event.

Martin et al. (2021) report new ichthyosaur material retrieved from lower Toarcian of Beaujolais, France, composed of a partially articulated skull and a subcomplete skeleton preserved in a carbonate concretion, identified as stenopterygids. These specimens are among the finest preserved Toarcian exemplars known from Europe and, in one of them, soft tissue preservation is suspected. Taphonomic processes related to exceptional preservation of these remains in Lagerstätte-type deposits are discussed.

Two other works are focused on ichnology. Fernández-Martínez et al. (2021) study trace fossils from the Asturian Basin (north Spain) with special attention to the ichnogenus Halimedides. This opportunistic ichnogenus is associated with the recovery of the trace maker community after the reestablishment of favourable, oxic, conditions.

The work of Simo and Reolid (2021) is focused on the characterization of trace fossil assemblages from Pliensbachian and Toarcian successions from the Pieniny Klippen Belt, the Central Western Carpathians (North Slovakia) and the Subbetic (SE Spain). Conclusions suggest that hemipelagic bioturbated micritic limestone and marlstone contain trace fossils which are typical of deep shelf environment.

The study of Reolid et al. (2021) is focused on the early Toarcian flooding occurring in the North Gondwana Palaeomargin as well as the impact of the Jenkyns Event from the analysis of sedimentology, ichnology, calcareous nanofossils, inorganic geochemistry and stable isotopes. The data obtained point to environmental changes during the early Toarcian and the incidence of local bottom topography in the expression of the Jenkyns Event, including the development of oxygen-depleted conditions disrupted by high-energy events.

The work of Boomer et al. (2021) focuses on a condensed sequence (latest Pliensbachian to early Toarcian) from Somerset (SW England). The chronostratigraphic framework is based on abundant ammonites, diverse assemblages of ostracods, foraminifera and calcareous nanofossils and low-diversity dinoflagellate assemblages, and the negative CIE demonstrates the record of the Jenkyns Event. Faunal, geochemical and sedimentological evidence suggests that deposition largely took
place in a relatively deep-water shelf environment under a well-mixed water column. However, the biotic crisis, the presence of weakly laminated sediments and changes in microplankton assemblage composition within the Jenkyns Event indicate dysoxic (never anoxic), bottom-water conditions.

Müller et al. (2021) report new high-resolution geochemical data from two pelagic upper Pliensbachian–lower Toarcian sections from the Gerecse Hills (north-central Hungary), where the negative CIE occurs in a highly condensed (c. 30 cm) laminated marl and black shale bed in the Tölgyhát section, or is in a stratigraphic gap contemporaneous with the Jenkyns Event as in the Kisgerecse section. Their results suggest that calcification crises associated with excessive CO2 input into the ocean–atmosphere system during the Jenkyns Event severely affected pelagic carbonate systems.

Rodrigues et al. (2021) present the first detailed review of upper Pliensbachian–lower Toarcian kerogen assemblages from the southern areas of the West Tethys shelf (between Morocco and northern Spain) and demonstrate the use of the Phytoclast Group as a tracer of palaeoenvironmental changes in the early Toarcian. To understand the patterns and drivers of organic matter distribution in the late Pliensbachian–early Toarcian, comparisons are drawn with kerogen data and δ13C Org from Tethys and Panthalassa shelf locations from other climate belts. Changes in the opaque phytoclast/non-opaque phytoclasts are intimately related to climate gradients associated with the increment in water availability regarding different locations in the climate belts.

Fonseca et al. (2021) use a multi-proxy approach applied to the study of the organic content of the sediments of the Paris Basin representing the Jenkyns Event. The majority of the organic fraction of the Serpentinite Zone is dominated by bacterial biomass, with phytoplankton playing a secondary role, suggesting a marine environment with bottom water stagnation, possibly related to basin palaeogeomorphology and circulation patterns, with episodic euxinia.

Xu et al. (2021) present new molecular biomarker and organic petrographic data from Da’anzhai Member of the Sichuan Basin, China. They show for the first time the clear processes through which lacustrine algal growth during the Jenkyns Event accounts for a significant organic-matter flux to the lakebed in the Sichuan mega-lake. Lacustrine water column stratification during the event probably facilitated the formation of dysoxic–anoxic conditions at the lake bottom, favouring organic-matter preservation and carbon sequestration into organic-rich black shales in the Sichuan Basin at that time. This study provides insight into the wider understanding of continental response and carbon burial in major lake systems during past greenhouse climatic events.

Ruebsam and Schwark (2021) summarize and synthesize evidence for the presence of an Early Jurassic cryosphere in the Northern Hemisphere, based on sedimentological, palaeobotanic and geochemical data and thereby provide a comprehensive review on Jurassic climate developments.

Finally, Silva et al. (2021) report a very detailed assessment of high-resolution elemental and isotopic geochemical datasets from the upper Pliensbachian–lower Toarcian marl–limestone alternations cropping out at the La Cerradura section from the Betic Cordillera (Spain). This study shows that the periodic changes in lithology and sedimentary geochemistry observed at La Cerradura occur at orbital frequencies, suggesting an astronomical control on local–regional climate and environmental change in the mid–low-latitude South Iberian palaeomargin during the Pliensbachian and Toarcian.

Conclusions

An increasingly better understanding of the Earth System in the context of past climate changes is crucial for predictions about the fate of the diversity of life and the future of our society. The study of the Jenkyns Event captures the collapse of the global marine ecosystems and their subsequent recovery. One of the main challenges is understanding the mechanisms that triggered this hyperthermal event and its collateral effects, such as weathering, acidification, anoxia and biotic crisis. A better comprehension of the biotic response of different organisms occupying various trophic levels and habitats or climate belts to environmental adverse conditions is fundamental for understanding future potential mass extinctions.

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