

Advances in the understanding of the Toarcian Oceanic Anoxic Event (IGCP-655 annual report)

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Introduction

The study of catastrophic events that affected past marine ecosystems provides us the unique opportunity to establish models which can be applied to ongoing environmental changes and to understand future evolution of the biotas. The growing interest of the society for the ongoing and potential future environmental changes attests for the value represented by the analysis of past climatic changes. In the case of the Toarcian Oceanic Anoxic Event (T-OAE, Early Jurassic; ~182 Ma), a dramatic change of marine ecosystems related to massive extinction has been documented in several areas around the world. The Pliensbachian–Toarcian transition and the T-OAE are two global episodes recording worldwide palaeoenvironmental perturbations (Jenkyns, 1988; Jenkyns and Clayton, 1997; Hesselbo et al., 2007). The end of the Pliensbachian regression is followed by a transgression occurring in the Early Toarcian (Haq et al., 1987; de Graciansky et al., 1999). This transgression was also coeval with a widespread deposition of black shales (Jenkyns, 1988), a global warming (García Joral et al., 2011; Korte and Hesselbo, 2011; Suan et al., 2011), and perturbations of the carbon cycle indicated by a negative carbon isotopic excursion (CIE) documented in both marine and terrestrial material (Jenkyns and Clayton, 1986; Schouten et al., 2000; Hesselbo et al., 2007; Al-Suwaidi et al., 2010; Caruthers et al., 2011; Izumi et al., 2012; Reolid, 2014).

An important second-order mass extinction mainly of benthic organisms is documented at the Pliensbachian/Toarcian boundary and in the Polymorphum (= Tenuicostatum)/Levisoni (= Serpentinum) zones boundary (Little and Benton, 1995; Aberhan and Fürsich, 2000; Vörös, 2002; Cecca and Macchioni, 2004; Wignall et al., 2005; Gómez and Goy, 2011; Danise et al., 2013; Caruthers et al., 2014; Ullman et al., 2014; Rita et al., 2016). This extinction was probably driven by oxygen-depletion affecting platforms and oceanic deep environments of Boreal and Tethys domains (Röhl et al., 2001; Bucefalo Palliani et al., 2002; Wignall et al., 2005; Hermoso et al., 2009; Reolid et al., 2012; Rita et al., 2016).

A multidisciplinary, integrated analysis of the T-OAE from stratigraphic successions outcropping in various settings all over the world and the need for taking into account biotic (microfossils, macroinvertebrates and vertebrate assemblages) and abiotic data (sedimentology, cyclostratigraphy, mineralogy, elemental geochemistry, organic geochemistry and isotopic geochemistry) makes the development of an

international framework essential by involving researchers from different countries and having different scientific skills. The IGCP-655 project of the IUGS-UNESCO constitutes this international framework where researchers with different disciplinary fields collaborate and share conceptual advances.

Our project aims to investigate the climatic changes related to the sea-level rise, carbon cycle perturbation, sea water acidification, global warming and second-order mass extinction occurred at the Pliensbachian/Toarcian boundary and during the T-OAE. This goal will be achieved through the analysis of rock and fossil records from Algeria, Argentina, Canada, England, France, Germany, Greece, Italy, Iran, Japan, Morocco, North Siberia, Portugal, South China, Spain and Switzerland. Through detailed studies of Upper Pliensbachian to Middle Toarcian biostratigraphy, ichnology, palaeoecology, ecostratigraphy, sedimentology, mineralogy, geochemistry, biogeochemistry and cyclostratigraphy in the cited regions, this project is attempting to document the collapse of the global marine ecosystems and their subsequent recovery. The mechanisms related to the biotic response of various fossil groups (calcareous nanofossils, radiolarians, foraminifera, ostracods, dinoflagellates, bivalves, brachiopods, ammonites, and vertebrates) to climate and environmental adverse conditions will be apprehended. IGCP-655 also try to reconstruct the Early Jurassic oceanic and climatic conditions and investigate feed-back effects between carbon cycle perturbation and global warming as well as compare and correlate all the acquired data in a global stratigraphic framework.

To summarize, the main goals of this project are:

- (1) To unravel the impact of carbon cycle perturbation and the related global warming and oxygen depletion on marine ecosystems and productivity.
- (2) To elucidate the causes triggering this environmental change.
- (3) To clarify the initial phases of the biotic crisis and the factors controlling the biotic recovery for organisms at different trophic levels, from various habitats and climate zones. A special attention will be devoted to the adaptation strategies of opportunist and specialist organisms during the surviving and extinction phases (e.g., Lilliput effect, Lazarus effect, resilience, among others).

These objectives will be attained mainly by collaborative fieldwork in reference Pliensbachian to Toarcian successions, including the Lower Toarcian GSSP (Rocha et al., 2016), and related laboratory work. The IGCP-655 is a project including 98 researchers from 64 research centres corresponding to 25 countries. As a result, the IGCP-

655 and workshops organized provide a friendly platform for participants to communicate their own research results and also bring together global experts, and research facilities to solve a truly global-scale problem.

Main Advances on the T-OAE during 2017

The T-OAE is recognized as one of the most important environmental perturbations of the Mesozoic, with a dramatic impact on marine biota revealed by a significant mass extinction event in benthic and pelagic groups (e.g., Wignall et al., 2005). Still, questions regarding the mechanisms involved, the major environmental changes affecting biotas, the global scale and the synchronism remain unresolved. There is no general consensus about the causes or triggering mechanisms of the T-OAE, including the massive enrichment of isotopically light carbon and its transfer between the different reservoirs (e.g., Hesselbo et al., 2000; Kemp et al., 2005), or the production of thermogenic methane during the concomitant intrusive eruption of the Karoo-Ferrar province (e.g., McElwain et al., 2005). Several environmental changes may have been involved in the mass extinction event, such as generalized anoxia, the enhancement of greenhouse conditions and a severe warming, or the incidence of sea-level changes (e.g., Hallam, 1987; McArthur et al., 2000; Bailey et al., 2003; Ghaeder and Macquaker, 2011; Gómez and Goy, 2011; Reolid et al., 2012; Rita et al., 2016; among others). Originally, the T-OAE was considered as a global phenomenon, based on the apparently simultaneous deposition of organic-rich facies in many localities around world (Jenkyns, 1988). However, recent studies point to a significant geographical variability of the event and to the incidence of local or regional-scale processes influencing marine (McArthur et al., 2008; Rodríguez-Tovar and Uchman, 2010; Reolid et al., 2018) and terrestrial environments (e.g., Rodrigues et al., 2016; Baker et al., 2017). It is especially relevant the advance in our knowledge of the different phases of extinction and recovery of ecosystems and the survival strategies to this event.

The contributions of the members of the IGCP-655 during the first year of activity, 2017, have improved our understanding of the T-OAE. Most of these advances were presented in the 1st International Workshop on the T-OAE (October, 4–7th 2017, Jaén) and published in the Abstract Book of this meeting (Reolid (ed.), 2017). The major advances can be summarized in different research topics:

Sedimentology and Stratigraphy

The analysis of sedimentary successions of the Pliensbachian–Toarcian, including the black shales facies, is an important tool for interpreting environmental conditions and eustatic changes and constitutes the framework for analyzing palaeontological and geochemical data. Some studies have shown the frequency of tempestite deposits during the Early Toarcian in areas such as the South Iberian Palaeo-margin (Molina et al., 2017) and the Tibetan Carbonate Platform (Han et al., 2017). The increase of storm deposits during the T-OAE emphasizes the close link between carbon-forced global warming and tropical cyclones.

The analysis of mineral resources has focused on the Mn-carbonate

ore deposits from Hungary (Molnar et al., 2017). Moreover the presence of celestine concretions with anomalous high $\delta^{34}\text{S}$ in the South Iberian Palaeo-margin has been interpreted as precipitation in cold seeps. Bruneau et al. (2017) have worked on 3D stratigraphic numerical models for prediction of organic-rich deposits.

Cyclostratigraphic studies have been applied to Iberian Range (Val et al., 2017), High Atlas (Martinez et al., 2017) and Wales (Ruhl et al., 2017) with special emphasis on the orbital chronology. Ruhl et al. (2017) compare the high-precision numerical time-scale for the Early Toarcian with the Karoo-Ferrar volcanism and observe the negative CIE was not a direct consequence of volcanic carbon release.

Incidence of the T-OAE on Marine Communities

Some works have focused on the analysis of benthic microfossils. Soulémane et al. (2017a, b) have analyzed the turnover of ostracod assemblages at the Pliensbachian–Toarcian transition and at the T-OAE in the Southwestern Tethys, including North Gondwana and South Iberian palaeomargins. The study of diversity and composition of foraminiferal assemblages is a valuable tool to approach palaeoenvironmental conditions during the Toarcian biotic crisis (e.g., Rita et al., 2016). The analysis of foraminiferal morphogroups has been used with very good results on the North Siberian and North Algeria Toarcian outcrops (Glinskikh et al., 2017; Sebane and Touahria, 2017) for characterizing low oxygen conditions at the beginning of the Toarcian. Herrero (2017) has evidenced a step-wise extinction of benthic foraminifera in the Iberian Range during the Early Toarcian from outcrops where neither black shales nor foraminifera mass extinction are recorded.

The analysis of calcareous nannofossils and the relationship with the carbonate production, palaeoceanography and trophic regime during the T-OAE, has been studied by Ferreira et al. (2017) and Visentin et al. (2017). Based on the Lusitanian Basin record, Correia et al. (2017a, b) discussed the palynological response to the T-OAE, with a particular emphasis on dinoflagellates. In addition, phytoplankton community dynamics have been deduced from high-resolution biomarker analyses (Ruebsam and Schwark, 2017).

There are significant advances on the incidence of the T-OAE on the macroinvertebrate communities (e.g., Baeza-Carratalá et al., 2017; Caswell and Frid, 2017; Martindale and Aberhan, 2017; Monarrez et al., 2017; Posenato et al., 2017). Brachiopods and bivalves have been the main studied groups. Baeza-Carratalá et al. (2017) expose an interesting example of adaptive strategies of brachiopods during the T-OAE from the study of a deep-water brachiopod, resilient assemblage from Spain.

Many works have focused on the body size trends of organisms at the Early Toarcian extinction event, as for belemnites (Rita et al., 2017a), brachiopods and bivalves (Piazza et al., 2017), benthic foraminifera (Rita et al., 2017b) and calcareous nannofossils (Ferreira et al., 2017).

Ichnological analyses are especially interesting due the potential of trace fossils for interpreting changes in the sedimentation, oxygenation and nutrient availability. Miguez-Salas et al. (2017) and Rodríguez-Tovar et al. (2017) show good examples from the Lusitanian Basin with unusual behaviour and palaeobiological changes of tracemakers as a response to the T-OAE.

The study of fossil vertebrates was conducted on especially well-

preserved specimens and facies from Canada, Germany and England (e.g., Konwert and Stumpf, 2017; Martindale et al., 2017; Vincent et al., 2017). The main studied groups were actinopterygians (Konwert and Stumpf, 2017; Maxwell and Martindale, 2017; Maxwell and Stumpf, 2017), ichthyosaurs (Plet et al., 2017) and plesiosaurs (Vincent et al., 2017).

Geochemistry, Environmental Conditions and Palaeoclimatology

Various types of geochemical analyses are progressively providing an increasing set of information and allowing us to better understand the environmental conditions governing the climate, the oceanographic circulation, the weathering intensity, and the activity of volcanism. Thus, the massive enrichment of isotopically light carbon and its transfer between the different reservoirs have been proposed as causes triggering the negative CIE of the T-OAE.

Stable isotopes geochemistry was based mainly on $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$. Most of the analyses have been performed on bulk rock sample (e.g., Bougeault et al., 2017; Them et al., 2017a), belemnite rostra (Ait-Itto et al., 2017; Pugh et al., 2017), brachiopod shells (Ferreira et al., 2017), and organic matter (Silva et al., 2017). Also $\delta^{98/95}\text{Mo}$ has been studied from Central and North European sections for interpreting the incidence of euxinic conditions and water renewal during the T-OAE (Dickson et al., 2017). The osmium isotope ($^{187}\text{Os}/^{188}\text{Os}$) stratigraphy has been used to reconstruct the seawater composition and to approach the enhanced weathering during the T-OAE as a response to climatic warming (Them et al., 2017b).

The analysis of organic matter includes the determination of the total organic carbon (TOC), total sulfur, palynofacies and biomarkers. Some studies have focused on the reconstruction of paleoclimatology from analysing the charcoal and phytoclast abundances and palynofacies (Baker et al., 2017; Rodrigues et al., 2017; Xu et al., 2017). These works also give information about the processes happened in terrestrial environments, such as the incidence of wildfires on the pO_2 (Baker et al., 2017).

IGCP-655 Activities 2017

The first steps of the project were the preparation of a website (<http://igcp655-toae.com/>) as well as the organization of working groups for different topics.

Some educational activities have been developed (Fig. 1) by Luís V. Duarte (Univ. Coimbra) with the collaboration of the Portuguese Association of Biology and Geology Teachers in Morocco (March 2017; co-supervised by Driss Sadki, Univ. Meknes), and Peniche GSSP (April 2017) and with the *Casa das Ciências* (<https://www.casadasciencias.org/>; July 2017). The educational and science popularization of the T-OAE recorded at Peniche was emphasized in Duarte et al. (2017).

The main activity of the IGCP-655 has been the *1st International Workshop on the Toarcian Oceanic Anoxic Event (IW-TOAE)*, October 4–7th 2017 in the University of Jaén (Spain) organized by the Prof. Matías Reolid (Figs. 2 and 3). The workshop brought together specialists from all over the world to share new ideas and cooperate in the study of T-OAE. Researchers coming to the IW-TOAE presented interesting advances on the study of the Toarcian Oceanic Anoxic Event, including works on different disciplines such as biostratigraphy, ichnology, palaeoecology, cyclostratigraphy, sedimentology, mineralogy, geochemistry, and biogeochemistry from regions as diverse as Maghreb, South and North Europe, Arabian Peninsula, Siberia and Himalaya. There were 38 scientific attendees, over 18 oral presentations, and 17 posters with high-quality scientific contributions, and constructive discussions, within a friendly and cooperative atmosphere during the workshop. A total of 14 young scientists attended the IW-TOAE.

The IW-TOAE meeting comprised four days of activities. The first day, October 4th, we started with a very interesting short training course on ichnology and the use for interpreting bioevents by Prof. Francisco J. Rodríguez-Tovar and Dr. Javier Dorador of the University of Granada (Spain). The title of the course was “*The ichnological record as a tool to assess different order bio-events*”. The course, for a

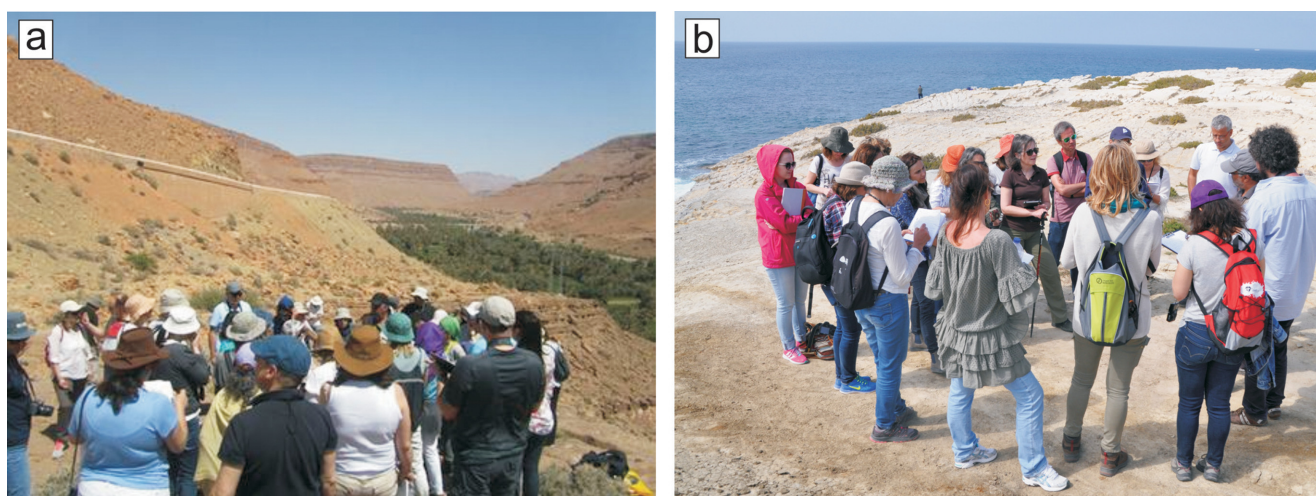


Figure 1. Educational activities for Biology and Geology High-School Teachers. (a) Visit of the Lower Jurassic of the High Atlas (Morocco) with professors Duarte (Univ. Coimbra) and Sadki (Univ. Meknes). (b) Visit of the Peniche GSSP for the Pliensbachian–Toarcian boundary, Portugal with the Professor Duarte.



Figure 2. Activities of the IW-TOAE. (a) Prof. Francisco J. Rodríguez-Tovar (Univ. Granada) during the course on ichnology. (b) PhD student Asad Abdi (Ferdowsi Univ. Mashhad, Iran) during his oral presentation. (c) PhD student Iben Winter Hougaard (Univ. Copenhagen, Denmark) during her oral presentation. (d) Discussions during the poster session. (e) After congress social dinner.

total of 7 hours, began with a first part: An introduction to ichnology (Fig. 2a). The second part: The use to approach environmental conditions before, during and after bio-events with special interest to oceanic anoxic events included examples from the K/Pg boundary event, the T-OAE, the OAE-1, the OAE-2 and the PETM. The last part, Digital image treatment for ichnofabric characterization in sediment cores was focused on the high resolution digital image treatment and applications with practical examples.

On October 5th we continued with the scientific sessions as well as an invited conference by Stephen P. Hesselbo, professor of the University of Exeter (United Kingdom) titled *Changing perceptions of the Toarcian Oceanic Anoxic Event; past, present and future research questions and directions*. After the scientific sessions (oral and poster, Figs. 2b–d), participants enjoyed with a guided visit of the Jaén historical centre and the congress social dinner (Fig. 2e).

On October 6th, we visited the Fuente Vidriera section, a reference

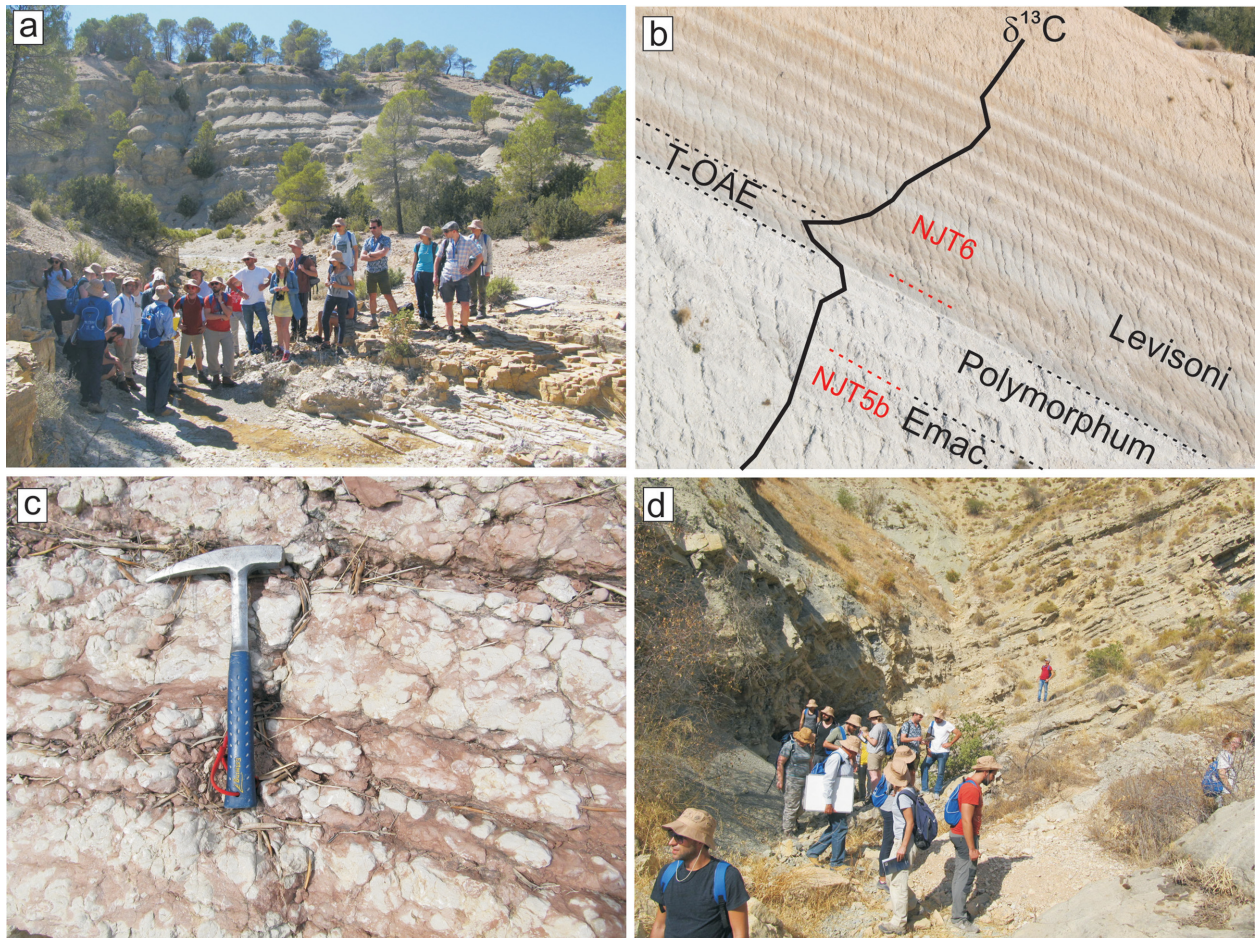


Figure 3. Field work and outcrops of the post-congress fieldtrip in the Betic Cordillera. (a) Fuente Vidriera outcrop, External Subbetic with the explanations of Prof. J.M. Molina (Univ. Jaén) about internal waves. (b) The T-OAE from La Cerradura section (External Subbetic), with the ammonite and calcareous nannofossil zones and the negative carbon isotopic excursion. (c) Ammonitico rosso facies section and the boundary of the middle and upper Toarcian of the Arroyo Mingarrón section (Median Subbetic). (d) Marl-limestone rhythmite of the Pliensbachian and lower Toarcian (Polymorphum Zone) in the Arroyo Mingarrón section.

outcrop located in the External Subbetic, Betic Cordillera (Murcia Province, Fig. 3a), where the Pliensbachian/Toarcian boundary and the T-OAE are well exposed (Rodríguez-Tovar and Uchman, 2010; Rodríguez-Tovar and Reolid, 2013). The researchers had the opportunity of sampling and having profitable discussion on the sedimentary expression of the T-OAE in this section (trace fossils, geochemical signal, $\delta^{13}\text{C}$ isotope excursion, microfossil assemblages) as well as the presence of internalites in the Middle Toarcian.

On October 7th, we visited the La Cerradura section close to Jaén, External Subbetic (Fig. 3b). The attendees discussed the previously published results for this outcrop such as geochemical proxies, stable isotopes, presence of a benthic barren interval in the Serpentinum Zone (Reolid et al., 2014) and the presence of spectacular celestine nodules. We continued our excursion southwards for visiting the Iznalloz section and Arroyo Mingarrón section of the Median Subbetic, located in the Granada Province (Figs. 3c and d). These sections are a good example for illustrating the fragmentation of the Iberian palaeomargin during the middle Pliensbachian, and of the presence of epioceanic trough (with marly deposits) and swells (with ammonitico rosso

facies) (Reolid et al., 2015, 2018).

The scientific and social activities during the meeting gave us many opportunities to explore new scientific networks and to share new ideas for advancing in the research on Mesozoic anoxic events. New collaborations have resulted after discussions, as well as new proposal for special sessions focused on the T-OAE in the framework of the IGCP-655.

IGCP-655 project supported some young researchers for attending the IGCP-655. They came from Iran, Morocco, Algeria, Portugal and Germany.

We are organizing now the next meeting in Coimbra-Peniche (Portugal), which will be held in September 2018. The second IW-TOAE will be organized by Prof. Luís Vitor Duarte (Universidade de Coimbra) September 6–9th 2018 including an Organic Matter Short Course, one day of scientific sessions and two days for fieldtrip visiting the outcrops of the Lusitanian Basin included the Peniche section (GSSP for the Pliensbachian/Toarcian boundary).

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