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by Matías Reolid<sup>1\*</sup>, Emanuela Mattioli<sup>2,3</sup>, Luís V. Duarte<sup>4</sup>, and Abbas Marok<sup>5</sup>

# The Toarcian Oceanic Anoxic Event and the Jenkyns Event (IGCP-655 final report)

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## Introduction

A better understanding the functioning of Earth System in the context of past climatic upheavals is essential for predictions about the fate of the diversity of life and the future of our society. The International Geoscience Program (IGCP), a joint initiative of UNESCO and IUGS, serves as a knowledge hub to facilitate international scientific cooperation in the geosciences. One of the strategical themes of the IGCP is *Global Change: evidence from the geological record*, which perfectly applies to the project IGCP-655, *Toarcian Oceanic Anoxic Event: Impact on marine carbon cycle and ecosystems*.

The study of oceanic anoxic events that affected past marine ecosystems provides us the chance to create models which can be applied to ongoing environmental global changes and to understand future evolution of habitats and ecosystems. The Toarcian Oceanic Anoxic Event (T-OAE, Early Jurassic) is a good past analogue for ongoing climatic changes. This event occurred during the early Toarcian (Serpentinum Zone), around 182 Ma ago, due to the Pliensbachian-Toarcian boundary is dated as 182.7 ± 0.7 Ma in the International Chronostratigraphic Chart v.2020/01 (Cohen et al., 2013 updated). However, the U-Pb geochronology of Sell et al. (2014) indicated that Pliensbachian-Toarcian boundary is older than 183.5 Ma and the beginning of the T-OAE was dated at 183.1 Ma. The term Toarcian Oceanic Anoxic Event was used initially by Farrimond et al. (1989). The T-OAE was an abrupt paleoenvironmental perturbation affecting the diversity of marine ecosystems (e.g., Jenkyns, 1988; Jenkyns and Clayton, 1997; Hesselbo et al., 2007). The end of the Pliensbachian sea-level regression was followed by a transgression which occurred during the Early Toarcian (Hallam et al., 1987; De Graciansky et al., 1998; Pittet et al., 2014; Haq, 2018) coeval with a widespread deposition of black shales in the majority of epicontinental basins (Jenkyns, 1988), and a global warming (Suan et al., 2011; García Joral et al., 2011; Korte and Hesselbo, 2011; Them et al., 2017a). A perturbation of the carbon cycle indicated by a negative carbon isotopic excursion (CIE) has been documented (Fig. 1) in both marine and terrestrial material (e.g., Jenkyns and Clayton, 1986; Schouten et al., 2000; Hesselbo et al., 2007; Al-Suwaidi et al., 2010; Suan et al., 2010; Caruthers et al., 2011; Izumi et al., 2012; Reolid,

2014; Rodrigues et al., 2019; Ruebsam et al., 2019, 2020a).

This Early Jurassic biotic crisis constitutes a second-order mass extinction for benthic organisms (Little and Benton, 1995; Aberhan and Fürsich, 2000; Cecca and Macchioni, 2004; Wignall et al., 2005; Gómez and Goy, 2011; Danise et al., 2013, 2019; Caruthers et al., 2014; Rita et al., 2016). This biotic crisis was probably driven by oxygen-depletion affecting platforms and oceanic deep environments (Röhl et al., 2001; Bucefalo Palliani et al., 2002; Wignall et al., 2005; Hermoso et al., 2009; Caruthers et al., 2014; Them et al., 2018; Reolid et al., 2012, 2019a).

The IGCP-655 project of the IUGS-UNESCO has constituted an international network of researchers with different disciplinary skills who collaborate and share conceptual advances. The IGCP-655 includes 111 researchers from 65 research centres corresponding to 26 countries. As a result, the IGCP-655 and the workshops organized provided a friendly platform for participants to communicate their own research results and to merge international experts, and research facilities to solve a truly global-scale problem. This project has favoured a multi-disciplinary, integrated analysis of the T-OAE from stratigraphic successions outcropping in different regions all over the world combining biotic (microfossils, macroinvertebrates and vertebrate assemblages) and abiotic data (sedimentology, cyclostratigraphy, mineralogy, elemental geochemistry, and isotopic geochemistry).

Our project aims at investigating the 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, ichnology, paleoecology, ecostratigraphy, sedimentology, mineralogy, geochemistry, biogeochemistry and cyclostratigraphy. Our project attempts at documenting the collapse of global marine ecosystems and their subsequent recovery. One of the main challenges is the knowledge of the mechanisms related to the biotic response of various organisms at different trophic levels, from different habitats and climate zones (calcareous nannofossils, radiolarians, foraminifera, ostracods, dinoflagellates, bivalves, brachiopods, ammonites, and vertebrates) to climate and environmental adverse conditions. Finally, the IGCP-655 also focused on the understanding of the feedbacks between carbon cycle perturbation and global warming and the impact on marine ecosystems and primary productivity.

## Classic and Promising new Pliensbachian-Toarcian Stratigraphic Sections

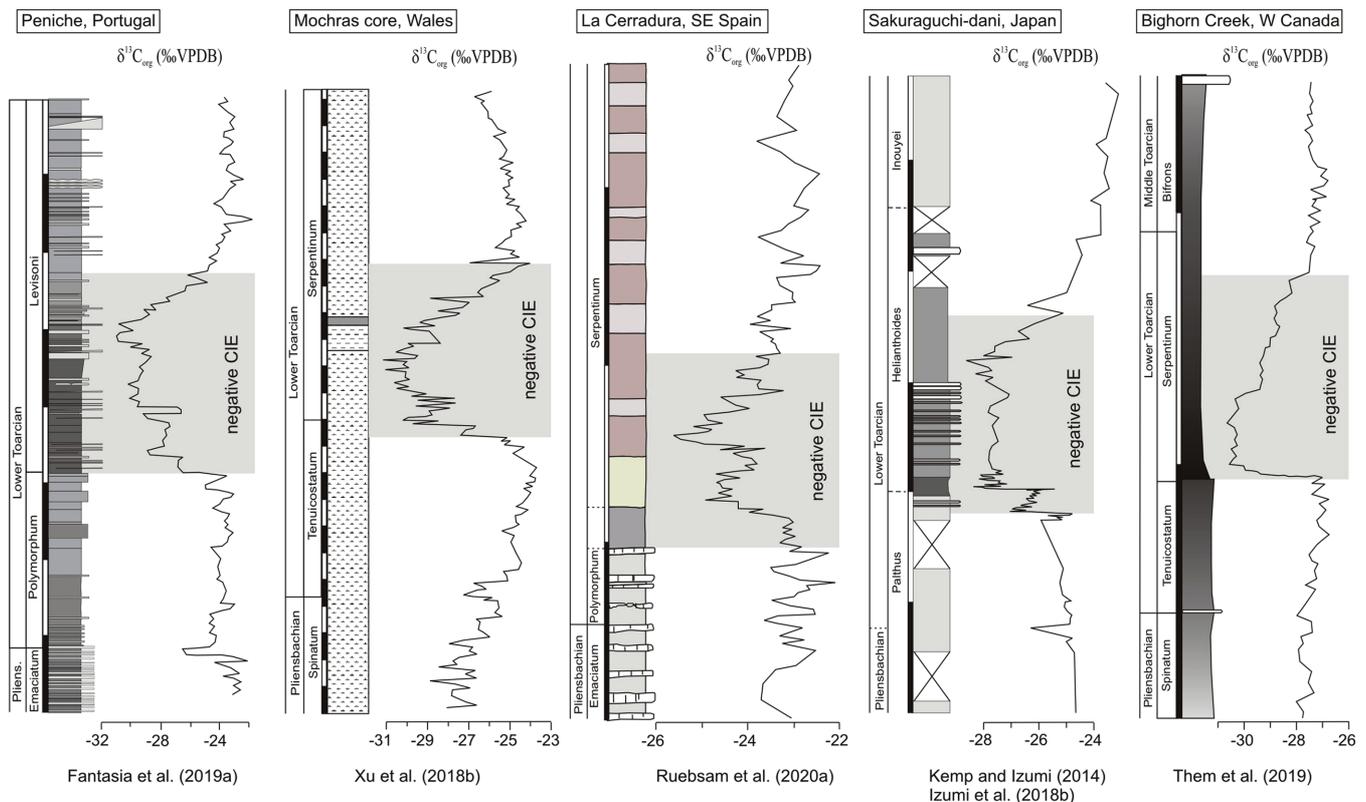
The recent and future advances in the knowledge of the T-OAE are derived from the collaborative fieldwork in reference to Pliensbachian to Toarcian successions. It includes the Peniche section (Lusitanian Basin, Portugal; Fig. 1), the Lower Toarcian GSSP (Rocha et al., 2016) where studies are continuously developing (e.g., Baker et al., 2017; Correia et al., 2017a; Duarte et al., 2017; Fantasia et al., 2019a; Ferreira et al., 2019; McArthur et al., 2019; Rita et al., 2019). Other classic sections such as Valdorbria (Umbria Marche Basin, Italy), María Pares (Lusitanian Basin), Yorkshire (Cleveland Basin, UK; Fig. 2) and Sancerre (Paris Basin) have been the subject of study during the IGCP-655 project, for analyses on foraminifera (Reolid et al., 2019b), palynostratigraphy (Correia et al., 2017a; Slater et al., 2019), benthic macroinvertebrates (Caswell and Dawn, 2019), sedimentology (Kemp et al., 2018), geochemistry (Dickson et al., 2017; Thibault et al., 2018; Reolid et al., 2019b) and cyclostratigraphy (Boulila and Hinnov, 2017; Saker-Clark et al., 2019).

Other classic material for the research on the T-OAE is the Mochras core (Cardigan Bay Basin, Wales; Fig. 1), where continuous research on magnetostratigraphy (Xu et al., 2018a), organic and inorganic geochemistry (Xu et al., 2018b), foraminiferal assemblages (Reolid et al., 2019a) and cyclostratigraphy based on  $\delta^{13}C_{TOC}$  (Storm et al., 2020) have

been recently published. Additional cores in the Lombardian Basin (Northern Italy), Colle di Sogno and Gajum cores, can be considered reference material for the pelagic lower Toarcian of the western Tethys and will provide high resolution data (Erba et al., 2019).

During the last three years, other promising sections for the Upper Pliensbachian-Lower Toarcian have been studied in Switzerland (Riniken and Gipf sections from Jura and Creux de l'Ours section from Sub-Briançonnais Basin; Fantasia et al., 2019b), in the South Iberian Paleomargin (La Cerradura section; Reolid et al., 2019c; Rodrigues et al., 2019; Ruebsam et al., 2020a; Fig. 1), in the North Gondwana paleomargin in Morocco (Issouka, Amellago and Talghemt sections; Bodin et al., 2016; Ait-Itto et al., 2017, 2018; Boulila et al., 2019; Rodrigues et al., 2020) and in Algeria (Raknet El Kahla section; Ruebsam et al., 2020b).

In Asia, marine deposits from Tibet (Bilong Co section, Chen et al., 2017; Fu et al., 2017) and cores of lacustrine deposits from Sichuan Basin (Xu et al., 2017) have been analysed confirming the incidence of the carbon cycle perturbation in basins out of marine environments. Moreover, sections from Western Panthalassa paleomargin show both negative CIE and oxygen-depleted conditions, such as in the Toyora area from Japan (Sakuraguchi-dani section; Izumi et al., 2018a, b; Kemp et al., 2019; Fig. 1). In the other side of the Panthalassa, more sections have expanded the knowledge of the T-OAE away from Tethyan paleomargins. Among others, we can indicate the East Tributary Bighorn Creek section (Fig. 1) and Haida Gwaii section in North America



**Figure 1.** Recent works showing the negative CIE obtained from  $\delta^{13}C_{org}$  values in different parts of the world: Peniche section from Lusitanian Basin, Mochras Core from Cardigan Bay Basin, La Cerradura section from South Iberian Palaeomargin, Sakuraguchi-dani section from Toyora area in the west Panthalassa, and East Tributary of Bighorn Creek section from east Panthalassa. The light-grey shaded area corresponding to the negative CIE has been located in the different sections between the level of sharp decrease of  $\delta^{13}C_{org}$  values and the return to pre-excursion values.

Eastern Panthalassa paleomargin (Western Canada; Caruthers et al., 2011; Them et al., 2017b) and Arroyo Lapa section from Neuquen Basin (Argentina; Al-Suwaidi et al., 2016; Ros-Franch et al., 2019).

## Main Advances of the IGCP-655 on the T-OAE

The T-OAE is documented as one of the most significant global events of the Mesozoic, but still there is no general consensus about the causes: volcanic CO<sub>2</sub> and thermogenic CH<sub>4</sub> related to the emplacement of the Karoo-Ferrar Large Igneous Province (McElwain et al., 2005; Hesselbo et al., 2007; Fantasia et al., 2019a); b) destabilization of marine methane hydrates (Hesselbo et al., 2000; Kemp et al., 2005); 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).

Several environmental changes have been involved in the mass extinction event in the marine ecosystems, such as marine deoxygenation, ocean acidification, rapid greenhouse warming event, and incidence of sea-level changes (e.g., Hallam, 1987; McArthur et al., 2000; Bailey et al., 2003; Jenkyns, 2003; Gómez and Goy, 2011; Trecalli et al., 2012; Rita et al., 2016; Caswell and Frid, 2017; Them et al., 2018). Numerous studies point to a significant geographical variability of this event and to the effect of regional-scale processes influencing marine (McArthur et al., 2008; Rodríguez-Tovar and Uchman, 2010; Reolid et al., 2014, 2018; Han et al., 2018; McArthur, 2019) and terrestrial environments (e.g., Rodrigues et al., 2016; Baker et al., 2017).

The contributions of the members of the IGCP-655 during the three years of activity (2017-2019), have improved our understanding of the T-OAE. Most of these advances were presented in the three annual meetings of the project, the International Workshop on the T-OAE in Jaén, Spain (2017), Coimbra, Portugal (2018) and Erlangen, Germany (2019). The major advances are summarized in three main research topics:

### *Stratigraphy and Sedimentology*

The analysis of stratigraphic successions of the Pliensbachian-Toarcian is an important tool for interpreting environmental conditions and eustatic changes and constitutes the framework for subsequent analyses of paleontological and geochemical data. Some studies have documented the frequency of tempestite deposits during the Early Toarcian in areas such as the South Iberian Paleomargin (Molina and Nieto, 2019), the Tibetan Carbonate Platform (Han et al., 2018) and the Andean Basin in northern Chile (Fantasia et al., 2018). The increase of storm deposits during the Early Toarcian highlight the close link between global warming and tropical cyclones (Krencker et al., 2015). Many works have focused on the interpretation from the geological record of the interaction of the oceanographic changes, climatic changes and carbonate productivity (e.g., Baroni et al., 2018; Han et al., 2018; Izumi et al., 2018a; Suan et al., 2018). Some studies put special attention on the analysis of sea-level fluctuations in the context of the sequence stratigraphy. Krencker et al. (2019) interpreted that a forced regression preceded the transgression related to the T-OAE. Fantasia et al. (2019a, 2019b) studied stratigraphic fluctuations of  $\delta^{13}\text{C}$ , TOC and sedimentary features for interpreting sea-level changes and paleoceanographic

incidence.

Cyclostratigraphic studies have been applied to Iberian Range (Val et al., 2017), Middle Atlas and High Atlas of Morocco (Martinez et al., 2017; Ait-Itto et al., 2018) and Wales (Xu et al., 2018a) with special emphasis on the orbital chronology. Ait-Itto et al. (2018), Them et al. (2018), Xu et al. (2018b) and Fantasia et al. (2019a) studied the incidence of volcanism on the paleoenvironmental change. Ruebsam et al. (2019) proposed that the cryosphere demise in high latitude was related to the global warming and the glacioeustatic sea-level change. Reolid et al. (2019c) focused in the analyses of carbon and sulfur isotopes from celestine concretions in the Lower Toarcian of South Iberian Paleomargin for interpreting the potential development of cold seeps during the lattermost Pliensbachian and early Toarcian.

### *Effect of the T-OAE on Marine Communities*

Most of the works on fossil assemblages have focused on the analysis of benthic forms. The analysis of the diversity and composition of foraminiferal assemblages is a valuable tool for interpreting paleoenvironmental conditions during the Toarcian biotic crisis. The analysis of foraminiferal morphogroups has been employed with very good results on the SE France (Jozsa et al., 2018), the Lusitanian (Maria Pares section, Reolid et al., 2019b) and the Cardigan Bay Basin (Mochras core; Reolid et al., 2019a), for characterizing the different phases of the biotic crisis and the recovery of the foraminiferal assemblages. These works have evidenced the incidence of the oxygen-depleted conditions, the role of opportunist forms and the subsequent recovery of the diversity after the biotic crisis. Salazar-Ramírez et al. (2019) have shown a stepwise extinction of benthic foraminifera in the Basque-Cantabrian Basin (Spain) during the Early Toarcian and faunal turnover in the Serpentinum Zone.

The other microfossil group intensely studied is ostracoda. Soulimane et al. (2017a, b) analyzed the turnover of ostracod assemblages at the Pliensbachian-Toarcian transition and at the T-OAE in different paleomargins from the Southwestern Tethys. Finally, Soulimane et al. (2020) propose a distribution of ostracod bioprovinces and the changes during the beginning of the Toarcian in the western Tethys.

The analysis of calcareous nannofossils, and the relationship with carbonate productivity and paleoceanography during the T-OAE, has been studied by Ferreira et al. (2017). The analysis of calcareous nannofossils has allowed the refinement of biostratigraphy as well as a better knowledge of diversity fluctuations during the Pliensbachian and Toarcian (Ferreira et al., 2019; Menini et al., 2019). Based on the Lusitanian Basin record, Correia et al. (2017a, 2017b) studied the response of dinoflagellates to the T-OAE.

Relevant advances have been obtained concerning to the incidence of the T-OAE on macroinvertebrate communities, mainly brachiopods (e.g., Baeza-Carratalá et al., 2017, 2018; García Joral et al., 2018; Danise et al., 2019; Piazza et al., 2019), bivalves (Posenato et al., 2018; Brame et al., 2019; Damborenea and Pagani, 2019; Ros-Franch et al., 2019), and cephalopods (Rita et al., 2018). Many works have focused on the analysis of diversity and changes in the body-size trends of organisms at the Early Toarcian extinction event as well as in the recovery stage (García Joral et al., 2018; Rita et al., 2018, 2019; Caswell and Dawn, 2019; Danise et al., 2019; Piazza et al., 2019; Ros-Franch et al., 2019). Most of these papers show a decrease of body-size as a precursor of

the biotic crisis, and the recovery after stressing conditions disappear. The decrease in size was also recorded for calcareous nannofossils (Ferreira et al., 2017).

Ichnological analyses have been useful for interpreting changes in the sedimentation, oxygenation and nutrient availability in the substrate. Therefore, Rodríguez-Tovar et al. (2017, 2019) show good examples from the Lusitanian Basin with paleobiological changes of tracemakers and opportunistic behavior as a response to the T-OAE. Reolid and Reolid (2020) have analysed the geochemical distribution pattern from spotted marl-limestone successions in the La Cerradura section.

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; Muscente et al., 2019). The main studied groups were actinopterygians (Konwert and Stumpf, 2017; Maxwell and Martindale, 2017; Maxwell and Stumpf, 2017; Johnson et al., 2019), elasmobranchs (Stumpf and Kriwet, 2019), ichthyosaurs (Plet et al., 2017), plesiosaurs (Vincent et al., 2017) and teleosauroids (Johnson et al., 2019).

The Early Toarcian global warming affected also terrestrial ecosystems. Rodrigues et al. (2019) proposed a decreased  $^{13}\text{C}$  fractionation during photosynthesis in C3 plants and arid environments from the Iberian Paleomargin. Slater et al. (2019) showed that the fossil spore-pollen assemblages from Pliensbachian-Toarcian indicated that vegetation shifted from a high-diversity assemblage with conifers, seed ferns and lycophytes, to a low-diversity assemblage of cheirolepid conifers, cycads and *Cerebropollenites*-producers adapted to warm drought-like conditions.

### ***Geochemistry, Environmental Conditions and Paleoclimatology***

Various types of geochemical proxies are gradually leading to a better understanding of the environmental factors controlling the climate, the oceanographic circulation, the weathering intensity, and the role of volcanism.

Stable isotopes geochemistry was based mainly on  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$ , but also on  $\delta^{34}\text{S}$  and  $\delta^{15}\text{N}$ . Most of the analyses have been performed on bulk rock sample (e.g., Bougeault et al., 2017; Them et al., 2017a), belemnite rostra (e.g., Ait-Itto et al., 2017; Arabas et al., 2017; Rosales et al., 2018), brachiopod shells (Ferreira et al., 2017; Baghli et al., 2020), and organic matter (e.g., Silva et al., 2017; Izumi et al., 2018a; Suan et al., 2018; Thibault et al., 2018; Rodrigues et al., 2019; Ruebsam et al., 2019, 2020a). Also  $\delta^{98/95}\text{Mo}$  has been analysed 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 characterize the seawater composition and to approach the enhanced weathering during the T-OAE as a response to climatic warming (Them et al., 2017b). Them et al. (2019) studied the Hg content of sediments and detected an Hg anomaly during the T-OAE using many sections around the world and interpreting combined volcanic input and emerged land provenance.

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 paleoclimatic reconstruction from analysing the charcoal and phytoclast abundances and palynofacies (Baker et al., 2017; Xu et al., 2017; Fonseca et al., 2018; Suan et al., 2018;

Kemp et al., 2019; Rodrigues et al., 2019, 2020). These works also give information about the processes that happened in terrestrial environments, such as the incidence of wildfires on the  $\text{pO}_2$  (Baker et al., 2017). Finally, Ruebsam et al. (2020a) report the negative CIE from inorganic carbon, bulk organic carbon and fractions of molecular land plant fossils from Early Toarcian sediments that coincided with global warming and a carbon cycle perturbation. Based on differences in the magnitude of the CIE recorded in land plants and marine substrates Ruebsam et al. (2020a) infer that the Early Toarcian warming was paralleled by an increase in atmospheric  $\text{CO}_2$  levels from  $\sim 500$  ppmv to  $\sim 1000$  ppmv.

Stable isotopes geochemistry ( $\delta^{13}\text{C}$ ,  $\delta^{18}\text{O}$ ) has great potential for determining carbon cycle perturbations, paleotemperature, paleoceanographic changes and interpreting enhancement of the hydrological cycle (e.g., Izumi et al. 2018a, b; Rosales et al., 2018; Fantasia et al., 2019a). Redox-sensitive elements were used for interpreting oxygen-depleted conditions (e.g., Izumi et al., 2018b; Reolid et al., 2019b; Thibault et al., 2018; Fantasia et al., 2018, 2019a) as well as the diameter of pyrite framboids (Izumi et al., 2018b; Suan et al., 2018). Some works have focused the interpretations in the potential development of euxinic conditions during the T-OAE (Ruebsam et al., 2018; Suan et al., 2018; Thibault et al., 2018).

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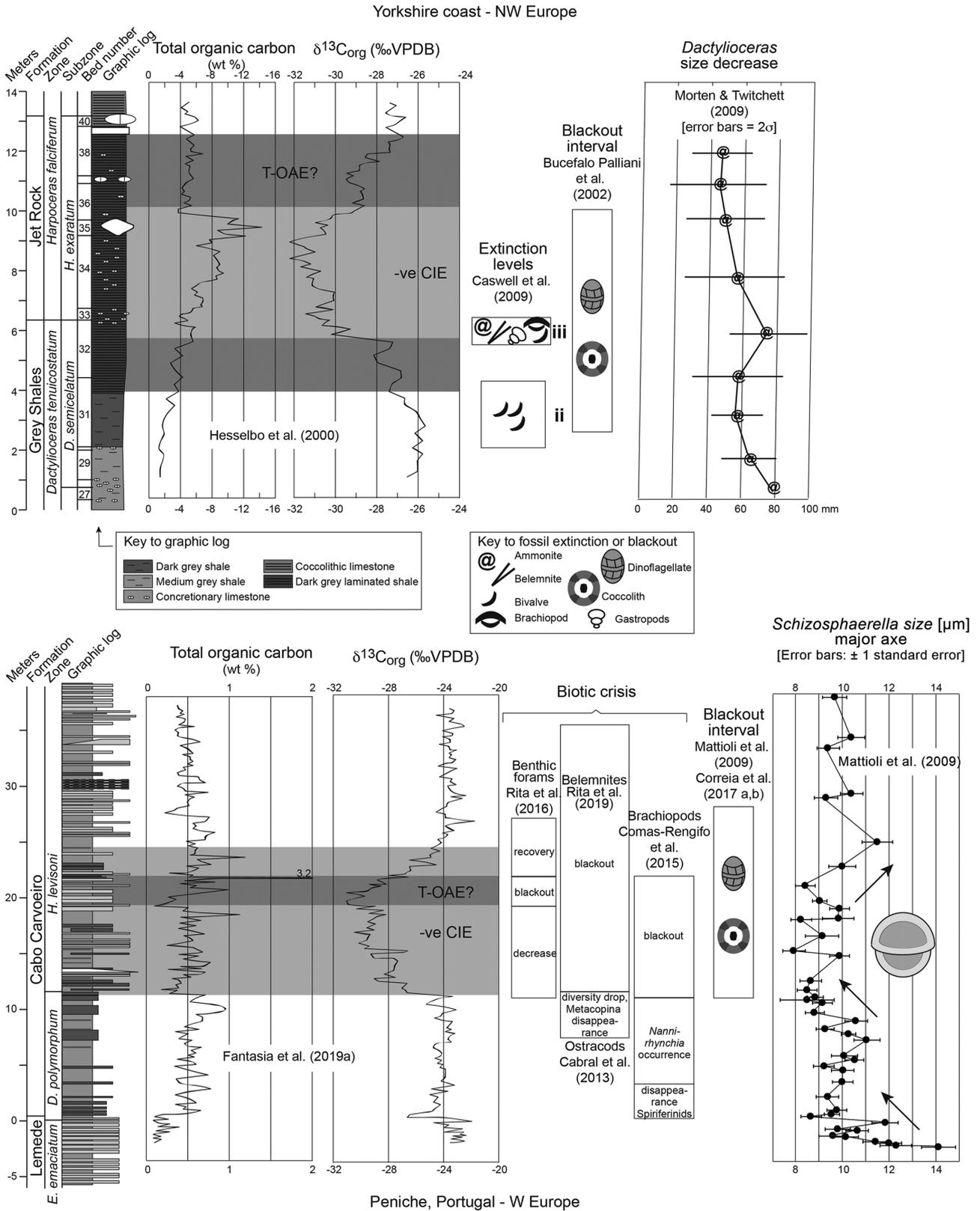
### **The Use of Terms T-OAE and Jenkyns Event**

Global effects of the Toarcian environmental perturbations have been recognized, since the 80s, with the record of black shales as an evidence of seawater deoxygenation (e.g., Jenkyns and Clayton, 1986; Jenkyns, 1988). Later on, such sedimentary records have been associated with a prominent negative CIE, which interrupted a long-lasting positive excursion (Hesselbo et al., 2000; Xu et al., 2018b; Storm et al., 2020). If the black shale record is variable according to the paleogeographic context (Wignall et al., 2005; McArthur, 2019), the CIE seems to be a common feature of most of the studied sites (Fig. 1). There are other events in Earth history recording positive or negative, global CIE which are named after pioneer researchers, such as the Weissert Event (positive CIE of the mid Valanginian; Erba et al., 2004), Farahoni Event (positive CIE of the latest Hauterivian; e.g., Baudin and Riquier, 2014), Selli Event or Selli level (positive CIE of the early Aptian; e.g., Menegatti et al., 1998) and Bonarelli Event (positive CIE of the Cenomanian-Turonian boundary; Luciani and Cobianchi, 1999).

Müller et al. (2017) proposed to rename the T-OAE as the Jenkyns Event, in honour of the seminal contribution of Professor Hugh Jenkyns to the understanding of this event. Accordingly, we hereby propose to use “T-OAE” when studying marine deposits with evidence of oxygen-depleted conditions. The term “Jenkyns Event” has to be used for the global changes that occurred during the Early Toarcian. These include:

a) Carbon cycle perturbation evidenced by a prominent negative CIE affecting marine environments (e.g., Saelen et al., 1996; Reolid, 2014; Baghli et al., 2020) and land ecosystems (as evidenced in land plant organic matter, e.g., Hesselbo et al., 2007; Ruebsam et al., 2020a).

b) Oxygen-depleted conditions in marine ecosystems, in some areas with generalized anoxia and euxinia (e.g., Gill et al., 2011; Izumi et al., 2018a; Ruebsam et al., 2018; Suan et al., 2018), but not affecting all basins and paleomargins (e.g., Boomer et al., 2009; Reolid et al.,



**Figure 2.** Synthesis of main environmental and biotic changes, namely extinctions, temporary disappearance and body-size decrease, occurring in two lower Toarcian iconic sections, namely the Yorkshire coast in NE England and the Peniche section in W Portugal. The ii and iii phases of biotic perturbations from Yorkshire section are described in Caswell et al. (2009). The dark-grey shaded intervals, corresponding to the local expression of the T-OAE, have been placed as following: (1) in the Yorkshire coast, wt% TOC values steadily higher than 2% and faunal extinction occurrence; (2) in the Peniche section, wt% TOC peak, and belemnites and benthic fauna blackout. The light-grey shaded area corresponding to the negative CIE (the Jenkyns event) has been placed in both areas between the level of sharp decrease of  $\delta^{13}C_{org}$  values and the return to pre-excursion values.

2014, 2015; Miguez-Salas et al., 2017; McArthur, 2019).

c) Increase of TOC 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; McArthur, 2019).

d) Biotic crisis recorded with different incidence in marine ecosystems (e.g., Little and Benton, 1995; Caswell et al., 2009; Gómez and Goy, 2011; Danise et al., 2015; Caswell and Frid, 2017; Reolid et al., 2019a), but also recorded in terrestrial ecosystems with changes in diversity and composition in land plants (e.g., Mander and McElwain, 2019; Slater et al., 2019) and the increase of wildfires in some areas (Baker et al., 2017). The term crisis comprises: extinctions, decrease or temporary disappearance (blackout) of taxa, as well as reduction in body-size as observed for calcareous nannofossils (Mattioli et al., 2004a, b; Reolid et al., 2014; Clémence et al., 2015), micro- (benthic foraminifera; Rita et al., 2016) and macroinvertebrates (ammonites, Morten and Twitchett, 2009; belemnites, Rita et al., 2019; brachiopods, García Joral et al., 2018; Piazza et al., 2019). See Figure 2.

e) 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), increasing weathering (e.g., Montero-Serrano et al., 2015; Fu et al., 2017), variations in detrital and nutrient input to marine basins (e.g., Rodríguez-Tovar and Reolid, 2013; Danise et al., 2015; Fantasia et al., 2019a; Kemp et al., 2019), and changes in marine productivity and a sea-level rise (e.g., Hallam, 1987; Röhl and Schmid-Röhl, 2005; Wignall et al., 2005).

## IGCP-655 Activities

The main activity of the IGCP-655 has been the three editions of the *International Workshop on the Toarcian Oceanic Anoxic Event (IW-TOAE)*. The 1<sup>st</sup> IW-TOAE happened on October 4-7<sup>th</sup> 2017 in the University of Jaén (Spain) organized by the Prof. Matías Reolid. There were 38 scientific attendees, over 18 oral presentations, and 17 posters. The 1<sup>st</sup> IW-TOAE meeting comprised four days of activities. The first day was dedicated to a short training course “*The ichnological record as a tool to assess different order bio-events*” by Prof. Francisco J. Rodríguez-Tovar and Dr. Javier Dorador of the University of Granada (Spain). Next day continued with the scientific sessions as well as an invited lecture by Prof. Stephen P. Hesselbo, (University of Exeter, UK) entitled “*Changing perceptions of the Toarcian Oceanic Anoxic Event; past, present and future research questions and directions*”. In the last two days the participants visited the best Toarcian sections of the Subbetic (Betic Cordillera, SE Spain) such as the Fuente Vidriera section (Fig. 3a), the La Cerradura section, the Iznalloz section and the Arroyo Mingarrón section (see field guide, Reolid et al., 2018).

The 2<sup>nd</sup> IW-TOAE took place in the University of Coimbra (Portugal) from 6 to 9<sup>th</sup> of September, 2018, organized by the Prof. Luis V. Duarte, with the attendance of 47 researchers from 15 countries. There were 20 oral presentations and 15 posters with high-quality scientific contributions. The meeting comprised four days of activities. A first day for the scientific sessions began with the invited lecture by Prof. Hugh Jenkyns (University of Oxford, UK) titled “*The Toarcian Oceanic Anoxic Event: lessons from the Cretaceous*”. The two following days were



**Figure 3.** Researchers attending the different excursions to Pliensbachian-Toarcian sections during the three editions of the *International Workshop on Toarcian Oceanic Anoxic Event (IW-TOAE)*. **A.** Visit to the Fuente Vidriera section in the Subbetic (Betic Cordillera, South Spain) during the 1<sup>st</sup> IW-TOAE (October 2017). **B.** Visit to the Peniche section in the Lusitanian Basin (Portugal) during the 2<sup>nd</sup> IW-TOAE (September 2018). **C.** Visit to the Dotterhausen Quarry (Swabian Alb, Germany) during the 3<sup>rd</sup> IW-TOAE (September, 2019).

dedicated to the field trip visiting the classic Lower Jurassic sections of the Lusitanian Basin (see field guide, Duarte and Silva, 2018). Among the visited outcrops were Maria Pares (or Rabaçal) and Peniche sections (Fig. 3b), this latter considered the worldwide reference for the

Pliensbachian–Toarcian transition (Toarcian GSSP). The last day of the meeting was dedicated to a short training course entitled “*Organic matter characterization in anoxic marine facies: palynofacies and organic geochemistry approaches*”, coordinated by Prof. João Graciano Mendonça Filho from the Federal University of Rio de Janeiro (Brazil).

The 3<sup>rd</sup> IW-TOAE was hosted by the Geozentrum Nordbayern of the Friedrich-Alexander University in Erlangen (Germany) between 2<sup>nd</sup> and 5<sup>th</sup> of September, 2019. This meeting began in the first day with three training courses: “*3D imaging techniques, from CT-scanning acquisition to Drishti 3D-imaging software, and biometric analysis*” taught by Christian Schulbert and Prof. Kenneth De Baets (Univ. Erlangen, Germany); “*Biomolecules and molecular fossils*” by Dr. Wolfgang Ruebsam (Univ. Kiel); and “*R short course on size/extinction/diversity patterns through time*” thought by Prof. Dr. Manuel Steinbauer (Univ. Erlangen). The second day was focused on the scientific sessions including 24 oral and 14 poster communications with the invited lecture “*The T-OAE: Marine ecosystem response across time and space*” of Dr. Bryony Caswell (University of Hull, UK). The two following days were dedicated to the field trip focused on the T-OAE in the Swabian Alb and Franconian Alb, south Germany, with special focus on facies, geochemistry and fossil assemblages. Among the visited outcrops were the Dotternhausen Quarry of the Schwäbische Alb Geopark (Fig. 3c), the Buttentheim clay pit and the Teufelsgraben (see field guide, De Baets and Rita, 2019).

The scientific and social activities during the workshops gave many opportunities to explore new scientific networks and to share new ideas for advancing in the research on Mesozoic anoxic events. A number of early career scientists, PhD students and post-docs also attended the workshop. The educational function of the project is thus valuable.

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