State of the Science: Mesozoic climates and oceans – a tribute to Hugh Jenkyns and Helmut Weissert

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Abstract

The study of past greenhouse climate intervals in Earth history, such as the Mesozoic, is an important, relevant, and dynamic area of research for many sedimentary geologists, geochemists, palaeontologists and climate modellers. The Mesozoic sedimentary record provides key insights into the mechanics of how the Earth system works under warmer conditions, providing examples of

natural climate change and perturbations to ocean chemistry, including anoxia, that are of societal relevance for understanding and contextualizing ongoing and future environmental problems. Furthermore, the deposition of widespread organic-carbon-rich sediments ("black shales") during the Mesozoic means that this is an era of considerable economic interest. In July 2015, an international group of geoscientists attended a workshop in Ascona, Switzerland to discuss all aspects of the Mesozoic world and to celebrate the four-decade-long contributions to our understanding of this fascinating era in Earth history made by Hugh Jenkyns (University of Oxford) and Helmut Weissert (ETH Zurich). This volume of *Sedimentology* arose from that meeting and contains papers inspired by (and co-authored by!) Hugh and Helmi. Here a brief introduction to the volume is provided that reviews aspects of Hugh and Helmi's major achievements; contextualizes the papers of the Thematic Issue; and discusses some of the outstanding questions and areas for future research.

The research legacy of Hugh Jenkyns & Helmut Weissert

Hugh Jenkyns was awarded a PhD from the University of Leicester (UK) in 1970 with a thesis on the origin of the Jurassic carbonate platform and pelagic basinal deposits of Western Sicily (Jenkyns, 1970a); a study that laid the foundations for much of his work in the early 1970s exploring the origin of condensed sequences and platform drowning, as well as broader issues of Tethyan evolution (e.g. Jenkyns, 1970b, 1971; Bernoulli & Jenkyns, 1974). In 1974, with Ken Hsü, he edited the first volume of the IAS Special Publication series, on the topic of “Pelagic Sediments: on Land and under the Sea” (Hsü & Jenkyns, 1974) and participated in Deep Sea Drilling Project (DSDP) Leg 33 in the central Pacific. During this leg, Lower Cretaceous organic-carbon-rich sediments were recovered at Site 317 on the Manihiki Plateau. These were described by Jenkyns (1976) as indicating “…an episode of stagnant deoxygenated bottom-water conditions…” and were suggested to be “…correlative with carbonaceous sediments drilled on DSDP Leg 11 in the western Atlantic…”. These observations, coupled with others drawn from Tethyan sections on land (Figure 1) and other DSDP legs in the Pacific and Atlantic, provided the evidence for Schlanger and Jenkyns (1976) to propose that “…certain stratigraphically restricted carbon-rich horizons are...the result of…widespread and thick O_2 minimum zones in the world ocean [rather] than the result of the structural-topographic isolation of relatively local basins”. Schlanger and Jenkyns (1976), referred to these stratigraphic horizons as representing “oceanic anoxic events” (OAEs), a concept that was to rapidly gain ground and set the agenda for much of Mesozoic palaeoceanographic research for the following decades. Since the seminal paper in 1976, Hugh Jenkyns has continued to be at the forefront of OAE research and, more broadly, Mesozoic palaeoclimatology and palaeoceanography. His major contributions include demonstrating the existence of an OAE in the Toarcian (Early Jurassic) (Jenkyns, 1985, 1988); constraining the Early Jurassic timescale through cyclostratigraphy (Weedon & Jenkyns, 1999); provision of an original interpretation for the origin of Pacific guyots (Jenkyns & Wilson, 1999) and leading on the application of novel geochemical proxies to Mesozoic sediments (e.g. Jones *et al.*, 1994; Jenkyns *et al.* 2001, 2004, 2007;

Lu *et al.*, 2010; Pogge von Strandmann *et al.*, 2013). Throughout his work, he has been able to draw on a wide variety of datasets and make links that provide deep insights into the workings of the Earth system during the Mesozoic, exemplified in this volume by his contribution on the variety of geochemical and sedimentological signatures associated with the Plenus cold event during OAE2 (Jenkyns *et al.*, this volume).

Helmi Weissert completed his PhD at the ETH Zürich, Switzerland in 1979 under supervision of Ken Hsü, with a study on the, superficially, monotonous Cretaceous deep-water deposits of the Maiolica limestones. By analyzing the stable isotopic signatures of these pelagic carbonates, he was amongst the first to apply carbon-isotope variations as a new stratigraphic tool for correlating sedimentary strata and to investigate their biogeochemical and palaeoenvironmental significance (Weissert, 1979, 1989, 1990; Weissert *et al.*, 1985). During the 1970s and early 1980s, the field of Mesozoic palaeoceanography was just emerging, fostered by the integration of geological observations with the novel discoveries from ocean drilling. During his early career, he took part in DSDP Leg 73 to the South Atlantic Ocean encountering new palaeoceanographic concepts and ideas, and developing research on Pliocene climates and oceanography (Weissert *et al.*, 1984; Weissert & Oberhänsli, 1985). Although the Mesozoic remained his primary stratigraphic focus, his work on Neogene palaeoceanography certainly influenced his later work on deep-time sedimentary systems. His high-resolution (for the time) approach to Mesozoic carbon-isotope stratigraphy was applied to Late Jurassic–Early Cretaceous sequences, and successfully integrated with biostratigraphic and palaeomagnetic data, to produce a detailed stratigraphic framework for this time interval (e.g. Weissert & Channell, 1989; Weissert & Lini, 1991; Lini *et al.,* 1992; Weissert & Mohr, 1996). In doing so, Helmi and his students identified a prominent carbon-isotope anomaly in the Valanginian (e.g. Weissert & Lini, 1991; Lini *et al.,* 1992; Hennig *et al.,* 1999), occurring prior to the major OAEs of the Cretaceous and known today as the “Weissert” event (Figure 1; Erba *et al.,* 2004). His next step was the establishment of pelagic basin-to-carbonate platform transects in order to trace the impact of oceanographic events (including OAEs) in the shallow-water domain. An important finding was the stratigraphic correspondence of pelagic black shale episodes with shallow-water carbonate platform drowning events (Weissert *et al.,* 1998; Wissler *et al.,* 2003; Burla *et al.,* 2008), effectively illustrating the complex interplay between greenhouse climates, oceanography, and the global carbon cycle. More recently, Helmi Weissert’s work focused on the role of ocean acidification in deep time (Mehay *et al*., 2009; Erba *et al*., 2010), the timing and consequences of Cretaceous OAEs (e.g. Giogoni *et al.,* 2012), perturbations of the Early Mesozoic carbon cycle (e.g. Galli *et al*., 2005), and on the overall evolution of CO_2 and climate during the Mesozoic (Weissert & Erba, 2004; Millán *et al.* 2009). In his research, Helmi Weissert combined work on deep-sea drill cores with materials from on-land sections, with a strong preference for the exceptional outcrops of the Swiss and Italian Alps that have provided ideal analogues for the study of deep-ocean sediments and their geochemical signatures. Besides his significant contributions to the field of Mesozoic chemostratigraphy and palaeooceanography, his studies have provided new views on global climate change and carbon-cycle dynamics in deep time.

During their careers, Hugh Jenkyns and Helmi Weissert have only been co-authors on one paper (Erba *et al.,* 2015), yet their individual contributions and direct interactions have complemented and inspired each other. Carbon-isotope stratigraphy, in addition to providing a powerful tool for stratigraphic correlation, has been used to argue for the causes and consequences of OAEs. Each of the three most widespread OAEs (occurring in the Early Toarcian, Early Aptian and Late Cenomanian) has been shown to have occurred synchronously with fluctuations in carbon-isotope ratios of carbonates and organic matter, interpreted as representing perturbations to the ocean-atmosphere carbon reservoir (Figure 2; e.g. Scholle & Arthur, 1980; Jenkyns & Clayton, 1986, 1997; Weissert *et al.,* 1985, 1998; Weissert, 1989; Weissert, & Bréhéret, 1991; Jenkyns *et al.,* 1994; Gröcke *et al*., 1999; Hesselbo *et al.,* 2000; Weissert & Erba, 2004; Jenkyns, 2010). The current general model for the genesis of oceanic anoxic events (Figure 3; Weissert, 2000; reviewed in Jenkyns, 2003, 2010) invokes a source of carbon, which, as CO_2 in the atmosphere, caused greenhouse warming. The release of carbon triggering an OAE may be detectable by carbon-isotope stratigraphy as negative excursions, as postulated sources (including volcanism, methane hydrates, and thermogenic methane; Figure 3) are isotopically lighter than the ocean-atmosphere carbon reservoir (but note that not all OAEs, or OAE-like events, are associated with detectable negative excursions). Greenhouse warming at the onset of an OAE is hypothesized to have caused a number of effects that were conducive to increased rates of organic-carbon deposition, including elevated freshwater run-off (delivering nutrients), stratification of restricted basins, and enhanced wind-driven upwelling. Nutrients may also have been sourced from alteration of basalt (e.g. Erba & Larson, 1999), produced by eruption of large igneous provinces (LIPs). Increased primary productivity and expansion of oxygen-minimum zones led to the deposition of the characteristic black shales, associated with OAEs in many parts of the ocean (Figures 1, 2 and 3). The burial of organic carbon is recognized by positive excursions in carbon-isotope stratigraphy (Figure 2), which may also suppress the signal of isotopically light inputs (e.g. Jenkyns, 2010), which leads to difficulties in estimating the true fluxes of carbon into, and out of, the surficial carbon reservoirs. The sequestration of carbon into the sedimentary record ultimately is thought to have caused a reversal of greenhouse conditions (Figure 3), eventually terminating the OAE. Although this simple model (albeit with added nuances) has been applied to many events, the fit to each event is variable. For example, OAE2 in the Late Cenomanian conforms to the conceptual model well (Jenkyns, *et al*., this volume), except for the absence of a definitive negative δ^{13}C excursion; in contrast the Late Valanginian “Weissert” Event, a prominent positive carbon-isotope excursion (Figure 2), is not associated with a discrete period of time characterized by widespread black-shale deposition, leading some to speculate that organic carbon was deposited on land instead (e.g. Westermann *et al.,* 2010). Similarly OAE1a does not quite fit the model – although it is represented by globally distributed black shale, carbon-isotope values, after an initial negative excursion, become positive in the latter stages of anoxic conditions and continue to increase long-after black shale deposition ceased (e.g. Menegatti *et al.,* 1998). These, and other events, demonstrate the complexity of reconstructing interactions between the carbon cycle and palaeoclimate based on the sedimentary record and continue to provide new questions for science.

State of the science

Although it is now clear that during the Jurassic and Cretaceous there were intervals of widespread low-oxygen conditions in the ocean associated with major carbon-cycle perturbations, many questions remain regarding the context, origins, and wider significance of the OAEs, and the background carbon cycling and climates of the Mesozoic. A brief description and discussion of these issues is presented here.

Many records of OAEs have been identified, yet there is still a need to identify, document and interpret new localities at outcrop and in the ocean, particularly in the Southern and Arctic Oceans. As can be seen in Figure 4, there is a considerable geographic sampling bias towards records of OAEs from the circum-North Atlantic and Tethyan region. New localities, both outside and within this region, can provide important constraints on the extent, and variability, of low-oxygen conditions and can help provide a more complete picture of palaeoceanographic and palaeoclimatic change during OAEs. For example, it has long been recognized that although anoxic (and even euxinic) conditions were widespread during the Cretaceous OAEs, such conditions were not ubiquitous (e.g. Jenkyns, 1980, 2010; Pancost *et al.*, 2004; Robinson *et al.*, 2004, 2008; Takashima *et al.* 2011; Eldrett *et al.*, 2014; Westermann *et al.,* 2014; Zhou *et al.,* 2015) and the deposition of black shales was, in some cases, diachronous (e.g. Tsikos *et al.,* 2004; Petrizzo *et al.*, 2008). Consequently, the sedimentological and geochemical expression of individual OAEs can be quite different depending on local conditions (e.g. Bornemann *et al.*, this volume; Müller *et al.*, this volume).

The OAE concept grew from cores recovered by deep-sea drilling (Schlanger & Jenkyns, 1976; Jenkyns, 1980), yet with much of the Mesozoic ocean floor now lost to subduction, there is also a need to explore orogenic regions associated with accretion of oceanic crust and sediments in order to provide evidence of palaeoceanographic conditions in these "lost" regions of the Mesozoic oceans. Although sediments in these terranes are often diagenetically altered and, in some cases, weakly metamorphosed, they can still provide valuable evidence for variations in the record of palaeoceanographic events including carbon-isotope stratigraphy that provides correlations to other regions (e.g. Robinson *et al.*, 2008; Ikeda and Hori 2014; Wohlwend *et al.*, this volume). In addition to searching for new records of OAEs, it is also informative to consider periods of more localized organic-carbon accumulation that did not occur during OAEs in order to assess the controls on this process under "normal" conditions during the Mesozoic and the role of orbital forcing (e.g. Giorgioni *et al.*, this volume; Xu *et al.* this volume). Furthermore, high organic-carbon burial rates and associated low-oxygen conditions have a significant effect on preservation and diagenetic processes, which can result in exceptional palaeontological archives (e.g. Heimhofer *et al.,* this volume).

OAEs were first identified by their sedimentological characteristics and, later, their carbon-isotopic records, but can now be shown to be complex geochemical events that led to perturbations in the concentrations and isotopic ratios of many elements, reflecting changing local and global environmental conditions. The ongoing expansion of analytical techniques available to determine the concentration and isotopic ratio of metals (e.g. ICP-MS, MC-ICP-MS), and the increased interest in applying these methods to modern seawater and to sedimentary archives, has led to a revolution in palaeoceanography and in the study of OAEs. Key radiogenic and unconventional stable isotopic systems used in sedimentary archives include strontium ($^{87}Sr/^{86}Sr$) osmium ($^{187}Os/^{188}Os$), calcium ($\delta^{44}Ca$), lithium ($\delta^{7}Li$) and neodymium isotopes (ε_{Nd}). To date, many studies using these systems have demonstrated tight temporal coincidence between OAEs and basaltic volcanism, increased weathering and changes in ocean circulation patterns (e.g. Jones & Jenkyns, 2001; Cohen *et al.,* 2004; MacLeod *et al.*, 2008; Turgen & Creaser, 2008; Tajeda *et al.*, 2009; Blättler *et al.,* 2011; Pogge von Strandmann *et al.*, 2013; Zheng *et al.* 2013, 2016; Lechler *et al.*, 2015; Percival *et al.*, 2016), providing support for the conceptual models of feedbacks and relationships posited to be important during OAEs (Figure 3). However, of all the environmental changes associated with OAEs, it is the paucity of oxygen that had the most striking effect on the sedimentological record in the form of laminated black shales, often commonly interbedded with pelagic carbonates deposited in well-oxygenated conditions. In this aspect of OAE research, concentrations and isotopes of redox-sensitive elements, such as Cr, Fe, I, Mn, Mo, N, S, Tl, U and V, have proven particularly valuable in reconstructing changing redox conditions both locally and globally (e.g. Kuypers *et al.,* 2002; Pearce *et al.*, 2005; Jenkyns *et al.,* 2001, 2007, this volume; Jenkyns, 2010; Lu *et al.,* 2010; Montoya-Pino *et al.,* 2010; Gill *et al.,* 2011; Nielsen *et al.,* 2011; Owens *et al.*, 2013, this volume; Westermann *et al.*, 2014; Zhou *et al.,* 2015; Dickson *et al.*, 2016, this volume; Gomes *et al.,* 2016; Holmden *et al.,* 2016). Through the integration of the different geochemical systems discussed here, it has been possible to develop a detailed understanding of the temporal (and, arguably, mechanistic) links between changes in the physical environment, seawater chemistry and biogeochemical cycles during OAEs (e.g. Owens *et al.,* 2013; Pogge von Strandmann *et al.*, 2013; Dickson *et al.*, 2016, this volume; Jenkyns *et al.,* this volume).

The Mesozoic world has long been an attractive target for climate and ocean modelling, due to the challenges presented by warm polar regions and continental interiors and oceans that were periodically dysoxic and anoxic (e.g. Parrish & Curtis, 1982; Parrish *et al.*, 1982, Sloan & Barron, 1990, Chandler *et al.*, 1992, Valdes & Sellwood, 1992; Barron *et al.*, 1995). Increased computational power has allowed global climate models (GCMs) to be used to test hypotheses regarding the long-term controls on climate and ocean circulation and the importance of atmospheric composition (e.g. Poulsen *et al.*, 2001, 2003, 2015; Zhou *et al.*, 2008; Lunt *et al.*, 2016).

Additionally, less computationally demanding models of climate and (bio-) geochemical cycles are available that can be used to understand the underlying physical and biogeochemical processes controlling the sedimentological and geochemical variability observed in the Mesozoic geological record (e.g. Kump & Arthur, 1999; Donnadieu *et al.*, 2006, 2016; Montienaro *et al.*, 2012; Zhou *et al.,* 2015; Bauer *et al.*, this volume). Climate models are providing increasingly detailed spatial and temporal simulations of the Mesozoic world, but in order to be of maximum value they need to be compared with robust palaeoclimatic and palaeoenvironmental data taken from the geological record. Such data includes estimates of palaeotemperatures from oxygen-isotopes of carbonate fossils or from organic geochemical palaeothermometers, such as TEX_{86} (e.g. Robinson *et al.*, this volume), reconstructions of seasonality through detailed elemental analysis of seasonal growth bands in macrofossils, such as bivalves (e.g. de Winter & Claeys, this volume) and reconstructions of local palaeoceanographic conditions from sedimentological, geochemical and palaeontological datasets (e.g. Petrizzo *et al.*, this volume).

Impact beyond the Mesozoic

The OAE concept has also been proving useful in explanations of palaeoenvironment change for times both before and after the Mesozoic. There are many examples of black shale deposition associated with geochemical anomalies for both the Early Palaeozoic, (e.g. McLaughlin *et al.*, 2012; Vandenbroucke *et al*. 2016) and the Late Palaeozoic (e.g. Carmichael *et al*. 2014, 2016; De Vleeschouwer *et al*. 2014); as more data are acquired from a range of depositional settings, so the global nature of these events, and their similarities to Mesozoic counterparts, are becoming more clearly established. However, it is also the case that for these deeper time events, coincidence in time to potential extrinsic triggers such as large igneous provinces are not at all well established, let alone inference of causal linkages. It remains to be seen whether the Palaeozoic ‘exceptions to the rule’ will eventually provide insights into additional Earth System mechanisms also operating in the Mesozoic but so far undiscovered.

Similarly, comparisons and contrasts between OAEs and Cenozoic warming events, such as the Paleocene-Eocene Thermal Maximum or the Miocene Monterey Event, has elucidated common processes and highlighted the extreme magnitude of the Earth system perturbations that have occurred in the earlier history of the planet (e.g. Jenkyns 2003, 2010; Cohen *et al*. 2007; Brandano *et al.*, this volume). The widespread distribution of studied localities and overall larger datasets for Cenozoic events generally provides greater opportunity to comprehend the potential rapidity of environmental processes, and the timing of consequent environmental changes in the different reservoirs of the lithosphere, hydrosphere and biosphere, something that has not yet been achieved with any degree of confidence for the Mesozoic.

Outlook

Although it has now been 40 years since the publication of Schlanger and Jenkyns (1976), the field of Mesozoic palaeoceanography and palaeoclimatology still has many unanswered questions. As discussed above, the search, on land and under the sea, for new localities in areas that have been either tectonically quiescent or active over time, remains an important endeavour that helps to constrain the spatial pictures of Mesozoic palaeoenvironments. A future focus on underexplored regions (e.g. the high latitudes and the southern hemisphere) would be of great benefit, but there is still scope for new findings in areas that appear to have been well sampled. Unfortunately, many of the classic DSDP records of Jurassic and Cretaceous oceanography, cored at a time when the science objectives were rather different but which provide tantalizing glimpses of the past, were poorly recovered, and in some cases little material remains after years of sampling. This situation is undoubtedly a limiting factor on the extent of our knowledge as it can prohibit the application, at high resolution, of new, insightful proxies. Thankfully, both IODP (International Ocean Discovery Program) and ICDP (International Continental Drilling Project) are continuing to support the development and implementation of Mesozoic drilling projects (e.g. Bralower *et al.,* 2013; Hesselbo *et al.,* 2013; Wagner & Dunkley-Jones, 2015), many of which will come to fruition in the coming years. Additionally, industry boreholes and independently funded drilling campaigns, such as the Tanzanian Drilling Project (e.g. Jimenez Berrocoso *et al.,* 2015), or the KARIN Project in the Karoo Basin (see https://www.uj.ac.za/faculties/science/Pages/Karoo-Research-Initiative-in-CIMERA.aspx), also have a critical role in furthering the science.

Although the vast majority of studies have focused on marine sediments, the Mesozoic terrestrial record is a rich archive, yet our understanding of how terrestrial faunas and floras respond to climatic and environmental extremes is based on a rather limited number of studies (e.g. Kujau *et al.* 2013; Cors *et al.* 2015). Furthermore, the quantification of terrestrial climatic variability has generally been reliant on floral proxies (e.g. Spicer *et al.,* 2008), although new opportunities exist since the recognition of climate signals in early diagenetic soil carbonates (e.g. Ludvigson *et al.,* 1998) and the emergence of organic biomarker palaeothermometry (e.g. Kemp *et al.,* 2014).

A sampling bias also exists in geological time, with many studies focused on key events, such as the major OAEs, and, relatively, fewer efforts to understand the intervening intervals of time. As Helmi Weissert demonstrated, major chemical perturbations, such as the Late Valanginian carbon isotope excursion, occur without any, at first, striking lithological signature. As stratigraphic resolution has increased, so more events have begun to emerge from the record (e.g. Riding *et al.* 2013). Investigating the long-term climatic, geographic and oceanographic context is key to help understand why the OAEs and similar events were so prevalent in the Mesozoic. Furthermore, efforts to document the mechanisms operating in events with either global (e.g. T-OAE, OAEs 1a and 2) and regional (OAEs 1b, 1c, 1d and 3) lithological signatures is absolutely necessary to constrain the climatic, geochemical, and palaeoceanographic mechanisms, and determine to what extent a single universal model (such as that shown in Figure 3) can realistically be applied. The model(s) used to explain OAEs has much in common with those used to explain other carbon-cycle perturbations occurring throughout Earth history (including some associated with mass extinction events and other extreme perturbations), so a better understanding of the mechanisms operating during OAEs will likely help to constrain the causes of consequences of major environmental and biotic change throughout the Phanerozoic.

In order to extract the maximum information from sedimentary archives, both old and new, marine and terrestrial, it is essential that proxies continue to be developed, tested and applied. Some variables of climatic and oceanographic interest can, in some settings, be relatively well constrained by multiple approaches (e.g. local redox, temperature). However, other important variables, such as atmospheric gas composition, are still poorly known, yet essential if valid comparisons are to be made with climate and Earth system models. Some progress has made been in determining the trends of CO_2, for example during OAEs (e.g. Barclay *et al.,* 2010; Jarvis *et al.,* 2011; Naafs *et al.,* 2016) but estimation of absolute values has not been without problems and remains a source of considerable uncertainty in Mesozoic palaeoclimate reconstructions. Hope for new proxy estimates exists in advances being made in the understanding of the physiology and chemistry of plants in relationship to pCO_2 (e.g. Schubert & Jahren 2013; Franks *et al.,* 2014). In addition to CO_2, climate modeling suggests that pO_2 may also be an important determinant in regulating Mesozoic climates (Poulsen *et al.,* 2015), presenting an, arguably, greater challenge for proxies than pCO_2 reconstructions. Past pO_2 levels have proven very difficult to constrain, with estimates for the Cretaceous varying from less than to greater than present-day levels, but recent work on gas inclusions in halite may signal the way ahead (Blamey *et* *al.,* 2016). Modelling studies, with key boundary conditions such as atmospheric composition accurately estimated, are essential to helping unravel the complexities of the Mesozoic world and they can provide hypotheses to be tested, often with estimates of rates and magnitudes of environmental change. Testing the outputs of models therefore requires a detailed re-reading and understanding of the stratigraphic record, with an appreciation for sedimentary processes, diagenesis, and timescales – an approach that both Hugh Jenkyns and Helmi Weissert have championed throughout their careers.

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FIGURE CAPTIONS

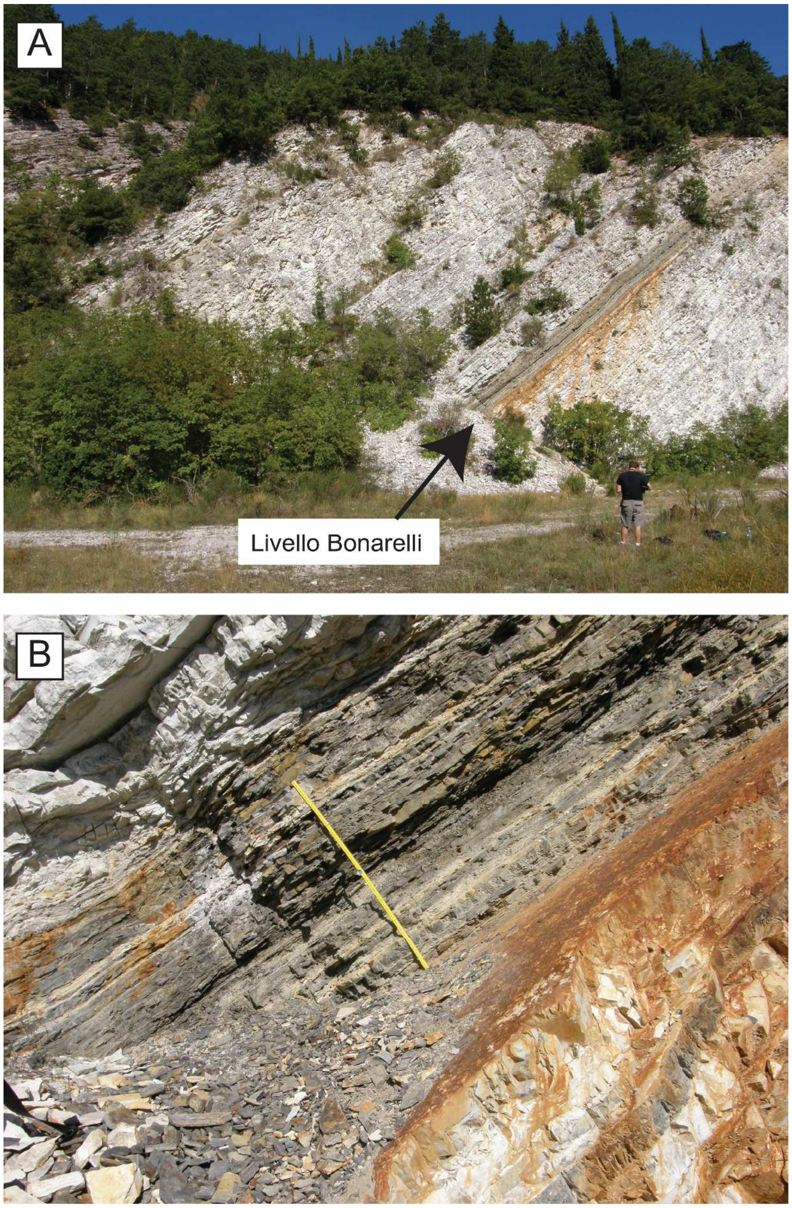
Figure 1 Example of black shale deposited during oceanic anoxic events. (A) Livello Bonarelli, deposited during OAE2 in the Furlo Quarry, Umbria-Marche region, Italy (B) close up view of Livello Bonarelli in Furlo Quarry, where it is ~1.2 m thick. Within the black shales are lighter coloured radiolarian sands. Above and below the black shales are pelagic limestones (white sediments) with relatively thin chert beds (dark grey to black sediments). Metre-stick for scale.

Figure 2 Bulk carbonate carbon-isotope ($\delta^{13}C_{carb}$) stratigraphy of the Jurassic and Cretaceous (modified from Takashima *et al*., 2006) and age of prominent ‘Oceanic Anoxic Events’ and other related phenomena. Carbon-isotope data from (1) Van de Schootbrugge *et al.* (2005); (2) Hesselbo *et al.* (2000); (3) Morettini *et al.* (2002); (4) Dromart *et al.* (2003); (5) Weissert *et al.* (1998); (6) Erbacher *et al. (*1996);□ (7) Jenkyns *et al.* (1994); (8) Jarvis *et al.* (2002); and (9) Abramovich *et al.* (2003).

Figure 3 Cartoon illustrating major aspects of the positive and negative feedbacks that led to the onset and termination of oceanic anoxic events, as described in the text. The figure has been modified from Jenkyns (2010), based on an original figure in Weissert (2000).

Figure 4 Maps showing the distribution of localities presenting black shales and sediments containing more than 1% total organic carbon associated with oceanic anoxic events in the (a) Early Toarcian (T-OAE), (b) Early Aptian (OAE1a) and (c) Cenomanian–Turonian (OAE2). The Toarcian map is adapted from the data and plate reconstruction presented in Jenkyns (1988), Jenkyns *et al.,* (2002) and Gröcke *et al.,* (2011). The plate tectonic reconstruction is similar to those presented in Smith *et al.,* (1981). Early Aptian sites are based upon the compilation of Erba *et al.,* (2015), but excludes localities with <1%TOC or no TOC data. Cenomanian–Turonian OAE2 sites are based upon Schlanger *et al.,* (1987) and Takashima *et al.,* (2006) with new data from Dickson *et al*. (this volume). Early Aptian and Late

Cenomanian plate reconstructions are from the Ocean Drilling Stratigraphic Network (http://www.odsn.de).



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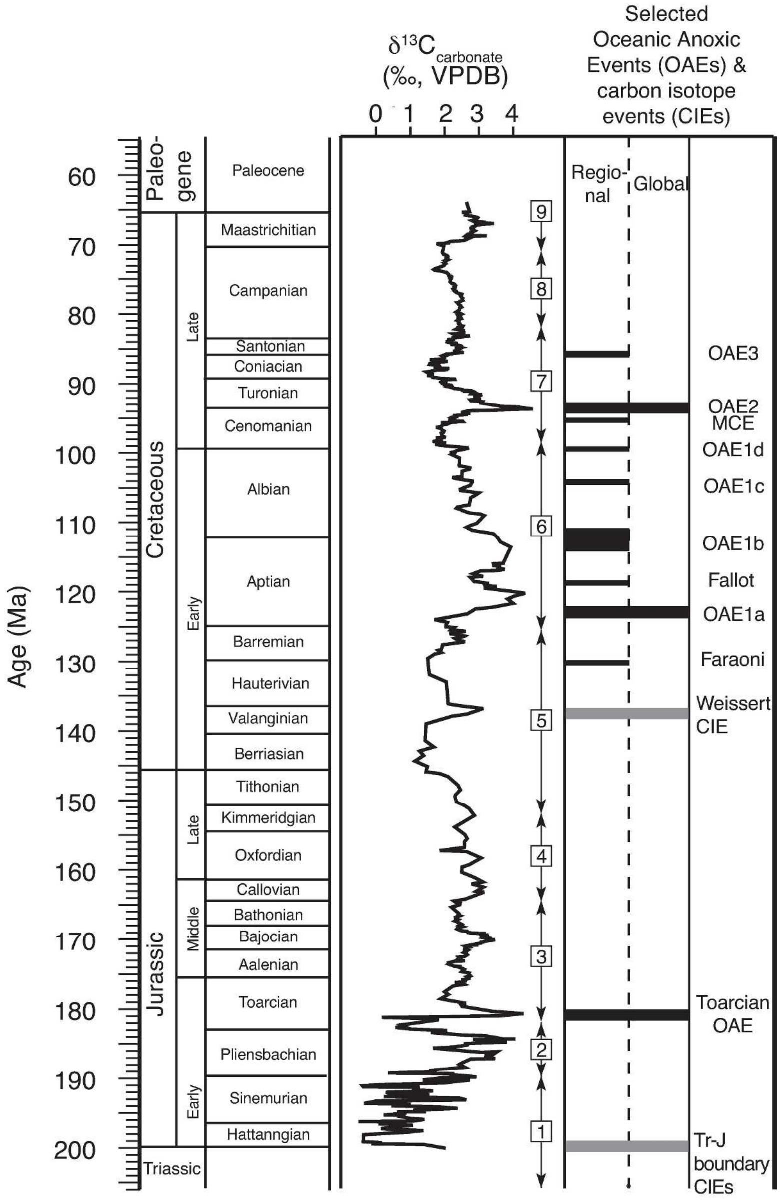

Figure 2. Bulk carbonate carbon-isotope (δ13Ccarb) stratigraphy of the Jurassic and Cretaceous (modified from Takashima et al., 2006) and age of prominent 'Oceanic Anoxic Events'). Carbon-isotope data from (1) Van de Schootbrugge et al. (2005); (2) Hesselbo et al. (2000); (3) Morettini et al. (2002); (4) Dromart et al. (2003); (5) Weissert et al. (1998); (6) Erbacher et al. (1996); (7) Jenkyns et al. (1994); (8) Jarvis et al. (2002); and (9) Abramovich et al. (2003).

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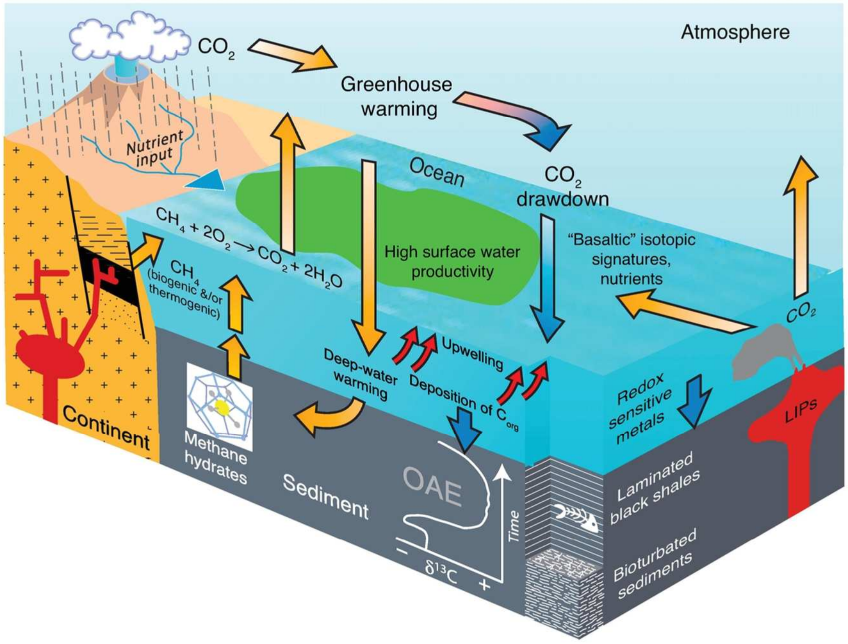
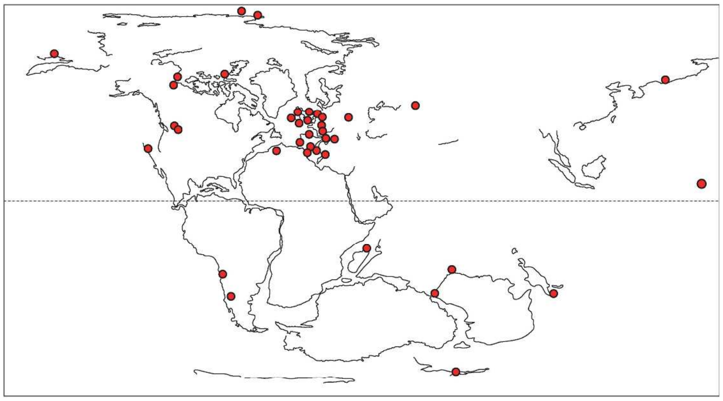


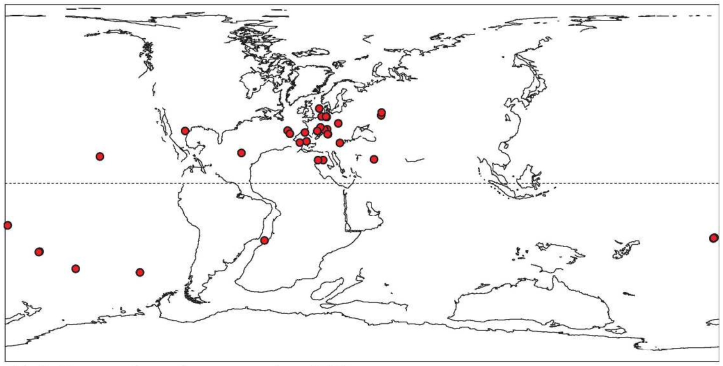
Figure 3 Cartoon illustrating major aspects of the positive and negative feedbacks that led to the onset and termination of oceanic anoxic events, as described in the text. The figure has been modified from Jenkyns (2010), based on an original figure in Weissert (2000).

127x94mm (300 x 300 DPI)

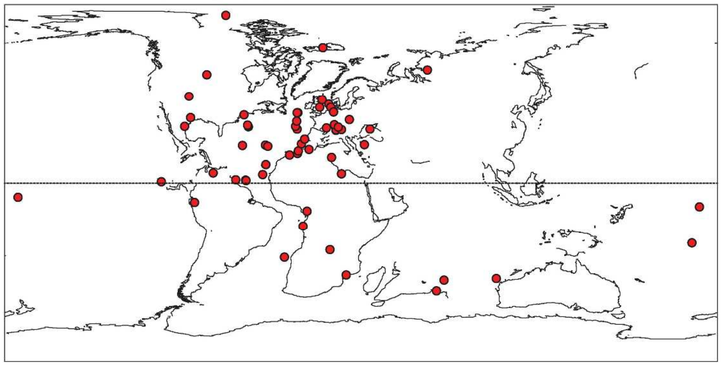
a) Toarcian palaeogeography ~183 Ma



b) Early Aptian palaeogeography ~120 Ma



c) Late Cenomanian palaeogeography ~95 Ma



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198x332mm (300 x 300 DPI)