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

Stuart A. Robinson[1*], Ulrich Heimhofer[2], Stephen P. Hesselbo[3], Maria Rose Petrizzo[4]

1: Department of Earth Sciences, University of Oxford, South Parks Road, Oxford, OX1 3AN, UK
2: Institute for Geology, Leibniz University Hannover, Callinstraße 30, 30167 Hannover, Germany
3: Camborne School of Mines, and Environment and Sustainability Institute, University of Exeter, Penryn Campus, Treliever Road, Penryn, Cornwall, TR10 9FE, UK
4: Dipartimento di Scienze della Terra "A. Desio", Università degli Studi di Milano, via Mangiagalli 34, 20133 Milano, Italy

*stuart.robinson@earth.ox.ac.uk

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.

Acknowledgements

We are grateful to all the contributors to this Thematic Issue of Sedimentology and the participants in the workshop in Ascona. We thank Hugh Jenkyns, Helmi Weissert, an anonymous reviewer and Emmanuelle Pucéat for their comments on this manuscript. We express our gratitude to the editors of Sedimentology, Nigel Mountney and Tracy Frank, and Elaine Richardson in the Editorial Office for all their help and support in the compilation of the issue.

References

Abramovich, S., G. Keller, D. Stüben and Z. Berner (2003) Characterization of late Campanian and Maastrichtian planktonic foraminiferal depth habitats and vital activities based on stable isotopes. *Palaeogeog., Palaeoclimat., Palaeoecol.* **202**,1-29.

Barclay, R.S., McElwain, J.C. and Sageman, B.B. (2010) Carbon sequestration activated by a volcanic CO_2 pulse during Ocean Anoxic Event 2. *Nature Geoscience,* **3**, 205–208

Barron, E.J., Fawcett, P.J., Peterson, W.H., Pollard, D., and Thompson, S.L., (1995) A “simulation” of mid-Cretaceous climate. *Palaeoceanography*, **10**, 953-962.

Bauer, K.W., Zeebe, R.E., and Wortmann, U.G. (this volume). Quantifying the Volcanic Emissions Which Triggered OAE1a, and Their Effect on Ocean Acidification. *Sedimentology,* this volume.

Bernoulli, D. and Jenkyns, H.C. (1974). Alpine, Mediterranean and Central Atlantic Mesozoic facies in relation to the early evolution of the Tethys. *In:* R.H. Dott and R.H. Shaver, (eds), Modern and Ancient Geosynclinal Sedimentation, a Symposium, *Spec. Publ. Soc. Econ. Paleont. Miner.,* **19**, 129–160.

Blamey, N.J.F., Brand, U., Parnell, J., Spear, N., Lécuyer, C., Benison, K., Meng, F., and Ni, P., (2016), Paradigm shift in determining Neoproterozoic atmospheric. *Geology*, **44**, 651–654.

Blättler, C.L., Jenkyns, H.C., Reynard, L.M., and Henderson, G.M., (2011) Significant increases in global weathering during Oceanic Anoxic Event 2 indiciated by calcium isotopes. *Earth Planet. Sci. Letts.* **309**, 77-88.

Bornemann, A.,Erbacher, J., Heldt, M., Kollaske, T., Wilmsen, M., Lübke, N., Huck, S., Vollmar, N.M., and Wonik. T., (this volume). The Albian–Cenomanian transition and Oceanic Anoxic Event 1d in the Boreal Realm. *Sedimentology,* this volume;

Brandano, M., Cornacchia, I., Raffi, I., Tomassetti, L. and Agostini, S. (this volume). The Monterey Event within the Central Mediterranean area: the shallow-water record. *Sedimentology,* (this volume).

Bralower, T.J., Bown, E., Erba, E., Jenkyns, H., Leckie, M., and Robinson, S. (2013) Advancing our Understanding of Cretaceous Ocean Dynamics by Scientic Drilling *ECORD Newsletter***, 21**, p.22

Burla, S., Heimhofer, U., Hochuli, P. A., Weissert, H., Skelton, P., (2008). Changes in sedimentary patterns of coastal and deep-sea successions from the North Atlantic (Portugal) linked to Early Cretaceous environmental change. Palaeogeography, Palaeoclimatology, Palaeoecology, **257**, 38-57.

Carmichael, S.K., Waters, J.A., Suttner, T.J., Kido, E., and DeReuil, A.A. (2014). A new model for the Kellwasser Anoxia Events (Late Devonian): Shallow water anoxia in an open oceanic setting in the Central Asian Orogenic Belt. *Palaeogeogr., Palaeoclimatol., Palaeoecol.* **399**, 394–403.

Carmichael, S.K., Waters, J.A., Batchelor, C.J., Coleman, D.M., Suttner, T.J., Kido, E., Moore, L.M., Chadimova, L. (2016). Climate instability and tipping points in the Late Devonian: Detection of the Hangenberg Event in an open oceanic island arc in the Central Asian Orogenic Belt. *Gondwana Research*, **32**, 213-231.

Chandler, M.A., Rind, D., and Ruey, R. (1992) Pangean climate during the Early Jurassic: GCM simulations and the sedimentary record of paleoclimate. *GSA Bull.,* **104,** 543-559.

Cohen, A.S., Coe, A.L., Harding, S.M. and Schwark, L. (2004) Osmium isotope evidence for the regulation of atmospheric CO_2 by continental weathering. *Geology*, **32**, 157-160.

Cohen, A.S., Coe, A.L. and Kemp, D.B. (2007). The Late Palaeocene, Early Eocene and Toarcian (Early Jurassic) carbon isotope excursions: a comparison of their time scales, associated environmental changes, causes and consequences. J.Geol. Soc., Lond. **164**, 1093–1108.

Cors, J., Heimhofer, U., Adatte, T., Hochuli, P.-A., Huck, S., Bover-Arnal, T. (2015). Climatic evolution across oceanic anoxic event 1a derived from terrestrial palynology and clay minerals (Maestrat Basin, Spain). *Geological Magazine*, **152**, 632-647.

De Vleeschouwer, D., Crucifix, M., Bounceur, N., and Claeys, P. (2014). The impact of astronomical forcing on the Late. Devonian greenhouse climate. *Global, Planetary Change* **120**, 65–80.

de Winter, N.J. and Claeys, Ph. (this volume). Micro X-ray fluorescence (µXRF) line scanning on Cretaceous rudist bivalves: A new method for reproducible trace element profiles in bivalve calcite. *Sedimentology*, this volume.

Dickson, A.J., Jenkyns, H.C., Porcelli, D., van den Boorn, S., and Idiz, E. (2016). Basin-scale controls on the molybdenum-isotope composition of seawater during Oceanic Anoxic Event 2 (Late Cretaceous). *Geochim. Cosmochim. Acta*, **178**, 291–306

Dickson, A.J., Saker-Clark, M., Jenkyns, H.C., Bottini, C., Erba, E., Russo, F., Gorbanenko, O., Naafs, B.D.A.,Pancost, R.D., Robinson, S.A., and van den Boorn, S.H.J.M. (this volume) A Southern Hemisphere record of global trace-metal drawdown and orbital modulation of organic-matter burial across the Cenomanian–Turonian boundary (ODP Site 1138, Kerguelen Plateau). *Sedimentology*, this volume.

Donnadieu, Y., Pierrehumbert, R., Jacob, R., and Fluteau, F., (2006) Modelling the primary control of paleogeography on Cretaceous climate. *Earth Planet. Sci. Letts.,* 248, 426–437.

Donnadieu, Y., Pucéat, E., Moiroud, M., Guillocheau, F., and Deconinck, J.-F., (2016) A better-ventilated ocean triggered by Late Cretaceous changes in continental configuration. *Nat. Comms.,* DOI: 10.1038/ncomms10316

Dromart, G., Garcia, J.-P., Gaumet, F., Picard, S., Rousseau, M., Atrops, F., Lecuyer, C., and Sheppard, S.M.F. (2003). Perturbation of the carbon cycle at the Middle/Late Jurassic transition: Geological and geochemical evidence. *Am. Jour. Sci.,* **303**, 667–707.

Eldrett, J. S., Minisini, D. and Bergman, S.C. (2014) Decoupling of the carbon cycle during Ocean Anoxic Event 2. *Geology*, **42**, 567–570

Erba, E., Bartolini, A. and Larson, R.L. (2004) Valanginian Weissert oceanic anoxic event. *Geology*, **32**, 149-152.

Erba, E., Bottini, C., Weissert, H., Keller, C. E. (2010). Calcareous nannoplankton response to surface-water acidification around oceanic anoxic event 1a. Science, **329**, 428-432.

Erba, E., Duncan, R.A., Bottini, C., Tiraboschi, D., Weissert, H., Jenkyns, H.C. and Malinverno, A. (2015). Environmental consequences of Ontong Java Plateau and Kerquelen Plateau volcanism. *In:* Neal, C.R., Sager, W.W., Sano, T. & Erba, E., Eds, *The origin, evolution, and environmental consequences of oceanic Large Igneous Provinces*, Geol. Soc. Am. Spec. Paper, **511**, 271–303.

Erbacher, J., Thurow, J., and Littke, R., (1996). Evolution patterns of radiolaria and organic matter variations: A new approach to identify sea-level changes in mid-Cretaceous pelagic environments. *Geology,* **24**, 499–502.

Franks, P.J., Royer, D.L., Beerling, D.J., van de Water, P.K., Cantrill, D.J., Barbour, M.M. and Berry, J.A. (2014) New constraints on atmospheric CO_2 concentration for the Phanerozoic. *Geophys. Res. Lett.*, **41**, 4685–4694.

Galli, M. T., Jadoul, F., Bernasconi, S. M., Weissert, H. (2005). Anomalies in global carbon cycling and extinction at the Triassic/Jurassic boundary: Evidence from a marine C-isotope record. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **216**, 203-214.

Gill, B.C., Lyons, T.W., Jenkyns, H.C., (2011). A global perturbation to the sulfur cycle during the Toarcian Oceanic Anoxic Event, *Earth Planet. Sci. Letts.,* **312,** 484–496.

Giorgioni, M., Weissert, H., Bernasconi, S. M., Hochuli, P. A., Coccioni, R., Keller, C. E. (2012). Orbital control on carbon cycle and oceanography in the mid-Cretaceous greenhouse. Paleoceanography, **27**, PA1204.

Giorgioni, M., Tiraboschi, D., Erba, E., Hamann, Y., and Weissert□, H., (this volume) Sedimentary patterns and palaeoceanography of the Albian

Marne a Fucoidi Formation (Central Italy) revealed by high-resolution geochemical and nannofossil data. *Sedimentology*, this volume.

Gomes, M.L., Hurtgen, M.T. and Sageman, B.B. (2016) Biogeochemical sulfur cycling during Cretaceous Ocean Anoxic Events: A comparison of OAE1a and OAE2. *Paleoceanography***, 31,** 233–251**.**

Gröcke, D., Hesselbo, S.P. and Jenkyns, H.C. (1999). Carbon-isotope composition of Lower Cretaceous fossil wood: ocean-atmosphere chemistry and relation to sea-level change. *Geology*, **27,** 155–158.

Gröcke, D.R., Hori, R.S., Trabucho-Alexandre, J., Kemp, D.B. and Schwark, L. (2011). An open ocean record of the Toarcian oceanic anoxic event. *Solid Earth,* **2**, 245-257

Heimhofer, U., Meister, P., Bernasconi, S., Ariztegui, D., Martill, D., de Moraes R.-N., Schwark, L. (this volume). Isotope and elemental geochemistry of black shale-hosted fossiliferous concretions from the Cretaceous Santana Formation fossil Lagerstätte (Brazil). *Sedimentology,* this volume.

Hennig, S., Weissert, H., Bulot, L. (1999). C-isotope stratigraphy, a calibration tool between ammonite- and magnetostratigraphy: the Valanginian-Hauterivian transition. *Geologica Carpathica*, **50**, 91-96.

Hesselbo, S.P., Gröcke, D., Jenkyns, H.C., Bjerrum, C.J., Farrimond, P., Bell, H.S.M., and Green, O.R., (2000). Massive dissociation of gas hydrate during a Jurassic oceanic anoxic event. *Nature,* **406**, 392–395

Hesselbo, S.P., Bjerrum, C.J., Hinnov, L.A., MacNiocaill, C., Miller, K.G., Riding, J.B., van de Schootbrugge, B., and the Mochras Revisited Science Team (2013) Mochras borehole revisited: a new global standard for Early Jurassic Earth history, *Sci. Dril*., 16, 81-91,

Holmden, C., Jacobson, A.D., Sageman, B.B., Hurtgen, M.T., (2016) Response of the Cr isotope proxy to Cretaceous Ocean Anoxic Event 2 in a pelagic carbonate succession from the Western Interior Seaway, *Geochim. Cosmochim. Acta,* **186**, 277–295.

Hsü K.J. and Jenkyns, H.C. (eds) (1974). Pelagic Sediments: on Land and under the Sea. Spec. Publ. Int. Ass. Sediment., **1**, 447 pp.

Ikeda, M. and Hori, R.S. (2014). Effects of Karoo–Ferrar volcanism and astronomical cycles on the Toarcian Oceanic Anoxic Events (Early Jurassic. *Palaeogeog., Palaeoclimat., Palaeoecol.,* **410**, 134–142.

Jarvis, I., Mabrouk, A., Moody, R.T.J., and Cabrera, S.D., (2002). Late Cretaceous (Campanian) carbon isotope events, sea-level change and correlation of the Tethyan and Boreal realms. *Palaeogeog., Palaeoclimat., Palaeoecol.,* **188**, 215–248.

Jarvis, I., Lignum, J.S., Gröcke, D.R., Jenkyns, H.C. and Pearce, M.A. (2011) Black shale deposition, atmospheric CO_2 drawdown and cooling during the Cenomanian-Turonian Oceanic Anoxic Event. *Paleoceanography*, **26**, PA3201, doi: 10.1029/2010PA002081.

Jenkyns, H.C., (1970a) Sedimentology of the west Sicilian Jurassic. *Unpublished PhD thesis, University of Leicester, UK.*

Jenkyns, H.C. (1970b) Growth and disintegration of a carbonate platform. *Neues Jb. Geol. Paläont., Mh*., **1970**, 325–344.

Jenkyns, H.C. (1971). The genesis of condensed sequences in the Tethyan Jurassic. *Lethaia*, **4**, 327–352.

Jenkyns H.C. (1976). Sediments and sedimentary history of the Manihiki Plateau, South Pacific Ocean. *In:* Schlanger, S.O., Jackson E.D., *et al., Initial Reports of the Deep Sea Drilling Project*, US Government Printing Office, **33**, 873–890.

Jenkyns, H.C. (1980). Cretaceous anoxic events: from continents to oceans. *J. Geol. Soc. Lond.,* **137**, 171–188.

Jenkyns, H.C. (1985). The Early Toarcian and Cenomanian-Turonian anoxic events in Europe: comparisons and contrasts. *Geol. Rdsch*., 74, 505–518

Jenkyns, H.C. (1988). The Early Toarcian (Jurassic) Anoxic Event: stratigraphic, sedimentary and geochemical evidence. *Am. J. Sci.*, 288, 101–151

Jenkyns H.C. (2003). Evidence for rapid climate change in the Mesozoic-Palaeogene greenhouse world. *Philos Trans A Math Phys Eng Sci*. **361(1810)**, 1885-1916.

Jenkyns, H.C. (2010). Geochemistry of oceanic anoxic events. *Geochem. Geophys. Geosys.,* **11**, Q03004**.**

Jenkyns, H.C., and Clayton, C.J., (1986). Black shales and carbon isotopes in pelagic sediments from the Tethyan Lower Jurassic. *Sedimentology* **33**, 87-106□.

Jenkyns, H.C., and Clayton, C.J., (1997). Lower Jurassic epicontinental carbonates and mudstones from England and Wales: chemostratigraphic signals and the early Toarcian anoxic event**.** *Sedimentology,* **44,** 687-706.

Jenkyns, H.C. and Wilson, P.A. (1999). Stratigraphy, paleoceanography and evolution of Cretaceous Pacific guyots: relics from a greenhouse earth. *Am. J. Sci.,* 299, 341–392

Jenkyns, H.C., Gale, A.S., and Corfield, R.M. (1994) Carbon- and oxygen-isotope stratigraphy of the English chalk and Italian Scaglia and its paleoclimatic significance. *Geol. Mag.,* **131**, 1–34.

Jenkyns, H.C., Gröcke, D.R. and Hesselbo, S.P. (2001). Nitrogen-isotope evidence for watermass denitrification during the Early Toarcian (Jurassic) Oceanic Anoxic Event. *Paleoceanography,* 16, 593–603.

Jenkyns, H.C., Forster, A., Schouten, S. and Sinninghe Damsté, J.S. (2004). High temperatures in the Late Cretaceous Arctic Ocean. *Nature*, 432, 888–892

Jenkyns, H.C., Matthews, A., Tsikos, H. and Erel, Y. (2007). Nitrate reduction, sulfate reduction, and sedimentary iron isotope evolution during the Cenomanian–Turonian oceanic anoxic event. *Paleoceanography*, 22, PA3208, doi:10.1029/2006PA001355.

Jenkyns, H.C., Dickson, A.J., Ruhl, M., van den Boorn, S.H.J.M., (this volume), Basalt–seawater interaction, the Plenus Cold Event, enhanced weathering and geochemical change: Deconstructing Oceanic Anoxic Event 2 (Cenomanian–Turonian, Late Cretaceous). *Sedimentology,* this volume.

Jimenez Berrocoso, A., Huber, B.T., MacLeod, K.G., Petrizzo, M.R., Lees, J.A., Wendler, I., Coxall, H., Mweneinda, A.K., Falzoni, F., Birch, H., Haynes, S.J., Bown, P.R., Robinson, S.A., Singano, J.M., (**2015)** The Lindi

Formation (upper Albian-Coniacian) and Tanzania Drilling Project Sites 36-40 (Lower Cretaceous to Paleogene): lithostratigraphy, biostratigraphy and chemostratigraphy, *Jour. African Earth Sci.,* **101**, 282-308

Jones, C.E., and Jenkyns, H.C. (2001) Seawater strontium isotopes, Oceanic Anoxic Events, and seafloor hydrothermal activity in the Jurassic and Cretaceous. *Am. Jour. Sci.* **301**, 112-149.

Jones, C.E., Jenkyns, H.C., Coe, A.L. and Hesselbo, S.P. (1994). Sr isotopic variations in Jurassic and Cretaceous seawater. *Geochim. Cosmochim. Acta,* 58, 3061–3074.

Kemp, D.B., Robinson, S.A., Crame, J.A., Francis, J.E., Ineson, J., Whittle, R.J., Bowman, V., and O'Brien, C., (2014). A cool temperate climate on the Antarctic Peninsula through the latest Cretaceous to early Paleogene, *Geology*, **42***,* 583-586

Kujau, A., Heimhofer, U., Hochuli, P. A., Pauly, S., Morales, C., Adatte, T., Föllmi, K.B., Ploch, I., Mutterlose, J. (2013). Reconstructing Valanginian (Early Cretaceous) mid-latitude vegetation and climate dynamics based on spore-pollen assemblages. *Review of Palaeobotany and Palynology*, **197**, 50-69.

Kump, L.R., and Arthur, M.A., (1999). Interpreting carbon-isotope excursions: carbonates and organic matter. *Chem. Geol.,* **161**, 181–198.

Kuypers, M.M.M., Pancost, R.D., Nijenhuis, I.A. and Sinninghe Damsté, J.S. (2002), Enhanced productivity led to increased organic carbon burial in the euxinic North Atlantic basin during the late Cenomanian oceanic anoxic event, *Paleoceanography*, **17**, 1051, doi:10.1029/2000PA000569

Lechler, M., Pogge von Strandmann, P.A.E., Jenkyns, H.C., Prosser, G. & Parente, M. (2015). Lithium-isotope evidence for enhanced silicate weathering during OAE 1a (Early Aptian Selli event). *Earth Planet. Sci. Letts*, **432**, 210–222.

Lini, A., Weissert, H., and Erba, E. (1992). The Valanginian carbon isotope event: a first episodes of greenhouse climate conditions during the Cretaceous. *Terra Nova*, **4**, 374-384.

Lu, Z., Jenkyns, H.C. and Rickaby, R.E.M. (2010). Iodine to calcium ratios in marine carbonate as a paleo-redox proxy during oceanic anoxic events. *Geology*, 38, 1107–1110

Lunt, D.J., Farnsworth, A., Loptson, C., Foster, G.L., Markwick, P., O'Brien, C.L., Pancost, R.D., Robinson, S.A., and Wrobel, N. (2016) Palaeogeographic controls on climate and proxy interpretation, *Clim. Past*, **12**, 1181-1198, doi:10.5194/cp-12-1181-2016.

MacLeod, K.G., Martin, E.E., and Blair, S W. (2008), Nd isotopic excursion across Cretaceous oceanic anoxic event 2 (Cenomanian□Turonian) in the tropical North Atlantic, *Geology*, **36**, 811–814.

McLaughlin, P.I., Emsbo, P. and Brett, C.E. (2012). Beyond black shales: the sedimentary and stable isotope records of oceanic anoxic events in a dominantly oxic basin (Silurian; Appalachian Basin, USA). *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **367-368**, 153–177.

Mehay, S., Keller, C.E., Bernasconi, S.M., Weissert, H., Erba, E., Bottini, C., and Hochuli, P.A. (2009). A volcanic CO_2 pulse triggered the Cretaceous oceanic Anoxic event 1a and a biocalcification crisis, *Geology*, **37**, 819-822.

Millán, M. I., Weissert, H., Fernández-Mediola, P.A., and García-Mondéjar, J. (2009). Impact of Early Aptian carbon cycle perturbations on evolution of a marine shelf system in the Basque-Cantabrian Basin (Aralar, Northern Spain). *Earth Planet. Sci. Letts*, **287**, 392-401.

Montienaro, F.M., Pancost, R.D., Ridgwell, A., and Donnadieu,□ Y. (2012) Nutrients as the dominant control on the spread of anoxia and euxinia across the Cenomanian-Turonian oceanic anoxic event (OAE2): Model-data comparison. *Paleoceanography,* **27**, doi:10.1029/2012PA002351

Montoya-Pino, C., Weyer, S., Anbar, A.D., Pross, J., Oschmann, W., van de Schootbrugge, B., and Arz, H.W., (2010)□ Global enhancement of ocean anoxia during Oceanic Anoxic Event 2: A quantitative approach using U isotopes. *Geology,* **38**, 315-318.

Morettini, E., Santantonio, M., Bartolini, A., Cecca, F., Baumgartner, P.O., and Hunziker, J.C., (2002) Carbon isotope stratigraphy and carbonate production during the Early–Middle Jurassic: Examples from the Umbria-Marche-Sabina Apennines (central Italy). *Palaeogeog., Palaeoclimat., Palaeoecol.,* **184**, 251–273.

Müller,T., Price, G.D., Bajnai, D., Nyerges, A., Kesjár, D., Raucsik, B., Varga, A., Judik, K., Fekete, J., May, Z. and Pálfy, J. (this volume). New multiproxy record of the Jenkyns Event (a.k.a. Toarcian Oceanic Anoxic Event) from the Mecsek Mountains (Hungary): differences, duration and drivers. *Sedimentology,* (this volume).

Naafs, B.D.A., Castro, J.M., De Gea, G.A., Quijano, M.L., D. N. Schmidt, D.N., Pancost, R.D., (2016) Gradual and sustained carbon dioxide release during Aptian Oceanic Anoxic Event 1a, *Nat. Geosci.,* **9,** 135–139.

Nielsen, S.G., Goff, M., Hesselbo, S.P., Jenkyns, H.C., LaRowe, D.E. & Lee, C.A. (2011). Thallium isotopes in early diagenetic pyrite – a paleoredox proxy? *Geochim. Cosmochim Acta*, **75**, 6690–6704

Owens, J.D., Gill, B.C., Jenkyns, H.C., Bates, S.M., Severmann, S., Kuypers, M.M.M., Woodfine, R.G. and Lyons, T.W. (2013) Sulfur isotopes track the global extent and dynamics of euxinia during Cretaceous Oceanic Anoxic Event 2. *Proc. Natl Acad. Sci. USA*, **110**, 18407–18412.

Owens, J., Lyons, T., Hardisty, D., Chris, C., Zunli, L., and Jenkyns, H.C. (this volume). Patterns of local and global redox variability during the Cenomanian–Turonian Boundary Event (OAE2) recorded in carbonates and shales from central Italy (Furlo, Marche–Umbria). *Sedimentology,* this volume

Pancost, R.D., Crawford, N., Magness, S., Turner, A., Jenkyns, H.C. and Maxwell, J.R. (2004). Further evidence for the development of photic□zone euxinic conditions during Mesozoic oceanic anoxic events. *J. Geol. Soc.,* 161, 353– 364.

Parrish, J.T. and Curtis, R.L., (1982). Atmospheric circulation, upwelling, and organic-rich rocks in the Mesozoic and Cenozoic eras. *Palaeogeogr., Palaeoclimatol., Palaeoecol.,* **40**, 31–66

Parrish, J.T., Ziegler, A.M., and Scotese, C.R. (1982) Rainfall patterns and the distribution of coals and evaporites in the Mesozoic and Cenozoic. *Palaeogeog., Palaeoclim., Palaeoecol.,* **40**, 67–101.

Pearce, C.R., Cohen, A.S., Coe, A.L., and Burton, K.W. (2008). Molybdenum isotope evidence for global oceanic anoxia coupled with perturbations to the carbon cycle during the Early Jurassic, *Geology*, **36**, 231–234.

Percival, L.M.E., Cohen, A.S., Davies, M.K., Dickson, A.J., Hesselbo, S.P., Jenkyns, H.C., Leng, M.J., Mather, T.A., Storm, M.S., and Xu, W., (2016). Osmium isotope evidence for two pulses of increased continental weathering linked to Early Jurassic volcanism and climate change. *Geology*, doi:10.1130/G37997.1

Petrizzo, M.R., Huber B.T., Wilson, P.A., and MacLeod, K.G. (2008). Late Albian paleoceanography of the western subtropical North Atlantic. *Paleocean.,* 23, doi:10.1029/2007PA001517

Petrizzo, M.R., Jiménez Berrocoso, A., Falzoni, F., Huber, B.T., and MacLeod, K.G., (this volume). The Coniacian-Santonian sedimentary record in southern Tanzania (Ruvuma Basin, East Africa): planktonic foraminiferal evolutionary, geochemical and palaeoceanographic patterns. *Sedimentology*, (this volume)

Pogge von Strandmann, P.A.E., Jenkyns, H.C. and Woodfine, R.G. (2013). Lithium isotope evidence for enhanced weathering during Oceanic Anoxic Event 2. *Nature Geosci.,* 6, 668–672

Poulsen, C.J., Barron, E.J., Arthur, M.A., and Peterson, W.H., (2001) Response of the mid-Cretaceous global oceanic circulation to tectonic and CO_2 forcings. *Paleoceanography*, **16**, 1-17

Poulsen, C.J., Gendaszek, A.S., and Jacob, R.L., (2003) Did the rifting of the Atlantic Ocean cause the Cretaceous thermal maximum? *Geology*, **31**, 115–118.

Poulsen, C.J., Tabor, C., and White, J.D. (2015) Long-term climate forcing by atmospheric oxygen concentrations. *Science,* **348,** 1238–1241.

Riding, J.B., Leng, M.J., Kender, S, Hesselbo, S.P., Feist-Burkhardt, S (2013). Isotopic and palynological evidence for a new Early Jurassic environmental perturbation. *Palaeogeog., Palaeoclim., Palaeoecol.,* **374**, 16-27.

Robinson, S.A., Williams, T. and Bown, P.R. (2004). Fluctuations in biosiliceous production and the generation of Early Cretaceous oceanic anoxic events in the Pacific Ocean (Shatsky Rise, Ocean Drilling Program Leg 198). *Paleoceanography*, 19, PA4024, doi:10.1029/2004PA001010.

Robinson, S.A., Clark, L.J., Nederbragt, A., and Wood, I.G., (2008) Mid-Cretaceous oceanic anoxic events in the Pacific Ocean revealed by carbon-isotope stratigraphy of the Calera Limestone, California, USA. *Bull. Geol. Soc. Am.*, 120, 1416–1427.

Robinson, S.A., Ruhl, M., Astley, D.L., Naafs, B.D.A., Farnsworth, A.J., Bown, P.R., Jenkyns, H.C., Lunt, D.J., O'Brien, C., Pancost, R.D., and

Markwick, P.J. (this volume). Early Jurassic North Atlantic sea-surface temperatures from TEX_{86} palaeothermometry, *Sedimentology,* this volume.

Schlanger, S.O. and Jenkyns, H.C. (1976). Cretaceous oceanic anoxic events: causes and consequences. *Geol. Mijnb.*, **55**, 179–194.

Schlanger, S.O., Arthur, M.A., Jenkyns, H.C., and Scholle, P.A., (1987). The Cenomanian Turonian Oceanic Anoxic Event I. Stratigraphy and distribution of organic-carbon rich beds and the marine $\delta^{13}C$ excursion. *Geol. Soc. London Spec. Publ.* **26**, 371-399.

Scholle, P., and Arthur, M.A., (1980). Carbon isotopic fluctuations in pelagic limestones: Potential stratigraphic and petroleum exploration tool. *AAPG Bull*. **64**, 67-87

Schubert, B.A., and Jahren. A.H. (2013). Reconciliation of marine and terrestrial carbon isotope excursions based on changing atmospheric CO_2 levels. *Nature Comms,* **4**, 1653, DOI: 10.1038/ncomms2659

Sloan, L.C., and Barron, E.J., (1990) “Equable” climates during Earth history? *Geology*, **18**, 489-492.

Smith A.G., Hurley, A.M., and Briden, J.C., (1981) Phanerozoic paleocontinental World Maps. Cambridge University Press, Cambridge, UK. 102 pp.

Spicer, R.A., Ahlberg, A., Herman, A.B., Hofmann, C.-C. Raikevich, M., Valdes, P.J., and Markwick, P.J., (2008). The Late Cretaceous continental interior of Siberia: A challenge for climate models. *Earth Planet. Sci. Letts.* **267**, 228–235.

Takashima, R., Nishi, H., Huber, B.T., and Leckie, R.M. (2006), Greenhouse World and the Mesozoic Ocean. *Oceanography*, **19**, 82-92.

Takashima, R., Nishi, H., Yamanaka, T., Tomosugi, T., Fernando, A.G., Tanabe, K., Moriya, K., Kawabe, F., and Hayashi, K., (2011). Prevailing oxic environments in the Pacific Ocean during the mid-Cretaceous Oceanic Anoxic Event 2. *Nat. Comms.,* DOI: 10.1038/ncomms1233.

Tejada, M.L.G., Suzuki, K., Kuroda, J., Coccioni, R., Mahoney, J.J., Ohkouchi, N., Sakamoto, T., and Tatsumi, Y. (2009). Ontong Java Plateau eruption as a trigger for the Early Aptian oceanic anoxic event, *Geology*, **37**, 855–858

Tsikos, H., Jenkyns, H.C., Walsworth-Bell, B., Petrizzo, M.R., Forster, A., Kolonic, S., Erba, E., Premoli Silva, I., Wagner, T., and Sinninghe Damsté, J.S. (2004), Carbon isotope stratigraphy recorded by the Cenomanian–Turonian Oceanic Anoxic Event: correlation and implications based on three key localities. *J. Geol. Soc. London*,, **161**, 711– 719

Turgeon, S. and Creaser, R.A. (2008) Cretaceous oceanic anoxic event 2 triggered by a massive magmatic episode. *Nature*, **454**, 323–326.

Valdes, P.J., and Sellwood, B.W. (1992) A palaeoclimate model for the Kimmeridgian. *Palaeogeog., Palaeoclim., Palaeoecol.* **95**, 47–72.

Van de Schootbrugge, B., Bailey, T.R., Rosenthal, Y., Katz, M.E., Wright, J.D., Miller, K.G., Feist- Burkhardt, S., and Falkowski, P.G. (2005). Early Jurassic climate change and the radiation of organic-walled phytoplankton in the Tethys Ocean. *Paleobiology* **31**, 73–97

Vandenbroucke, T.R.A., Emsbo, P., Munnecke, A., Nuns, N., Duponchel, L., Lepot, K., Quijada, M., Paris, F., Servais, T., Kiessling, W. (2016) Metal-induced malformations in early Palaeozoic plankton are harbingers of mass extinction *Nature Comms* **6**, Article Number 7966.

Wagner, T. and Dunkley Jones, T., (2015) Drilling the Cretaceous Palaeogene Tropical South Atlantic. *ECORD Newsletter,* **24,** p.20.

Weedon, G.P. and Jenkyns, H.C. (1999). Cyclostratigraphy and the Early Jurassic time scale: data from the Belemnite Marls, Dorset, Southern England. *Bull. Geol. Soc. Am.,* 111, 1823–1840.

Weissert, H.J. (1979). Die Palaeoozeanographie der suedwestlichen Tethys in der Unterkreide. *Unpublished PhD thesis, Eidgenössische Technische Hochschule, Zürich, Switzerland*.

Weissert, H.J., (1989). C-isotope stratigraphy, a monitor of paleoenvironmental change: a case study from the Early Cretaceous. *Surv. Geophys*. **10**, 1-61

Weissert, H. (1990) Siliciclastics in Early Cretaceous Tethys and Atlantic Oceans. *Mem. Soc. Geol. It.,* **44,** 59-69

Weissert, H. (2000). Deciphering methane's fingerprint**.** *Nature***, 406,** 356–357

Weissert, H., and Bréhéret, J.G., (1991). A carbonate-carbon isotope record from Aptian-Albian sediments of the Vocontian Trough. *Bull. Soc. Géol. Fr.* **162**, 1133-1140.

Weissert, H., and Channell, J.E.T., (1989). Tethyan carbonate carbon isotope stratigraphy across the Jurassic Cretaceous boundary: an indicator of decelerated carbon cycling. *Paleoceanography* **4,** 483 494.

Weissert, H., and Erba, E. (2004). Volcanism, CO_2 and palaeoclimate: A Late Jurassic-Early Cretaceous carbon and oxygen isotope record. *Jour. Geol. Soc.,* **161**, 695-702.

Weissert, H. and Lini, A. (1991), Ice age interludes during the time of Cretaceous greenhouse climate. *In:* Müller, D.W., McKenzie, J.A., Weissert, H. (Eds.), *Controversies in Modern Geology*. Academic Press, London, pp. 173-191.

Weissert, H., and Mohr, H., (1996). Late Jurassic climate and its impact on carbon cycling. *Palaeogeogr., Palaeoclimatol., Palaeoecol.* **122,** 27-43.

Weissert, H. and Oberhänsli, H., (1985), Pliocene Oceanography and Climate: An Isotope Record from the Southwest Angola Basin *In:* Hsu K.J. and Weissert, H. (eds.), *South Atlantic Paleoceanography*, Cambridge University Press, 79-98.

Weissert, H., McKenzie, J.A., Wright, R.C., Clark, M., Oberhänsli, H., and Casey, M., (1984) Paleoclimatic Record of the Pliocene at Deep Sea Drilling Project Sites 519, 521, 522, and 523 (Central South Atlantic); *In* Hsu, K.J. and LaBreque, J.L. *et al.* (eds.), *Initial Reports of the Deep Sea Drilling Project*, **73**, Washington, D.C., U.S.Govt. Printing Office, pp. 701-715

Weissert, H.J., McKenzie, J.A., Channell, J.E.T., (1985) Natural variations in the carbon cycle during the Early Cretaceous. *In:* Sundquist, E.T., Broecker, W.S. (Eds.), *The Carbon Cycle and Atmospheric CO2: Natural variations Archean to the Present*. Geophys. Monogr. **32**, 531 545.

Weissert, H., Lini, A., Föllmi, K.B., and Kuhn, O. (1998). Correlation of Early Cretaceous carbon isotope stratigraphy and platform drowning events: A possible link? *Palaeogeog., Palaeoclimat., Palaeoecol*., **137**, 189-203.

Westermann, S., Vance, D., Cameron, V., Archer, C. and Robinson, S.A. (2014). Heterogeneous oxygenation states in the Atlantic and Tethys Oceans during Oceanic Anoxic Event 2. *Earth Planet. Sci. Lett.,* **404**, 178–189.

Wissler, L., Funk, H., and Weissert, H. (2003). Response of Early Cretaceous carbonate platforms to changes in atmospheric carbon dioxide levels. *Palaeogeog., Palaeoclimat., Palaeoecol*, **200**, 187-205.

Wohlwend, S., Celestino, R., Reháková, D., Huck, S., and Weissert, H., (this volume), Late Jurassic to Cretaceous evolution of the eastern Tethyan Hawasina Basin (Oman Mountains). *Sedimentology*, this volume.

Xu, W., Ruhl, M., Hesselbo, S.P., Riding, J.B., and Jenkyns. H.C. (this volume). Orbital pacing of the Early Jurassic carbon cycle, black shale formation and seabed methane seepage. *Sedimentology,* this volume

Zheng, X.-Y., Jenkyns, H.C., Gale, A.S., Ward, D.J. and Henderson, G.M. (2013). Changing ocean circulation and hydrothermal inputs during Ocean Anoxic Event 2 (Cenomanian_Turonian): Evidence from Nd-isotopes in the European shelf sea. *Earth Planet. Sci. Letts*, **375**, 338–348.

Zheng, X.-Y., Jenkyns, H.C., Gale, A.S., Ward, D.J. and Henderson, G.M. (2016). A climatic control on reorganization of ocean circulation during the mid-Cenomanian event and the Cenomanian–Turonian oceanic anoxic event (OAE 2): Nd isotope evidence. *Geology*, **44**, 151–154.

Zhou, J., Poulsen, C.J., Pollard, D., and White, T.S., (2008) Simulation of modern and middle Cretaceous marine δ^{18}O with an ocean-atmosphere general circulation model. *Paleoceanography,* **23**, doi:10.1029/2008PA001596

Zhou, X., Jenkyns, H.C., Owens, J.D., Junium, C.K., Zheng, X.-Y., Sageman, B.B., Hardisty, D.S., Lyons, T.W., Ridgwell, A., and Lu, Z., (2015) Upper ocean oxygenation dynamics from I/Ca ratios during the Cenomanian–Turonian OAE2. *Paleoceanography*, **30**, 510–526.

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).

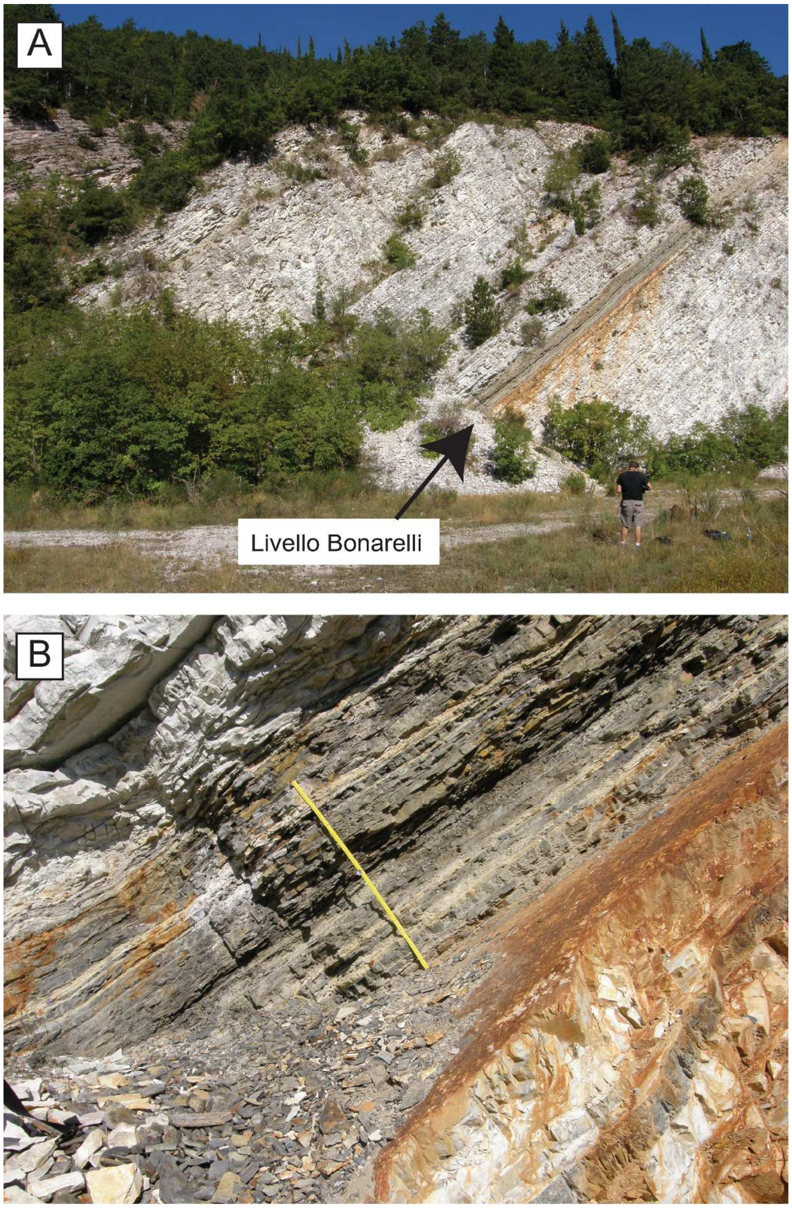


Figure 1 Example of black shale deposited during oceanic anoxic events. (A) Livello Bonarelli, deposited during OAE2 in the Furlo Quarry, Umbria-Marche region, Italy (B) close up view of Livello Bonarelli in Furlo Quarry, where it is ~1.2 m thick. Within the black shales are lighter coloured radiolarian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

207x316mm (300 x 300 DPI)

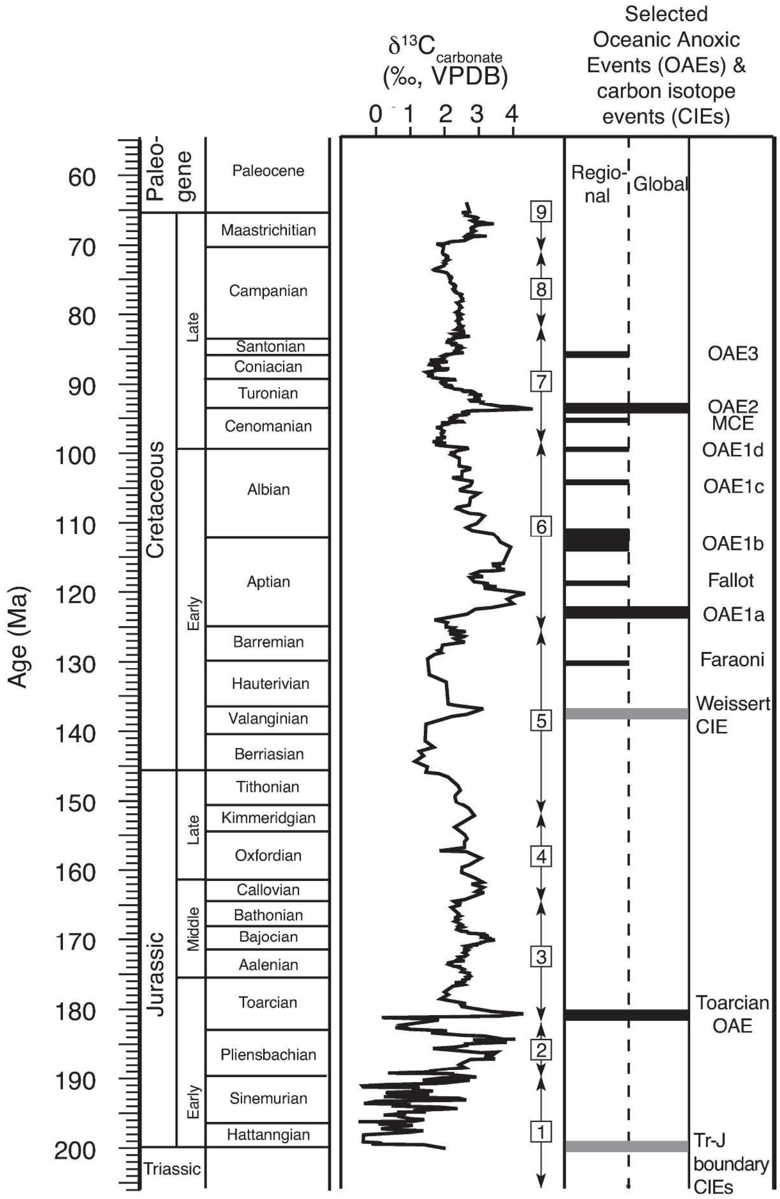


Figure 2. Bulk carbonate carbon-isotope (δ13Ccarb) stratigraphy of the Jurassic and Cretaceous (modified from Takashima et al., 2006) and age of prominent 'Oceanic Anoxic Events'). Carbon-isotope data from (1) Van de Schootbrugge et al. (2005); (2) Hesselbo et al. (2000); (3) Morettini et al. (2002); (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).

199x310mm (300 x 300 DPI)

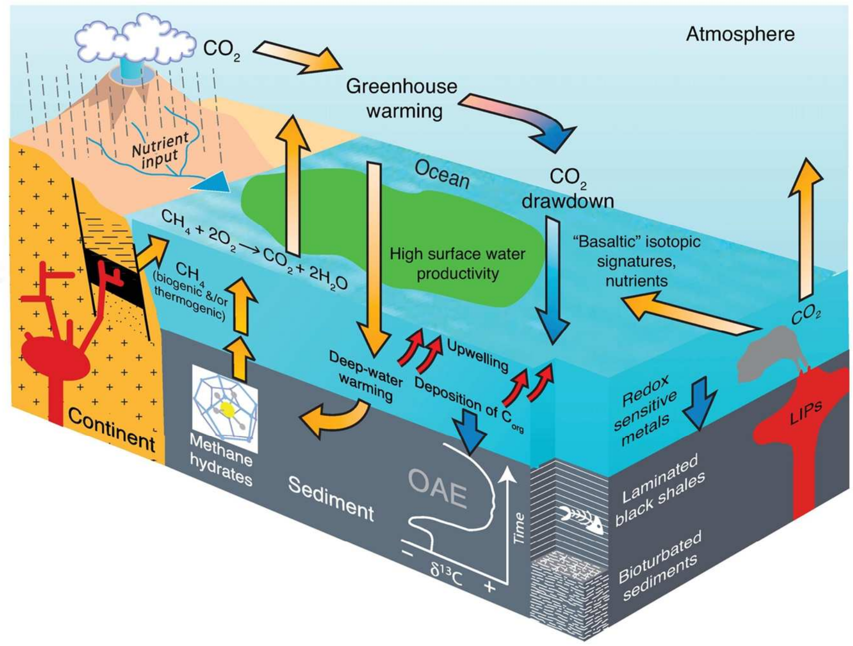
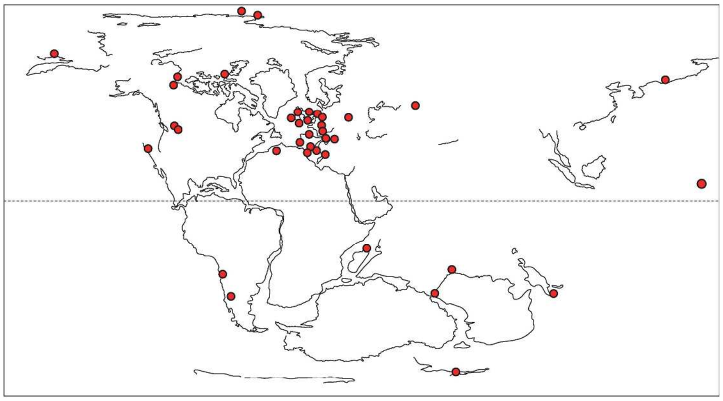


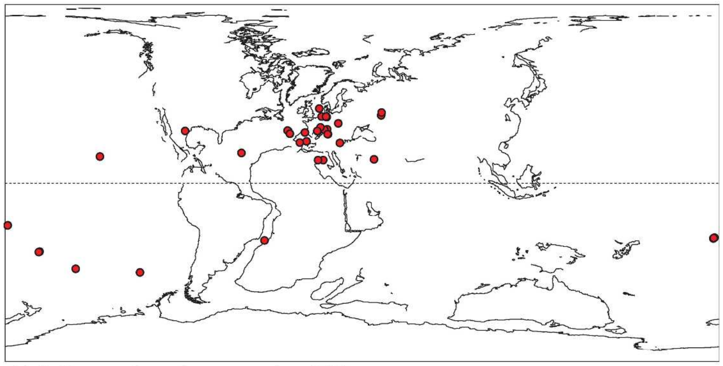
Figure 3 Cartoon illustrating major aspects of the positive and negative feedbacks that led to the onset and termination of oceanic anoxic events, as described in the text. The figure has been modified from Jenkyns (2010), based on an original figure in Weissert (2000).

127x94mm (300 x 300 DPI)

a) Toarcian palaeogeography ~183 Ma



b) Early Aptian palaeogeography ~120 Ma



c) Late Cenomanian palaeogeography ~95 Ma

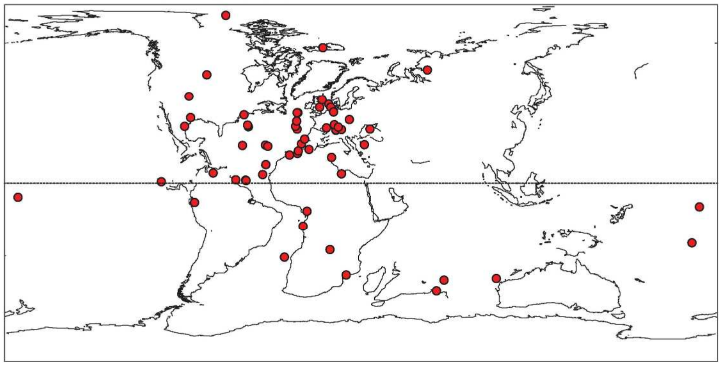


Figure 4 Maps showing the distribution of localities presenting black shales and sediments containing more than 1% total organic carbon associated with oceanic anoxic events in the (a) Early Toarcian (T-OAE), (b) Early Aptian (OAE1a) and (c) Cenomanian–Turonian (OAE2). The Toarcian map is adapted from 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).

198x332mm (300 x 300 DPI)