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Causes of oxic–anoxic changes in Cretaceous marine environments and their implications for Earth systems—An introduction

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ABSTRACT

This special issue originated from a session at the 33th International Geological Congress, Oslo, Norway, in August 2008: Causes of oxic-anoxic changes in Cretaceous marine and non-marine environments and their implications for Earth systems (IGCP 463 and 555), convened by Chengshan Wang, Michael Wagreich, and Bradley Sageman. The session aimed at bringing together contributions that shed light on the anoxic to oxic changes in the world oceans during the Cretaceous, including discussion on consequences for today's global change.

1. Introduction

This special issue originated from a session at the 33th International Geological Congress, Oslo, Norway, in August 2008: Causes of oxic–anoxic changes in Cretaceous marine and non-marine environments and their implications for Earth systems (IGCP 463 and 555), convened by Chengshan Wang, Michael Wagreich, and Bradley Sageman. The session aimed at bringing together contributions that shed light on the anoxic to oxic changes in the world oceans during the Cretaceous, including discussion on consequences for today's global change. The contributions of the sessions originated mainly from an ongoing UNESCO IGCP 555 (Rapid Environmental/Climate Change in the Cretaceous Greenhouse World: Ocean-Land Interactions). Focusing on the overall theme of anoxic to oxic changes in the world oceans during the Cretaceous, this special issue comprises a set of papers that focus mainly on aspects of marine sedimentary geology and geochemistry, and Cretaceous paleoceanography and climate evolution.

2. Rationale

Over the past few million years the Earth's climate was characterized by oscillating ice sheets and relatively cool climate. During most of the past 500 million years, the Earth's had no substantial ice sheets on the continents (Frakes et al., 1992). Fischer and Arthur (1977) coined the terms "icehouse" and "greenhouse" for these alternate states of the Earth's climate. These climate oscillations correspond mainly to changes in the Earth's orbital parameters, affecting the amount of radiation received from the sun at different latitudes and amplified by Earth's varying albedo.

The classic "greenhouse state" of the Earth is represented by the environmental conditions of the Cretaceous Period (Skelton et al., 2003), with sea level rising, flooding about 1/3 of the continental area and creating extensive seaways (Ronov et al., 1989). The Tethys closure produced small short-lived marginal sea basins and complex inter-ocean passageways (Dercourt et al., 1992). Emplacement of Large Igneous Provinces (LIPs) (Coffin and Eldholm, 1994; Larson, 1991) increased greenhouse gas concentrations and ocean fertility (Adams et al., 2010; Sinton and Duncan, 1997).

Much of our knowledge of Cretaceous climate has come from stable isotopes, particularly those of oxygen and carbon. Oxygen isotopes of marine fossils record the paleotemperature history of the ocean, indicating a cool early Cretaceous (Frakes, 1999), a hot mid-Cretaceous, and a warm late Cretaceous (Huber et al., 2002). Short-term paleoclimatic events are also documented by oxygen isotope data. During the Cenomanian–Turonian Thermal Maximum the equatorial Atlantic may locally have been as warm as 42 °C (Bice et al., 2006). In contrast, Miller et al. (1999, 2005), Stoll and Schrag (2000) and Price (1999) describe the evidence for possible brief glacial episodes. Carbon isotopes primarily reflect the relative burial rates of organic and inorganic carbon across the globe: a ratio controlled by terrestrial and oceanic productivity, erosion and sedimentation rates, sea level change, tectonic activity, and climate.

We now know that large, rapid climate perturbations occurred during the "greenhouse world" of Cretaceous (Jenkyns, 2003). Such events were not necessarily the direct result of orbital variations, but

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may reflect changes in atmospheric greenhouse gas content forced by magmatism and tectonic activity (Jahren, 2002). The greatest environmental changes during the Cretaceous concerned the oxidation state of the ocean recognized as “Oceanic Anoxic Events” (OAEs, Arthur and Sageman, 1994; Schlanger and Jenkyns, 1976). These episodes of organic-carbon-rich shale deposition were on a scale that has never been repeated. The major OAE intervals were the Weissert OAE in the Late Valanginian, the Early Aptian Selli (OAE 1a), Cenomanian-Turonian (OAE2), and Coniacian-Santonian (OAE3) (Erba, 2004; Leckie et al., 2002). OAEs are associated with major $\delta^{13}C$ excursions, both positive and negative (Arthur et al., 1988), and marine biotic extinction (Leckie et al., 2002). During OAEs, euxinic (i.e. H_2S-bearing) waters locally rose into the photic zone, allowing the growth of green sulfur bacteria (Pancost et al., 2004). Nederbragt et al. (2004) argue for a positive feedback linking oxygen depletion, phosphate regeneration, and oceanic productivity during the OAEs. OAEs may have been triggered by or accompanied by massive injection into the atmosphere of methane trapped as clathrates (Jahren, 2002; Jenkyns, 2003).

OAEs were often succeeded by deposition of Fe-oxide-rich “Oceanic Red Beds” (CORBs, Hu et al., 2005, 2006; Hu et al., 2009; Wang et al., 2004) reflecting ventilation of the ocean. Brief episodes of CORB deposition occurred after the mid-Cretaceous OAEs in the Tethyan Realm (e.g. Hu et al., 2006); some of them were correlated to cold episodes (Wagreich, 2009). Following OAE 2, CORBs became common in the deep ocean. CORBs and the change from anoxic to oxic conditions in the world oceans have been the focus of IGCP 463 “Upper Cretaceous oceanic red beds: Response to the oceanic/climate change” and IGCP 494 “From black shales to oceanic red beds during Mid-Cretaceous: several localities in Tethyan realm” (Wang et al., 2005, 2009).

Similar to the glacial–interglacial transitions of the recent past, the transitions from one climatic state to another in the Cretaceous, and thus from oxic to anoxic and vice versa, were very rapid. Although individual OAEs ranged between half a million and 2 million years in duration (Erba, 2004), the transitions from oxic to dysoxic conditions and back were very sudden (e.g. Erbacher et al., 2005) and there is growing evidence that during and after OAEs oxic to anoxic/dysoxic conditions oscillated on Milankovitch orbital scales (Friedrich, 2009; Wendler et al., 2009).

3. Contributions

The ten papers assembled in this thematic issue of Sedimentary Geology are part of the research presented at the session of the IGC. The objectives of this issue were mainly to provide new data and views on oxic-to-anoxic transitions, on depositional processes and causes and consequences in ancient case studies with a broad geographic distribution including southwestern and central Europe and Asia. The contributions have been grouped by their varied scope into 3 major thematic groups: (1) overview studies on paloceanography, paleoclimate and oxic–anoxic changes, (2) case studies of OAEs and related events, and (3) case studies of CORBs and anoxic–oxic transitions.

The first two papers provide an overall view of ongoing research into the causes and consequences of anoxic to oxic changes in the oceans. The paper by William Hay, starting with a summary of the Cretaceous greenhouse climate and oceanography, poses the humbling question “Can humans force a return to a ‘Cretaceous’ climate?” Hay investigates Cretaceous rates of changes and puts forward an “Eddy” ocean model favoring the formation of black shales and CORBs. Based on these facts, in addition to increased atmospheric greenhouse gas concentrations, a return to climatic conditions resembling those of the Cretaceous would require ice-free poles and large changes in atmospheric and oceanic circulation. Given the fast rates of ice sheet melting today Hay concludes that a return to climatic conditions resembling those of the mid-Cretaceous is not only possible, but also likely unless humanity can stop CO_2 emissions to the atmosphere and remove some of the excess CO_2 already introduced.

The paper by Chengshan Wang, Xiumian Hu, Yongjian Huang, Michael Wagreich, Robert Scott, and William Hay deals with CORBs – Cretaceous oceanic red beds – as a possible consequence of oceanic anoxic events. Based on the temporal and spatial relation between OAEs and CORBs, the authors put forward the idea of Arthur et al. (1988) that OAEs caused significant depletion of CO_2 in the ocean-atmospheric system and, consequently, led to oxic sedimentation. The authors conclude that OAEs may represent a negative feedback of the Earth's system in response to sudden, volcanism-induced warming episodes preventing further acceleration of warming through removal of organic carbon from the ocean-atmosphere, thus sequestering excess CO_2 via an increased productivity cycle.

The following two papers deal with Cretaceous oceanic anoxic events. Robert Locklair, Bradley Sageman and Abraham Lerman, in their contribution on marine carbon burial flux and the carbon isotope record of Late Cretaceous (Coniacian-Santonian) OAE 3, bring a novel modelling approach based on carbon reservoirs and isotope values. In this study, the role of variations in organic carbon and the carbonate accumulation rates on carbon isotopes are explored to develop a global carbon isotopic mass balance model. The authors conclude that the type of carbon burial, associated accumulation rates, and areal distribution of facies are important factors with respect to changes in the carbon isotopic signature of the Cretaceous oceans, i.e. widespread deposition of chalk facies in the Upper Cretaceous muted positive $\delta^{13}C$ shifts in the oceans.

The case study by María Najarro, Idoia Rosales and Javier Martín-Chivelet investigates a major palaeoenvironmental perturbation in an Early Aptian carbonate platform and poses the question if this is a prelude of Oceanic Anoxic Event 1a. By studying skeletal assemblages preceding the isotopic excursions of OAE 1a, the authors document conditions of environmental stress imposed by a combination of global change and increased basin subsidence, which triggered the drowning of the platform by progressive reduction of the growth potential of the carbonate factory. A combination of water freshening, nutrient poisoning, tectonic activity and rising eustatic sea level may have acted together, resulting in the progressive destabilisation of the marine environments and a change to less-effective carbonate factories.

The third group of papers investigates mainly oxic sediments, anoxic to oxic transitions, and associated climate oscillations. Stephanie Neuhuber and Michael Wagreich give an overview and synthesis on geochemistry of Cretaceous Oceanic Red Beds, with new geochemical data and interpretations of red color. Possible reactions involved in CORB formation are discussed. They conclude that the main fraction of iron in CORB sediments is fixed in silicate lattices and immobile. Surficial coatings of iron oxides on carbonate grains or shells cause the red color in the investigated CORBs. A main factor identified is that CORBs form most likely below old water masses depleted in nutrients and therefore decreased primary production.

The following paper by Mihaela C. Melinte-Dobrinescu and Relu-Dumitru Roban reports Cretaceous anoxic–oxic changes in the Moldavids (Carpathians, Romania). A major black shale interval from Late Barremian to Early Albian was identified, followed by CORBs from Late Albian to the Paleogene. Black shale formation is attributed to the existence of a small, silled basin of the Moldavian Trough, in which restricted circulation led to the density stratification of the water column. This case study shows that the beginning and the end of the overlying CORBs in the Moldavid units depends on various palaeogeographic and palaeoenvironmental settings, and it was controlled by the regional tectonic activity, i.e. tectonic deformation led to the establishment of an open circulation regime.

Case studies on CORBs start with a quantitative analysis of iron oxide concentrations within Aptian–Albian cyclic oceanic red beds in

ODP Hole 1049C from the North Atlantic by Xiang Li, Xiumian Hu, Yuanfeng Cai, and Zhiyan Han. These Aptian–Albian sediments are characterized by high frequency cycles that consist of alternating layers of red and green/white clayey chalk, and claystone. Quantitative diffuse reflectance spectra were used to identify hematite (red color) and goethite (yellow color) as the minerals responsible for the reddish color. Their data show that the Albian–Albian reddish beds contain only 0.1–0.8% hematite and 0.2–0.8% goethite. The authors suggest that hematite and goethite were derived from oxic environments during the period of deposition and early diagenesis. The oxic conditions were probably a function of the low accumulation rate of organic matter and the high content of dissolved oxygen in bottom water.

The next two papers provide CORB case studies from outcrops within the Tibetan Tethyan Himalaya. Xi Chen, Chengshan Wang, Wolfgang Kuhnt, Ann Holbourn, Yongjian Huang and Chao Ma report on the lithofacies, microfacies and depositional environments of Upper Cretaceous Oceanic red beds from the classic Chuangde section in southern Tibet. The authors identified that the depositional environments of these Campanian CORBs range from outer base-of-slope apron to basin zones. They conclude that oxic bottom water conditions prevailed below the toe-of-slope environment in the basin during CORB deposition and indicate that the presence of gray clasts suggests less oxic conditions at shallower water depths within the same basin. Bottom water oxygenation was enhanced by atmospheric CO_2 drawdown following OAEs and by deepwater cooling during the Campanian, which increased the concentration and solubility of O_2 in the ocean. The following paper by Guobiao Li, Ganqing Jiang and Xiaoqiao Wan reports on the age of the Chuangde Formation in Kangmar, southern Tibet of China, and speculates on implications for the origin of Cretaceous oceanic red beds (CORBs) in the northern Tethyan Himalaya. The investigated section of the Chuangde Formation indicates a broader age range from Campanian to Maastrichtian and argues against the age discrepancy of CORBs between the eastern and western parts of the northern Tethyan Himalaya as previously suspected. They argue that the lack of CORBs in shelf environments and the widespread occurrence of CORBs in slope/basinal environments suggest that the CORBs were likely formed by oxidation of reduced iron in the upper ocean water column, close to the chemocline, rather than in oxic bottom waters.

The final contribution to the special issue by Yuri D. Zakharov, Yasunari Shigeta, Alexander M. Popov, Tatiana A. Velivetskaya and Tamara B. Afanasyeva deals with climate oscillations in the Bering area (Alaska and Koryak Upland) and the isotopic and palaeontological evidence. This regional case study on the short- and long-term climate evolution of the area identifies significant seasonal contrast, marked in Alaska and the adjacent area during the Early Albian, as well as the Coniacian, and related to the possible penetration of cooler waters from the polar area via the Strait of Alaska. The authors interpret that recurrent terrestrial cooling in northern Alaska took place because of a barrier to poleward oceanic heat transport via the Western Interior Seaway (WIS) of North America during the Turonian and Santonian through Early Campanian, then during the Late Maastrichtian through Danian.

4. Concluding remarks

The contributions to this Sedimentary Geology special issue provide a heterogeneous but rich assembly of overview-type papers and single case studies comprising anoxic–oxic changes in several types of records, depositional processes, and basin types. Understanding of causes of changes from anoxic to oxic from a global perspective up to a single restricted basin view gives important constraints and identifies several mechanisms for such changes, involving climate, tectonics and biology.

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