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"OAE 3" – regional Atlantic organic carbon burial during the Coniacian–Santonian

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Abstract. The Coniacian–Santonian time interval is the inferred time of oceanic anoxic event 3 (OAE 3), the last of the Cretaceous OAEs. A detailed look on the temporal and spatial distribution of organic-rich deposits attributed to OAE 3 suggests that black shale occurrences are restricted to the equatorial to mid-latitudinal Atlantic and adjacent basins, shelves and epicontinental seas like parts of the Caribbean, the Maracaibo Basin and the Western Interior Basin, and are largely absent in the Tethys, the North Atlantic, the southern South Atlantic, and the Pacific. Here, oxic bottom waters prevailed as indicated by the widespread occurrence of red deep-marine CORBs (Cretaceous Oceanic Red Beds). Widespread CORB sedimentation started during the Turonian after Oceanic Anoxic Event 2 (OAE 2) except in the Atlantic realm where organic-rich strata continue up to the Santonian. The temporal distribution of black shales attributed to OAE 3 indicates that organic-rich strata do not define a single and distinct short-time event, but are distributed over a longer time span and occur in different basins during different times. This suggests intermittent and regional anoxic conditions from the Coniacian to the Santonian. A comparison of time-correlated high-resolution δ^{13}C curves for this interval indicates several minor positive excursions of up to 0.5 ‰, probably as a result of massive organic carbon burial cycles in the Atlantic. Regional wind-induced upwelling and restricted deep basins may have contributed to the development of anoxia during a time interval of widespread oxic conditions, thus highlighting the regional character of inferred OAE 3 as regional Atlantic event(s).

1 Introduction

Oceanic anoxic events (OAEs; Schlanger and Jenkyns, 1976) have been recognized in the geological record, especially in Cretaceous marine sections, as climatically influenced major perturbations of the Earth system, especially concerning Earth's carbon cycle. These events were characterized by the widespread deposition of pelagic sediments rich in organic matter such as black shales, and are considered as key mechanisms for organic carbon burial and, in such, buffering Cretaceous runaway super-greenhouse gas (e.g. Arthur et al., 1990). OAEs constitute perturbations of the carbon cycle expressed by major carbon isotope (δ^{13}C) excursions, both positive and negative (e.g. Leckie et al., 2002). Significant positive δ^{13}C excursions are mainly controlled by enhanced burial of organic carbon-rich deposits and characterize and define OAEs, especially in the absence of significant black shales (e.g. Tsikos et al., 2004). Principally, these organic-rich strata point to enhanced marine productivity and organic matter preservation during short duration events, e.g. Late Cretaceous OAE 2 (including a positive δ^{13}C signal of more than 2 ‰) has an estimated duration of 300–700 kyr (Sageman et al., 2006; Voigt et al., 2008), and high productivity-events may have been even considerably shorter at the onset of OAEs (Adams et al., 2010). Subsequently, extensive CO_2 drawdown probably resulted in cooling of the atmosphere already during major OAEs. However, during the last three decades of intensive investigations in Cretaceous OAEs, it became clear that not all OAEs (OAE 1a, 1b, 1c, 1d, OAE 2, OAE 3; see Arthur and Schlanger, 1979; Jenkyns, 1980, 2003) record similar scenarios, and more regional controls and several models have been suggested (e.g. Leckie et al., 2002; Hofmann et

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al., 2003; Beckmann et al., 2008; Hofmann and Wagner, 2011; Locklair et al., 2011). Triggering by major magmatic events (LIPs, Large Igneous Provinces) leading to extreme greenhouse gas concentrations plays a major control for such super-greenhouse events (Jones and Jenkyns, 2001; Barclay et al., 2010).

The Coniacian–Santonian (88.6–83.5 Ma; TS Creator 5.3; see http://www.tscreator.org; Ogg et al., 2004) is considered as the time during which the last Cretaceous oceanic anoxic event, OAE 3, took place (e.g. Arthur et al., 1990; Hofmann et al., 2003). Interestingly, OAE 3 was not identified in the classical paper by Schlanger and Jenkyns (1976) who only named two major oceanic anoxic events, but recognized and named later on (Ryan and Cita, 1977; Arthur and Schlanger, 1979; Jenkyns, 1980). In contrast to the mid-Cretaceous OAEs (OAE 1 and 2), OAE 3 occurred during a major cooling trend in Earth's long-term climate history from the mid-Cretaceous super-greenhouse/hothouse to more temperate greenhouse conditions (e.g. Norris et al., 2002; Friedrich et al., 2012). Whereas a global extent was recognized by Schlanger and Jenkyns (1976) for the early Aptian OAE 1a and the Cenomanian–Turonian boundary interval OAE 2, a more restricted occurrence of Coniacian–Santonian black shales was reported by Arthur and Schlanger (1979) and Jenkyns (1980). Subsequently, also a preference of these black shales for shallow water settings and Atlantic and Caribbean regions was noted by Jenkyns (1980).

More recent investigations confirmed this picture, reporting cyclic black shales and anoxic to dysoxic environmental conditions during the Coniacian–Santonian especially from low-latitude Atlantic ODP sites along the Ivory Coast–Ghana transform margin, e.g. ODP Leg 159 (Wagner, 2002; Hofmann et al., 2003; Jones et al., 2007) and the Demerara Rise, ODP Leg 207 (e.g. Friedrich and Erbacher, 2006; Beckmann et al., 2008), the Caribbean, and connected marginal and epeiric seas and seaways such as the Western Interior (Locklair et al., 2011), the Maracaibo Basin (Rey et al., 2004) and basins of northwestern Africa (El Albani et al., 1999). Overviews on the regional distribution of OAE 3 black shales (Wagner et al., 2004; Hofmann and Wagner, 2011) and the predominance of coeval oxidised deep water sediments elsewhere (CORBs – Cretaceous Oceanic Red Beds, Wagreich, 2009; Wang et al., 2009, 2011) corroborated the fact that OAE 3 is mainly restricted to the Atlantic, whereas most of the Tethys and the other ocean basins were largely characterized by oxic deep-water conditions and the deposition of red to brownish or light grey deep water sediments (Wagreich, 2009).

This paper follows earlier arguments on OAE 3 distribution in time and space, looks for possibilities and pitfalls of a more precise definition and model for OAE 3, and finally poses the question of if OAE 3 can be identified as a distinctive widespread oceanic anoxic event at all. OAE 3 stratigraphy and the carbon isotope evolution in time are regarded as key data for identification and interpretation of anoxic event(s) during the Coniacian–Santonian and the role of climate evolution on oceanic sedimentation.

2 Results

2.1 Spatial distribution

High organic carbon sediments of Coniacian–Santonian age, especially marine organic matter bearing black shales, appear in the southern part of North Atlantic, the South Atlantic, the Caribbean Sea, and surrounding basins and shelf areas like the Western Interior, the Maracaibo Basin (Venezuela), Columbia, Brazil, northern Namibia, Angola, Gabon, Ivory Coast, northwest Africa and Morocco (Sachse et al., 2012), Libya, and Egypt (Wagner et al., 2004; Wagreich, 2009; see Fig. 1). Apart from these inferred OAE 3 sites, black shales of Coniacian–Santonian age have only a spurious distribution, which mainly suggests very local factors controlling organic-rich sedimentation elsewhere, and not a widespread or global event layer, such as exemplified by reports of local organic-rich layers in Pakistan, Western Greenland, the Sverdrup Basin in Arctic Canada and southern Australia (Wagreich, 2009). The lack of black shales from the Tethys is notable, as a strong seaway connection of the Tethys with the latitudinal Atlantic had been established during the Late Cretaceous (e.g. Trabucho Alexandre et al., 2010).

Looking for published case studies on typical Coniacian–Santonian OAE 3 strata indicates the fact that such studies are relatively rare, especially if compared to numerous works dedicated to the slightly older Cenomanian–Turonian boundary interval OAE 2. Unambiguously identified organic-rich strata of Coniacian–Santonian age were reported from the equatorial Atlantic sites as drilled by deep-sea drilling such as ODP Leg 159 (site 959), at a transect along the Ivory Coast–Ghana transform margin, and on the opposite margin of the Atlantic, at the Demerara Rise off Suriname by ODP Leg 207 (sites 1257–1261). Both areas are characterized by a more or less continuous succession of black shales from the Upper Cenomanian onset of OAE 2 up to the Upper Santonian or Lower Campanian (Wagner et al., 2004; Friedrich and Erbacher, 2006; Wagreich, 2009). Both areas are also characterized by cyclic black shales interpreted to represent precession and eccentricity orbital cycles (Hofmann et al., 2003; März et al., 2008, 2009). Anoxia proceeded from these equatorial Atlantic sites into the Caribbean and large epeiric seas both to the north, i.e. the Western Interior Seaway (Dean and Arthur, 1998), and to the south, the Maracaibo Basin. The Western Interior Seaway record constitutes another classical OAE 3 area, with high organic carbon contents during the Coniacian–Santonian (Locklair et al., 2011). In Venezuela and Colombia, organic-rich, cyclic strata such as laminated black shale-limestone couplets prevailed for most of the Coniacian–Santonian up to the Lower Campanian (e.g. De Romero et al., 2003; Rey et al., 2004).

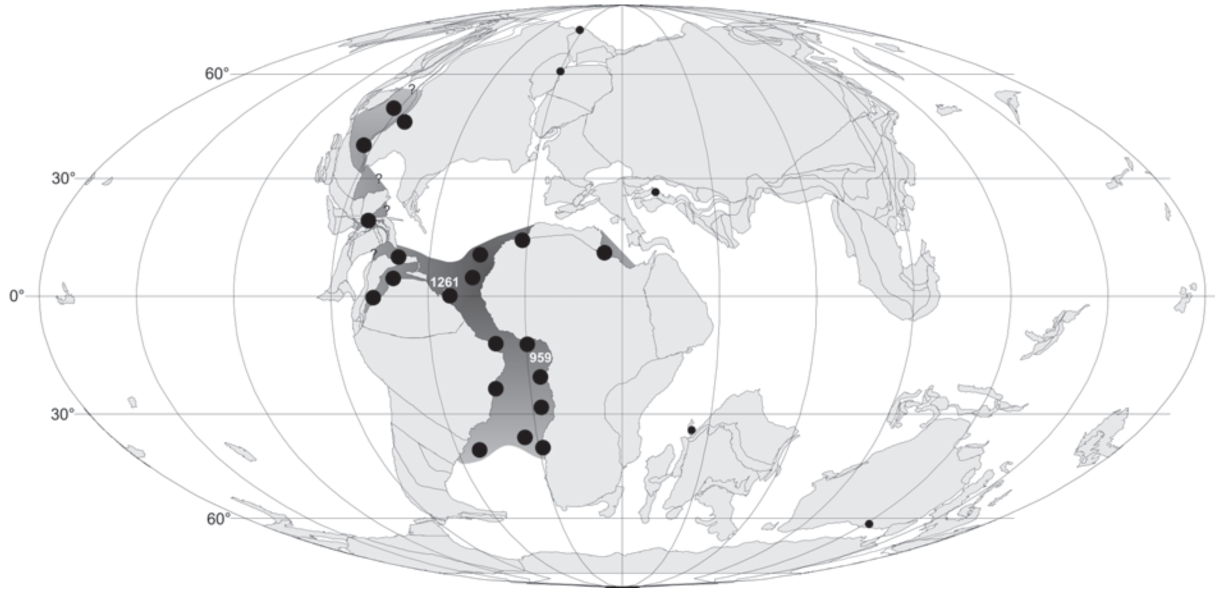

Fig. 1. Plate reconstruction for 86 Ma (around Coniacian–Santonian boundary; modified from Schettino and Scotese, 2002) with area of significant OAE 3 black shale sedimentation marked (large black circles) in the low latitudinal Atlantic and marginal basins and seaways (based on compilations of Wagner et al., 2004; Hofmann and Wagner, 2011; Wagreich, 2009), and other locations with reported local black shales (small black circles). ODP Legs 159 (off Ivory Coast) and 207 (Demerara Rise) with continuous black shales from OAE 2 to Santonian/Lower Campanian are indicated.

2.2 Timing, age and duration

Coniacian–Santonian times were characterized by a relatively shallow calcite compensation depth at least in the Atlantic, and, consequently, a marked increase in deposition of carbonate-free (red) shales, which are hardly biostratigraphically dateable as calcareous plankton, is lacking (e.g. Jansa and Hu, 2009). The biostratigraphic subdivision of this time interval is of rather poor resolution in the pelagic realm (see also Ogg et al., 2004) as exemplified by only 2–3 Tethyan/low latitude plankton Foraminifera globotruncanid zones for the entire time interval (*Dicarinella concavata*, *Dicarinella asymetrica*, eventually *Dicarinella asymetrica–Globotruncanita elevata* zones; e.g. Robaszynski and Caron, 1995; Petrizzo, 2003) and 3–5 (low latitude) nannoplankton zones (CC13-17, Sissingh, 1977, Perch-Nielsen, 1985; NC15-17, Roth, 1978; Bralower et al., 1995; UC 9-12, Burnett, 1998). Especially the CC zones of this time interval were strongly discussed as most of the primary markers of Sissingh (1977), including *Marthasterites furcatus* (base CC13), *Reinhardtites anthophorus* (base CC15), *Lucianorhabdus cayeuxii* (base CC 16) and *Calculites obscurus* (base CC17) were shown to be diachronous, ecologically controlled, and have an earlier and/or doubtful first occurrence (Burnett, 1998; Gale et al., 2007; Melinte and Lamolda, 2007; Lees, 2008). In fact, only one nannofossil event, the first occurrence of *Micula staurophora* (*Micula decussata* of some authors), is common to both (CC and UC) low-latitude nannofossil standard zonations. This results in a rather low-resolution chronostratigraphic subdivision of the Coniacian–Santonian in deep-water settings and in problems in correlating OAE 3 horizons from different locations and different studies (e.g. Flögel et al., 2008).

Numerical ages for the Coniacian–Santonian strongly rely on material from tuff layers and bentonites within the Western Interior where this time interval is characterized by a growing endemism and globotruncanids become rare or absent (Dean and Arthur, 1998). Therefore, biostratigraphic correlations of numerical ages into the pelagic world oceans are, at least, not straightforward and have to be dealt with caution. This may be exemplified by ongoing discussions on defining a GSSP for the base of the Santonian, and the differences in proposed nannofossil events that are connected to this boundary in the Western Interior Basin and elsewhere (see Gale et al., 2007; Melinte and Lamolda, 2007; Blair and Watkins, 2009). Using cyclostratigraphy within a macro- and microfossil framework and radiometric dates, Locklair and Sageman (2008) published a Coniacian–Santonian floating orbital time scale from the Western Interior (Niobrara Formation). According to their results, the duration of the Coniacian ranges from 3.26 to 3.50 myr, the Santonian from 2.24 to 2.53 myr, giving a total duration for the Coniacian–Santonian of 5.5. to 6 myr, which is in accordance with other recent age results (Ogg et al., 2004). Based on this timing, Locklair et al. (2011) calculated durations and carbon fluxes during the OAE 3 interval. However, their curves exemplify the problem of how to define OAE 3 in time, as several peaks of organic carbon can be recognized during this interval in the Western

Interior Basin. Their main OAE 3 level of organic carbon-rich strata lies within the middle Coniacian (Locklair et al., 2011, Figs. 4, 5), but several other levels may be identified within their sections.

Keeping in mind the above-mentioned problems in timing and correlation, the published stratigraphic levels attributed to OAE 3 vary considerably. Hofmann et al. (2003) and Hofmann and Wagner (2011) refer mainly to a late Coniacian and early Santonian age. The Western Interior Seaway OAE 3 intervals named by Locklair et al. (2011) are middle Coniacian, early Santonian and at the Santonian–Campanian boundary. Others refer even to a late Santonian–early Campanian age, e.g. as reported from the Middle East (Jenkyns, 1980). Although OAE 3 may be divided into several short-term events (Arthur et al., 1990), no clear OAE 3 level that applies to most of the sections and sites can be defined which is in strong contrast to the widespread OAE 2 horizon (e.g. Tsikos et al., 2004; Gebhardt et al., 2010).

2.3 Isotope data and correlations

As carbon isotope excursions (CIEs) can be used to define OAEs (Sageman et al., 2006), a closer look at the carbon isotope record from different sites of the Boreal to the Tethyan realm may help identifying OAE 3 and evaluating its paleogeographic distribution. Detailed, continuous, high-resolution and stratigraphically constrained carbon isotope data for the Coniacian–Santonian are relatively scarce as compared to the Campanian–Maastrichtian (e.g. Voigt et al., 2010) or the Cenomanian–Turonian, including OAE 2 (e.g. Tsikos et al., 2004; Voigt et al., 2008).

A recent compilation by Wendler et al. (2009; see also Wendler et al., 2011) compared data from Tibet (Tingri and Guru sections) with the Chalk reference curve of Jarvis et al. (2006; based on several English Chalk sections) and data from Contessa, Umbria, Italy (Stoll and Schrag, 2000). All of these sites, from Boreal to Tethys, do not include significant black shale intervals in the Coniacian–Santonian. To correlate with inferred OAE 3 sites (see Fig. 2), we added data from the Western Interior Basin (Locklair et al., 2011). Other carbon isotope records, e.g. from the La Luna Formation of Venezuela (de Romero et al., 2003) or the Demerara Rise (Friedrich et al., 2012), are too low-resolution during this time interval.

Figure 2 shows the carbon isotope records of the above-mentioned sites and possible OAE 3 levels. Minor carbon isotope excursions during the Coniacian–Santonian of ca. 0.5 ‰ as identified by Jarvis et al. (2006) can be correlated, i.e. the Navigation event at the Turonian–Coniacian boundary (see also Walaszczyk et al., 2010), the White Fall, Kingsdown, Horseshoe Bay, and the Santonian–Campanian boundary events. However, no clear correlation to organic-rich strata attributed to OAE 3 (grey boxes in Fig. 2) and to inferred times of OAE 3, i.e. late Coniacian–early Santonian, do exist. The general elevated carbon isotope values (ca. 0.7 ‰) during this time in the Tibetan sections (Wendler et al., 2009) seem to be regional phenomenon as no corresponding carbon isotope plateaus can be matched in the other sections. Its onset was well before significant OAE 3 black shales elsewhere, as already noted by Wendler et al. (2009).

2.4 Mechanisms and models

Models for OAE 3 organic carbon-rich sedimentation were put forward especially for the Atlantic off the Ivory Coast–Ghana transform margin (ODP site 959) and the Demerara Rise off Suriname (ODP Leg 207). In principle, wind-induced upwelling of nutrient-rich water masses was involved to explain high productivity, and subsequent deposition and preservation of organic-carbon-rich sediments at ODP site 959 (e.g. Wagner, 2002; Hofmann and Wagner, 2011). Increased oxygen consumption from the degradation of organic matter resulted in expansion of the oxygen minimum zone and stratification of the water column which controlled organic-carbon-rich deposition (Wagner et al., 2004). Black shale cyclicity was caused by both fluctuations in productivity and preservation (Hofmann et al., 2003; Beckmann et al., 2005a, b, 2008). Climate-controlled fluctuations (i.e. shifts in the paleo-Intertropical Convergence Zone – ITCZ) in continental runoff over Africa with precession and eccentricity bands of orbital frequencies modulated these anoxia (Hofmann et al., 2003; Beckmann et al., 2005a). Periods of warm and humid climate during maximum insolation, characterized by high precipitation, strong chemical weathering and excess freshwater runoff and supply from the African continent, enhanced the availability of dissolved nutrients and may have strongly influenced circulation in the semi-enclosed Deep Ivorian Basin (Beckmann et al., 2005a, b), thus controlling directly anoxia and black shale formation. Wagner et al. (2004) and Beckmann et al. (2005b) concluded that the chemical boundary conditions in the ocean have been as extreme as during OAE 2, but much more restricted in extent and duration, resulting in only brief intervals of lower photic zone euxinia. In addition, clay mineral composition, especially the presence of smectite, may have influenced the preservation of organic matter (Kennedy and Wagner, 2011).

Cyclic OAE 3 black shales (TOC up to 14 %, Beckmann et al., 2008) of Coniacian–Santonian age were also investigated and interpreted in detail at the Demerara Rise. Millennial- to centennial-scale and precession cycles of dysoxic to anoxic to euxinic conditions were recorded in the Upper Coniacian to Lower Santonian with persistent bottom water anoxia (e.g. März et al., 2008). Here, photic zone euxinia was restricted to a short time interval in the early Coniacian based on biomarker and inorganic geochemistry, and cycles from anoxic to sulfidic bottom water conditions prevailed in the deeper sites (März et al., 2008; Beckmann et al., 2008). März et al. (2008) and Friedrich and Erbacher (2006) interpreted the Demerara Rise OAE 3 black shale record as being controlled by fluctuations in the oxygen minimum zone due to

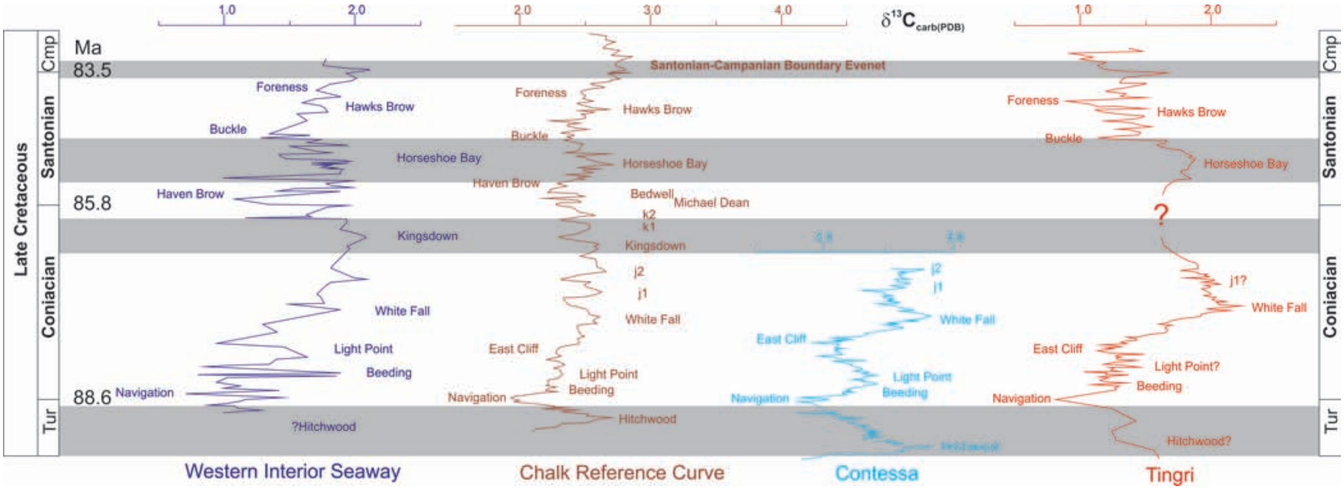

Fig. 2. Carbon isotope curves and correlations of carbon isotope events from inferred OAE 3 sites of the Western Interior (Pratt et al., 1993, stratigraphy according to Locklair et al., 2011), the English Chalk reference curve (Jarvis et al., 2006, based on several sections), and two Tethyan sections: the Contessa/Vispi quarry section in Italy (Stoll and Schrag, 2000) and the Tingri section in Tibet (Wendler et al., 2009). Carbon isotope curves are time-calibrated on a chronostratigraphic scale by using the Turonian–Coniacian boundary and the correlated negative carbon isotope event (Navigation event of Jarvis et al., 2006; see also Walaszczyk et al., 2010), the Coniacian–Santonian boundary, and the Santonian–Campanian boundary and its positive carbon isotope event (Santonian/Campanian Boundary Event of Jarvis et al., 2006; see also Gale et al., 2007 and Wendler et al., 2009) as tie points, and numerical ages from Ogg et al. (2004), Locklair and Sageman (2008) and TimeScaleCreator 5.3 (http://www.tscreator.org).

more oxygenated surface- to mid-waters which resulted in a downward shift of the oxic-anoxic chemocline in the water column of this semi-restricted basin.

In comparing both equatorial Atlantic sites and partly based on climate simulations, Flögel et al. (2008) reconstructed a generally higher and less variable continental runoff from South America compared to Africa for the Coniacian–Santonian. They concluded that contrasting runoff pattern supported more permanent anoxic conditions at the Demerara Rise off South America compared to Africa, and thus caused the lack of strong higher frequency anoxic-oxic cycles at the Demerara Rise. Upwelling was controlled by shifts in the position of the ITCZ due to variations in insolation (Hofmann and Wagner, 2011). A more regional control was reconstructed for the Deep Ivorian Basin, where the variations in the strength of the monsoonal system triggered precipitation, freshwater runoff and thus nutrient discharge to the eastern equatorial Atlantic, versus a trade-wind forcing of a large-scale dynamic, but long-lived upwelling system that resulted in high primary production in the western part of the equatorial Atlantic and thus prolonged anoxia from OAE 2 to OAE 3. This upwelling system probably also operated in the Caribbean and reached parts of the Maracaibo Basin, where wind-driven upwelling was also interpreted as the major control on black shale deposition (Macsotay et al., 2003).

3 Discussion

OAEs have been recognized primarily by the presence and stratigraphic correlation of organic-rich strata, i.e. black shales (Schlanger and Jenkyns, 1976). Subsequently, carbon isotope data indicated major excursions (e.g. Jenkyns, 1980), pointing to significant perturbations of the carbon cycle during OAEs. Therefore, to qualify for an OAE, (1) organic-rich strata must be widespread, (2) should be correlated in time to qualify as a supra-regional single event, and (3) should be accompanied by a significant carbon isotope excursion.

Based on the data presented on OAE 3, i.e. the spatial and temporal distribution of black shales and carbon isotope data, this time interval does not qualify as a global event. Inferred OAE 3 levels of organic-carbon-rich intervals cannot be correlated in time and do not define a single event horizon. The problem to date Coniacian–Santonian pelagic sediments, especially concerning calcareous "blue water" plankton, contributes to the squishy definition of a Coniacian–Santonian OAE. In fact, a time interval of 5.5 to 6 myr clearly cannot qualify as one event. In addition, no distinct short time (< 1 myr) peak of organic-rich sedimentation of a suspected OAE 3 can be defined during this interval. Only in the equatorial Atlantic and Venezuelan sites, the whole Coniacian–Santonian succession from OAE 2 upwards is characterized by massive black shales. In agreement with Friedrich and Erbacher (2006) and Hofmann and Wagner (2011), this prolonged interval of black shale deposition is interpreted primarily as a consequence of a semi-restricted basin, characterized by restricted deep-water circulation from the equatorial Atlantic to the South Atlantic (Friedrich et al., 2012). This led to enhanced preservation of organic matter on the sea floor and thus black shale formation in these areas and connected basins. An effective deep-water connection between the central and South Atlantic Oceans was established during the early Campanian and led to well-oxygenated bottom waters (and CORB deposition) in the entire Atlantic Ocean during the Campanian (Friedrich and Erbacher, 2006).

The Coniacian–Santonian comprises only small positive carbon isotope excursions (< 0.5 ‰). Minor carbon isotope events as identified by Jarvis et al. (2006) based on English Chalk sections and correlated with other, including Tethyan, sections like Contessa/Italy and Tibet (Jarvis et al., 2006; Wendler et al., 2009) characterize this interval. Some inferred OAE 3 event(s) can be correlated with those minor global carbon isotope excursions; others fall even into times of no significant excursions at all (Fig. 2). However, these minor events are in strong contrast in relation to major global OAE intervals such as OAE 1a in the Aptian or OAE 2 in the Cenomanian–Turonian boundary interval, where major carbon isotope excursions (> 2 ‰) are correlatable globally from the marine into the terrestrial realm and, consequently, can be used to define the durations of oceanic anoxic events. All recorded Coniacian–Santonian carbon isotope events are smaller in magnitude than the large (ca. 1 ‰), positive late Turonian Hitchwood event (Fig. 2) of Jarvis et al. (2006) which may suggest more organic carbon burial during this late Turonian event than for suspected OAE 3 times. The more restricted areal extent of organic carbon burial in the low- to mid-latitude Atlantic and its marginal seas and seaways explains well the minor 0.3–0.5 ‰ positive carbon isotope excursions, i.e. only ca. 1/5 of the carbon burial suggested for the global OAE 2. In addition, based on a global carbon isotopic mass balance model for OAE 3, Locklair et al. (2011) concluded that increased chalk carbonate deposition was able to mute positive carbon isotope excursions during OAE 3.

Black shale intervals from the equatorial Atlantic and adjacent marginal seas can be correlated, but without any definable and distinct through-going OAE 3 event horizon (Wagreich, 2009). However, to qualify as a more-than-regional anoxia, OAE 3 horizon(s) must be correlated also into other sites. Correlations to organic-rich deposits from sites outside the Atlantic are strongly doubtful. Therefore, the inferred "OAE 3" qualifies more as regional Atlantic organic carbon burial events. Thus, the cause of organic-rich sedimentation in the Atlantic during a time of worldwide oxic deep-water sedimentation is not a consequence of a global warming event, but organic-rich sedimentation during Coniacian–Santonian must have been driven by the special configuration of the Atlantic Ocean and the surrounding shelf basins and continents. Wagner (2002) and Hofmann et al. (2003) suggested a strong link of these black shales to wind-driven upwelling of nutrient-rich intermediate seawater, probably related to an estuarine circulation with respect to the Pacific from where nutrient-rich seawater derived, and the low-latitudinal Atlantic served as a nutrient trap for a prolonged time interval (Trabucho Alexandre et al., 2010). Beckmann et al. (2005b) and Flögel et al. (2008) furthermore invoked millennial- to centennial-scale climate variability, i.e. trade winds and monsoon circulation and precipitation, and cyclic upwelling to explain cyclic black shales within the low latitudes of the Atlantic. Restricted ocean circulation in the equatorial Atlantic region with semi-closed deep basins and high runoff from Africa and South America fostered, via high nutrient supply and upwelling due to trade winds, high primary productivity, which resulted in anoxia over an extended period within the Atlantic and adjacent seas, a unique situation for the equatorial Atlantic (Hofmann and Wagner, 2011). Variations in weathering intensity of the continents suggest oscillations between more arid and more humid intervals. Climate modelling results (Beckmann et al., 2005b) also indicate the existence of a pronounced seasonal dry-wet cyclicity during this time interval.

4 Conclusions

Based on the data presented on spatial and temporal distribution and carbon isotopes, inferred OAE 3 levels of organic-carbon-rich intervals are neither global nor contemporaneous and are characterized by only small positive carbon isotope excursions, if any. We conclude that inferred OAE 3 is not a global oceanic event but a regional anoxic event that is essentially restricted to the low- to mid-latitudinal part of the Atlantic and some adjacent epicontinental basins such as the Maracaibo Basin and the Western Interior Basin. It is absent in the Pacific and the Tethys. Furthermore, OAE 3 is not a clearly defined, short-time event, but distributed over a longer time span, at least from the Coniacian to the Santonian. Most of the typical "OAE 3" sections in the equatorial Atlantic display continuous organic matter-rich successions from Cenomanian–Turonian OAE 2 to Coniacian–Santonian black shales. Carbon isotope data indicate minor excursions of up to 0.5 ‰, probably as a result of massive and cyclic organic carbon burial in the Atlantic during this time interval. Global climate events, i.e. greenhouse warming, during the Coniacian–Santonian were not as prominent as during the mid-Cretaceous hothouse with its more globally distributed black shales and thus more significant negative feedback by organic carbon burial.

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