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Micropaleontological evidence for redox changes in the OAE3 interval of the US Western Interior: Global vs. local processes

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A B S T R A C T

The Coniacian-Santonian interval has been proposed as the youngest of the Cretaceous ocean anoxic events (OAE3), but this designation has long been debated. OAE3 is associated with a long-lasting (~3 myr) succession of black shales from the central and South Atlantic, Caribbean region, and the North American Western Interior; in the Western Interior it is characterized by an abrupt increase in total organic carbon (TOC) and corresponding trace metal indicators for anoxia. However, the modern concept of OAEs is predicated on detection of global carbon cycle perturbations as recorded by substantial carbon isotope excursions (CIE), and the protracted Coniacian-Santonian black shale interval does not have a large CIE. A more conservative definition of OAE3 might limit the event to the modest positive carbon isotope excursion restricted to the upper Coniacian *Scaphites depressus* Ammonite Zone. Trace metal proxies suggest that oxygen levels abruptly declined prior to the onset of this CIE in the Western Interior Sea (WIS), but it is unknown whether regional anoxic conditions were confined to sediments/pore waters, or how anoxia may have affected the biota. In an effort to characterize the oxygenation history of the WIS and to better understand the nature of the hypothesized OAE3, we present micropaleontological evidence of declining oxygen in bottom waters prior to the event using benthic foraminifera, which are sensitive to dissolved oxygen. Changes in benthic foraminiferal abundances suggest a decline in oxygen at least 1-myr prior to the CIE (including a nadir immediately below the start of the excursion), improving bottom water oxygen during the CIE, and re-establishment of persistent anoxia following the isotope excursion. Anoxia endured for nearly 3 myr in the central seaway, showing some signs of recovery toward the top of the Niobrara Formation. Our findings suggest that declining oxygen concentrations in the seaway eventually reached a tipping point, after which dissolved oxygen quickly dropped to zero.

The late Coniacian CIE is an exception to the trend of declining oxygen in the WIS, and part of a larger pattern in the oxygenation history of the Niobrara Formation which suggests that it does not adhere to standard black shale models. Transgressive periods, including the Fort Hays Limestone and the lower limestone unit of the Smoky Hill Shale (which corresponds to the CIE) are relatively oxic, while periods of highstand (i.e., most of the Smoky Hill) correspond to deteriorating oxygen conditions. This contrasts with the standard black shale model for sea level and oxygen, where transgressions typically correlate with maximum TOC enrichment, interpreted to result from both sediment condensation and oxygen deficiency. The association of global carbon burial/anoxia (as indicated by carbon isotopes) with a regional increase in oxygen and decrease in organic matter preservation is reminiscent of the Cenomanian-Turonian Greenhorn Limestone, which contains OAE2. In both cases, the facies are not typical black shales, but instead have appreciable carbonate content. Western Interior redox trends support the rejection of the original concept of a protracted Coniacian-Santonian OAE3 because it is not a distinct “event.” Increasing local oxygen during the late Coniacian CIE also argues against a narrower OAE designation for this event, because the excursion can't be tied to anoxia here or anywhere else it has been described. Nevertheless, the Late Coniacian Event (as we prefer to call this CIE) still represents an important perturbation of the global carbon cycle. This is emblematic of the shift away from widespread, discrete anoxic events during the ongoing paleoceanographic reorganization of the Late Cretaceous, even as large carbon cycle perturbations continued.

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1. Introduction

Numerous intervals of Mesozoic strata are characterized by organic carbon enrichment, laminated sediments, and depauperate benthic faunas; these observations have been interpreted as evidence for enhanced primary production and/or increased preservation of organic matter due to the prevalence of dysoxic to anoxic conditions in the deep sea, on continental margins, and in epicontinental seas (e.g., Schlanger and Jenkyns, 1976; Arthur and Schlanger, 1979; Leckie et al., 2002; Erba, 2004; Arthur and Sageman, 2005; Jenkyns, 2010). Particular stratigraphic intervals within these "black shale" successions are globally characterized by negative or positive excursions in carbon isotopes, interpreted to reflect the abrupt release of isotopically light CO_2, or burial of vast amounts of organic carbon, respectively (e.g., Jenkyns, 2010). The geographic extent of these events, combined with the isotopic evidence for disruption of the entire surface Earth carbon cycle, led early investigators to propose that they represented global scale perturbations in the ocean-climate system, and they were designated Oceanic Anoxic Events (OAEs; Schlanger and Jenkyns, 1976). Basin-specific responses to global forcing influence the onset and termination of black shale deposition, and subsequent research has revealed that black shales are not always synchronous during an OAE (e.g., Tsikos et al., 2004). The large $\delta^{13}C$ excursions marking major perturbations of the global carbon cycle have become the accepted definition of an OAE, rather than local black shale deposition (Jenkyns, 2010). However, numerous carbon isotope excursions (CIEs) exist in the geologic record (e.g., Jarvis et al., 2006), which are not considered OAEs because they are not associated with widespread black shales. Thus, OAEs should be defined as 1) distinct CIEs indicating a major carbon cycle perturbation correlative with 2) widespread evidence for marine anoxia.

The Coniacian-Santonian interval includes the last episode of widespread black shale deposition of the Mesozoic, which was designated OAE3 by Arthur and Schlanger (1979). Although not as geographically extensive as earlier OAEs, organic carbon-rich black shales from this interval are well documented from the central and South Atlantic, Caribbean, and surrounding epicontinental seas, with well-known localities summarized by Wagreich (2009), including the US Western Interior (e.g., Barlow and Kauffman, 1985; Pratt et al., 1993; Dean and Arthur, 1998; Bralower and Lorente, 2003; Wagner et al., 2004; Locklair et al., 2011; Tessin et al., 2015).

The status of "OAE3" as a true Oceanic Anoxic Event has been debated, both because of its geographically limited range and because some of the Coniacian-Santonian black shales, like those at Demerara Rise, are part of a continuous organic carbon-rich succession deposited from the Cenomanian to the Campanian (e.g., Erbacher et al., 2004) and driven by wind induced upwelling and continental runoff modulated by Milankovitch cycles (e.g., Hofmann and Wagner, 2011; Wagner et al., 2013). Other black shales associated with this interval are shorter-lived and often diachronous (Wagriech, 2012). OAE3 is also unusual in that it is characterized by a longer (up to 5 myr) period of organic carbon deposition and a more modest (~0.5‰ VPDB) positive carbon isotope excursion than events like the Cenomanian-Turonian OAE2 (Locklair et al., 2011; Wagriech, 2012). Although the magnitude of the isotope excursion may be muted by the widespread deposition of chalks that also characterize this interval (Locklair et al., 2011), the fact remains that it is not associated with a discrete black shale horizon like that of other OAEs, leading Wagriech (2012) to conclude that this was a regional event confined to the central and South Atlantic. However, the enhanced organic carbon burial of the Coniacian-Santonian precedes the general cooling of the Santonian-Campanian (e.g., Friedrich et al., 2012; Falzoni et al., 2016) and must have been an important influence on Late Cretaceous climate. Even if this is not an OAE in the traditional sense, the nature of organic matter burial during this interval remains an important aspect of Late Cretaceous ocean-climate dynamics.

Cretaceous strata in the Western Interior Seaway (WIS) of North America contain one of the best records of the broader Coniacian-Santonian OAE3 interval situated outside the influence of the tropical-subtropical Hadley Cell circulation believed to drive the deposition of the extended black shales found in the central Atlantic (Hofman and Wagner, 2011; Wagner et al., 2013). If OAE3 is truly a global event and not an Atlantic basin phenomenon, then the WIS should have a clear record of it. The organic-rich black shales of the Niobrara Formation and equivalent strata are important sources for unconventional hydrocarbon plays across the Western Interior, which have helped fuel renewed research, resulting in abundant geochemical and sedimentological data (e.g., Dean and Arthur, 1998; Longman et al., 1998; Savrda, 1998) and well-constrained age models (Locklair and Sageman, 2008; Joo and Sageman, 2014:; Sageman et al., 2014). Black shale deposition (specifically organic-rich marl with TOC values exceeding 5 wt.%) in the Niobrara Formation of the WIS begins abruptly, at a clear horizon that makes it fairly unique among OAE3 localities. However, this abrupt organic carbon enrichment precedes, by ~200 kyr, the onset of a 0.5‰ positive carbon isotope excursion (CIE) in the late Coniacian (correlative to the Kingsdown Event in the UK; Jarvis et al., 2006) that represents the best evidence of an OAE3 CIE in the WIS (Joo and Sageman, 2014). A more conservative definition of OAE3 than the traditional Coniacian-Santonian black shale interval would limit the event to this CIE, which spans the upper Coniacian *Scaphites depressus* Ammonite Zone. The goal of our research is to further characterize the nature of black shale deposition before, during, and after this CIE, both to better understand changes in the global ocean, and to determine whether the data support the designation of an OAE. The unique combination of attributes of the WIS – long history of research, well-defined age model, abrupt onset of black shale deposition, distance from other OAE3 sites – make it and ideal location to perform this test.

1.1. OAE3 in the WIS

Trace metal geochemistry from the upper Turonian-lower Campanian Niobrara Formation recovered in the Encana Aristocrat-Angus core in the Denver Basin (Fig. 1) is typical of data from cores drilled along the Front Range of Colorado and in western Kansas (including Berthoud State #3 and #4 cores: Dean and Arthur, 1998; USGS Portland Core: Tessin et al., 2015; Amoco Rebecca Bounds Core: Dean and Arthur, 1998; and Aristocrat-Angus Core: Locklair and Sageman, 2008; Locklair et al., 2011). The broad trends of redox sensitive trace-metals are remarkably consistent across these cores, and are characterized by: 1) enrichment in Mn and other elements associated with oxic environments in the Fort Hays Limestone Member, with highest Mn values at the base and declining values toward the top; 2) continued decline in Mn in the lower part of the lower limestone and shale unit of the basal Smoky Hill Shale Member, with values approaching zero toward the top of the unit; and 3) a sudden, strong increase in organic matter concentrations (in the Portland Core, for example, TOC jumps from almost zero to >8 wt% within several centimeters) with a corresponding rapid increase in Mo and other trace elements associated with anoxia/euxinia. A hiatus has been identified at this level, based on ammonite biostratigraphy (Walaszczyk and Cobban, 2007); a short diastem here is also supported by recent astrochronologic and radioisotopic dating (Sageman et al., 2014).

Trace metal redox proxies suggest declining oxygen conditions prior to the late Coniacian CIE (Locklair et al., 2011; Tessin et al., 2015). However, trace metal geochemistry alone cannot provide unequivocal information on whether this oxygen decline occurred

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