

## Accepted Manuscript

Calcareous Nannofossil Paleocology of the mid-Cretaceous Western Interior Seaway and Evidence of Oligotrophic Surface Waters during OAE2

Matthew J. Corbett, David K. Watkins

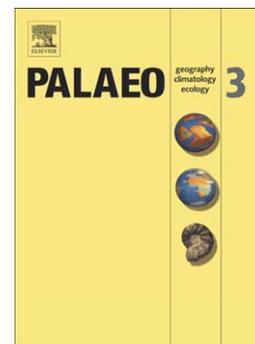
PII: S0031-0182(13)00463-X  
DOI: doi: [10.1016/j.palaeo.2013.10.007](https://doi.org/10.1016/j.palaeo.2013.10.007)  
Reference: PALAEO 6647

To appear in: *Palaeogeography, Palaeoclimatology, Palaeoecology*

Received date: 22 April 2013  
Revised date: 1 October 2013  
Accepted date: 15 October 2013

Please cite this article as: Corbett, Matthew J., Watkins, David K., Calcareous Nannofossil Paleocology of the mid-Cretaceous Western Interior Seaway and Evidence of Oligotrophic Surface Waters during OAE2, *Palaeogeography, Palaeoclimatology, Palaeoecology* (2013), doi: [10.1016/j.palaeo.2013.10.007](https://doi.org/10.1016/j.palaeo.2013.10.007)

This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.



**Calcareous Nannofossil Paleoecology of the mid-Cretaceous Western Interior  
Seaway and Evidence of Oligotrophic Surface Waters during OAE2**

Matthew J. Corbett<sup>1</sup> and David K. Watkins<sup>1</sup>

<sup>1</sup>Department of Earth and Atmospheric Sciences, University of Nebraska-Lincoln,  
Lincoln, NE, 68588-0340, USA

Corresponding Author: Matthew J. Corbett, mcorbett@huskers.unl.edu, 781-771-0596,  
214 Bessey Hall, Department of Earth and Atmospheric Sciences, University of  
Nebraska-Lincoln, Lincoln, NE, 68588-0340, USA

**Abstract**

Analysis of calcareous nannofossils, total organic carbon (TOC) values, and carbon isotope records from outcrop and drillcores in the central (Colorado and Kansas) and southern (Texas) Western Interior Basin (WIB) indicate predominantly oligotrophic surface water conditions during the late Cenomanian-Turonian Oceanic Anoxic Event 2 (OAE2). High-resolution bio-chemostratigraphy of this interval allows for detailed correlation of changes in nannofossil assemblages and TOC across the WIB and aids comparison with other global records. Prior to and at the onset of OAE2, the A interval in the  $\delta^{13}\text{C}$  positive excursion identified by Pratt and Threlkeld (1984), mesotrophic to eutrophic nannofossil taxa *Biscutum* and *Zeughrabdotus* are relatively high in abundance and foraminiferal assemblages record a high diversity “benthonic zone”. TOC sharply declines at the start of OAE2 despite evidence of high surface productivity and benthic diversity, implying the seafloor was briefly oxygenated during a period of enhanced

mixing in the expanding Western Interior Seaway. During the latter two thirds of OAE2 (intervals B and C in the excursion) TOC periodically increases, suggesting anoxic conditions returned at the substrate, despite persistently low abundances of *Biscutum* and *Zeugrhabdotus*, implying oligotrophic surface water conditions. The divergence of these two proxies suggests a highly stratified water column in the WIB, not higher productivity, resulted in anoxic conditions during OAE2.

If productivity was not the primary cause of increased carbon burial in the WIB it is probable that increased terrestrial runoff and incursion of warm, saline Tethyan waters from the south led to salinity stratification. In the absence of mixing, warm and saline bottom waters would have been isolated from freshened Boreal currents and become stagnant, allowing for preservation of greater amounts of organic material in the substrate. Nannofossil records from Cuba, KS are an exception, and reveal relatively high productivity throughout, suggesting occasional mixing of nutrients to the surface may have continued along the eastern margin of the central WIB.

Keywords: calcareous nannofossils, paleoecology, oceanic anoxic event 2, Western Interior Basin, Cenomanian-Turonian Boundary Event, surface water fertility

## 1. Introduction

The Cenomanian-Turonian boundary interval is marked by a major perturbation of the ocean-climate system known as Oceanic Anoxic Event 2 (OAE2). Oceanic Anoxic Events were characterized in the marine rock record by global increases in organic carbon burial in the form of carbonaceous shales, increased atmospheric CO<sub>2</sub> and

significant assemblage turnover within several fossil groups including ammonites, inoceramid bivalve clams, foraminifera and calcareous nannofossils (e.g., Elder, 1985; Leckie et al. 2002; Watkins et al. 2005). Higher organic carbon burial rates caused by widespread anoxia resulting from increased primary productivity are thought to have driven a major positive shift in  $\delta^{13}\text{C}$  values that is recognized globally (Arthur et al., 1987, 1988). The relationship between primary phytoplankton productivity and preservation of organic matter during OAE2 is contradictory between tropical (e.g., Demerara Rise, equatorial Atlantic) and mid-latitude shelf or epicontinental settings (e.g., the Cretaceous Western Interior Seaway, northern Atlantic, Europe; Figure 1) (Eleson and Bralower 2005; Hardas and Mutterlose 2007; Linnert et al. 2010, 2011).

During OAE2, in the latest Cenomanian and earliest Turonian, the western interior of North America was inundated by an epicontinental seaway that connected the Gulf of Mexico with the Arctic Ocean. The stratigraphic record of this interval in the central Western Interior Basin (WIB) is found within the deposits of the Greenhorn Formation. Evidence of the level of surface water fertility based on calcareous nannofossil assemblages in the WIB and other mid-latitude locations conflict with fertility levels and proxies for anoxia and carbon burial in the tropics (Demerara Rise), which is based on benthic foraminiferal populations and TOC values (Friedrich et al. 2006; Linnert et al. 2011). Peaks in high-fertility calcareous nannofossil taxa (e.g., *Biscutum* and *Zeugrhabdotus*) closely coincide with periods of high TOC and low abundance, low diversity benthic foraminiferal assemblages in the tropics (Friedrich et al. 2006; Hardas and Mutterlose 2007) suggesting that productivity drove anoxia.

Calcareous nannofossil data from higher latitude shelves and epeiric seas (Cuba, KS; the New Jersey Shelf; Eastbourne, UK; the Wunstorf Core, Germany) implies more oligotrophic, lower fertility conditions during OAE2 with sluggish circulation and stratification of the water column resulting in organic rich intervals (Eleson and Bralower 2005; Parente et al. 2008; Linnert et al. 2010, 2011). At these sites high fertility nannofossil taxa are found in very low abundances even though TOC remains elevated. While there are extensive studies of the Greenhorn Formation in the central WIB that provide explanations for bottom water anoxia during OAE2 (Watkins 1986; Burns and Bralower 1998; Leckie et al. 1998; Fisher and Arthur 2002; Eleson and Bralower 2005), little has been published regarding microfossil changes from the coeval Eagle Ford Formation at the southern aperture of the WIB.

Several publications discuss the macrofossil biostratigraphy of the Eagle Ford (Adkins and Lozo 1951; Hancock and Walaszcyk 2004; Cobban et al. 2008) but little recent or detailed work is available on the biostratigraphy and paleoecology of the microfossil assemblages. Smith (1981) published the only paper on the stratigraphy of the Eagle Ford Formation and Austin Group exposed across Texas that includes an extensive analysis of calcareous nannofossils. Unfortunately, the work does not apply the biostratigraphic zonation schemes now commonly used (Perch-Nielsen 1985; Burnett 1998) and many biostratigraphically important taxa were not recognized. In addition, nannofossil abundance was only recorded qualitatively and cannot be used to infer paleoecological changes through the succession. A more detailed and contemporary biostratigraphic analysis by Jiang (1989) contains a qualitative record of nannofossil

populations. Pessagno's (1967) regional study of Gulf coast planktic foraminifera is also restricted to a rough biostratigraphy for this interval and does not provide the detailed assemblage data found in later studies from the central WIB.

Here we provide new information (calcareous nannofossils, TOC,  $\delta^{13}\text{C}$ ) from the Eagle Ford Formation in the southern WIB and compare it with similar data from the central (Colorado, Kansas) Western Interior Basin (Fig. 1). This new information is compared to previously published data to better understand the temporal and spatial relationships between primary productivity, deep water anoxia, and organic carbon burial in the WIB during the period of oceanic anoxia, warm temperatures, and highest sea-level of the Cretaceous Period.

## **2. Background and Geologic Setting**

### **2.1. OAE2**

The Cretaceous represents an analogue period in Earth history to study global warmth in a "super greenhouse" climate as major biological and oceanographic changes were occurring in the world's oceans. Warmer, ice-free high latitudes allowed marine organisms to spread over wide geographic ranges (i.e., cosmopolitan species) (Huber et al. 1995) and higher sea-level resulted in the formation of large epeiric seas. Punctuating this record are several episodes of oceanic anoxia and shifts in the global carbon budget (Schlanger and Jenkyns 1976; Jenkyns 1980; Arthur et al. 1988; Kump and Arthur, ; Wilson and Norris 2001; Norris et al. 2002; Erba 2004; Jarvis et al., 2006; Friedrich et al., 2012). These perturbations were coincident with increased rate of organic carbon

burial at the global scale, which are recorded as positive and negative carbon isotope excursions within marine carbonate and organic matter, and are particularly important petroleum source rocks (Schlanger and Jenkyns 1976; Arthur et al. 1988). The maximum expression of these events, culminating in the warmest climate and highest sea-levels of the past 150 Myr, occurred during OAE2 (Norris et al. 2002; Forster et al. 2007).

Prevailing hypotheses suggest that during OAE2 increased stratification of the water column or elevated primary productivity at the sea surface resulted in oceanic anoxia and increased carbon burial following volcanic-induced global warming (Schlanger and Jenkyns 1976; Leckie et al. 2002; Erba 2004; Elson and Bralower 2005; Snow et al. 2005; Hardas and Mutterlose 2007; Linnert et al. 2010, 2011). Enhanced preservation of organic matter can occur during oligotrophic episodes through thermal and salinity driven stratification of the water column, which prevents mixing of oxygen and nutrients between the surface and deeper waters (Erbacher et al. 2001). Greater primary phytoplankton productivity, due to upwelling, increased run-off, or input of biolimiting elements into the oceans by hydrothermal activity can also result in greater organic matter flux to deeper water in the form of detritus and fecal pellets (Erba 2004, Watkins et al. 2005). Oxidation of organic matter by bacteria can eventually deplete O<sub>2</sub> levels in the water column, creating an expanded oxygen minimum zone (OMZ), and facilitating greater preservation potential in the substrate. One way in which to test these scenarios is to look for evidence of high levels of marine surface water productivity and compare this with total organic carbon (TOC) amounts preserved in the sediments.

## **2.2. Cenomanian-Turonian records of the Western Interior Basin, USA**

The upper Cenomanian Hartland Member of the Greenhorn Formation in the central WIB consists of dark, organic-rich shales indicative of a more restricted environment prior to maximum transgression of the seaway (Sageman, 1985). These shales are overlain by more calcareous shale and limestone couplets of the upper Cenomanian to Turonian Bridge Creek Member (Elder and Kirkland, 1985; Sageman et al., 1998).

The equivalent stratigraphy in the southern Western Interior is found in the Eagle Ford Formation. This unit has been extensively studied for its sedimentology, stratigraphy, and petroleum systems, because it is a major shale gas play in the Texas subsurface (Adkins and Lozo 1951; Grabowski 1995; Donovan et al. 2012). The lower Eagle Ford consists largely of organic rich carbonate mudstone, much like the Hartland Member of the Greenhorn Formation to the north. The lower unnamed member (Facies C of Donovan et al. 2012) of the upper Eagle Ford closely resembles the interbedded limestone-marlstones of the Bridge Creek Member of the Greenhorn Formation. These facies reflect comparable paleoenvironmental changes and relative sea-level variation during OAE2 in both regions.

The purpose of the present study is to extend knowledge of calcareous nannofossil stratigraphy and paleoecological inferences into the southern regions of the WIB, in order to compare the interval of OAE2 with new and historical records from the central WIB and other global records.

### **3. Study Localities**

In the Western Interior Basin a comprehensive analysis of nannofossil assemblages across the Cenomanian-Turonian boundary is limited to a handful of sites in Colorado and Kansas (Watkins 1986; Burns and Bralower 1998; Elson and Bralower 2005). Several new datasets are presented herein from the central WIB, as well as new investigation of sites along the southern opening with the Gulf of Mexico. These new data were obtained from outcrop samples at Mesa Verde National Park, Colorado and Cuba, Kansas, and the Fasken “A” #1-H and ACC #1 drillcores from Webb and Travis counties in Texas (Fig. 1).

A nearly 700 m thick exposure along the northern entrance to Mesa Verde National Monument (Fig. 1) was designated as the principal reference section for the Upper Cretaceous Mancos Shale by Leckie et al. (1997). Upper Cenomanian through middle Turonian stratigraphy is preserved in the lower ~35 m of the section in the Graneros and Bridge Creek members of the Mancos Shale. Calcareous nannofossils are relatively abundant in this part of the section and several key limestone and altered volcanic ash (bentonite) marker beds are identified in the Bridge Creek Member.

The Greenhorn Formation crops out along Route 36 near Cuba, Kansas (Fig. 1) at locations 6 and 7 of Hattin (1975), who described the sedimentology and macrofossil biostratigraphy in depth. The facies diagnostic of the Bridge Creek Member is diachronous across the WIB, though individual limestone marker beds can be traced across the basin. Equivalent strata around Cuba consist of more fine-grained calcareous to chalky shale within the Hartland, Jetmore, and Pfeifer members, though many limestone and bentonite marker beds are still recognized through Kansas (Hattin 1975,

1985; Desmares et al. 2007). Carbon isotope stratigraphy of the Cuba section is taken from Bowman and Bralower (2005). Calcareous nannofossil assemblages from this site have been studied before by Eleson and Bralower (2005), but are reanalyzed here to incorporate a more detailed biostratigraphic scheme (see Corbett et al. in review).

Calcareous nannofossil assemblages from the southern Western Interior Basin were examined in samples from the Fasken “A” #1-H and ACC #1 cores (Figs. 1, 4). Deposition of the upper Cenomanian-lower Turonian Eagle Ford Formation occurred on and around the Comanche Carbonate Platform, which spanned much of the southern opening of the Western Interior Seaway, and in deeper settings to the east and south along a submarine plateau created by the relict Edwards and Sligo reef margins (Goldhammer and Johnson 2002; Donovan et al. 2012). The Fasken “A” core is located within the South Texas Submarine Plateau, and is a more continuous section than the equivalent successions on the shallow carbonate platform (Donovan et al. 2012; Corbett et al. in review). The ACC #1 core is situated close to what would have been the exposed Llano Uplift on the eastern edge of the Comanche Platform. It is a more condensed section, and may be missing the OAE2 interval (Corbett et al. in review). The upper Cenomanian lower Eagle Ford Formation (or Cloice Member in the ACC #1 core) is composed of dark, organic-rich carbonate mudrocks. Organic content decreases into the upper Eagle Ford, and the Bouldin Creek/unnamed members in the Fasken “A” and ACC #1 cores are composed of interbedded limestone-marl couplets, reminiscent of the Bridge Creek Member of the Greenhorn Formation in the central Western Interior.

Three sites were chosen to compare the results presented here with similar data regarding the calcareous nannofossil response to OAE2 in other mid-latitude locations (the Amoco Rebecca Bounds #1 Core, KS, USA; the Wunstorf Core, Germany) and the tropics (ODP Site 1258, Demerara Rise) (Fig. 1). These sites were chosen because they contain detailed records of calcareous nannofossil assemblages, total organic carbon, and carbon isotope values. Burns and Bralower (1998) published their observations of *Watznaueria*, *Biscutum*, and *Zeugrhabdotus* abundance from the Amoco Rebecca Bounds Core, which contains a complete Greenhorn Formation on the western border of Kansas. This site and the data presented herein, allows for a detailed west to east cross section of nannofossil assemblage changes during OAE2 in the central Western Interior Basin. These results are compared to the Wunstorf Core (OAE2 European Reference section, northwest Germany) in a similar continental basin setting, and ODP Site 1258 at Demerara Rise in an oceanic and low latitude setting to enable comparisons of how these regions witnessed OAE2 (Hardas and Mutterlose 2007; Linnert et al. 2010).

#### 4. Methods

Calcareous nannofossils were studied using a Zeiss Photoscope III at a total magnification of 1250x using cross-polarized light, plane light, phase contrast, and through a one-quarter  $\lambda$  mica plate. Slides from outcrop and core samples were prepared using the double slurry and settling methods detailed by Watkins and Bergen (2003) and Geisen et al. (1999), respectively. The cascading counting technique developed by Styzen (1997) was used to collect assemblage data for most sample sets. Total counts of relevant taxa were then converted to percent relative abundances for easier comparison between

localities and previously published data. Data are archived at the World Data Center-A for Paleoclimatology <http://www.ncdc.noaa.gov/paleo/data.html> (Corbett and Watkins, submitted).

Three intervals, A, B, and C, were identified within the OAE2  $\delta^{13}\text{C}$  excursion by Pratt and Threlkeld (1984) which roughly correspond to the initial peak in  $\delta^{13}\text{C}$  and start of OAE2, the second  $\delta^{13}\text{C}$  peak, and the Cenomanian-Turonian boundary. These are used here to correlate assemblages between localities and are labeled on Figures 2, 4, and 5. Carbon isotope data for Mesa Verde and isotope and TOC data for the Fasken core are published in Corbett and Watkins (in review) and Donovan et al. (2012), respectively, and coincide with sampling of calcareous nannofossils in this study. The carbon isotope and TOC data for the Cuba, KS locality is published in Bowman and Bralower (2005) and is sampled at a higher resolution than the sample set analyzed here. The intervals marked by grey lines in Figure 4 between the base of the A interval (and OAE2) base of the Turonian (and the C interval) for Cuba and the Fasken core are identified largely on matching the pattern of  $\delta^{13}\text{C}$  values with reference curves developed by Kennedy et al. (2005) and Jarvis et al. (2006). The intervals labeled in Figure 5 refer to the interpretations from their respective sources (i.e. Scott et al. 1998; Erbacher et al. 2005; Voigt et al. 2008). For the Fasken core the highest peak in the excursion is interpreted as approximating the C interval. Nannofossil biostratigraphy from the ACC#1 core indicate most of the Cenomanian-Turonian boundary interval is missing (Corbett et al. in review). The carbon isotope data from Mesa Verde is too coarse to make a very accurate interpretation. In this case the macrofossil zones identified by Leckie et al. (2007) and

nannofossil datums are used to estimate the interval between A and C next to the isotope data.

Calcareous nannofossil data from sites investigated here, and comparable published data, were included in a quantitative biostratigraphic analysis of the Late Cretaceous by Corbett et al. (submitted). A Ranked and Scaled (RASC) optimum sequence of events was compared to the established CC (Perch-Nielsen 1985) and UC (Burnett 1998) biostratigraphic zonations, which allowed for the identification of the most reliable nannofossil bioevents (Fig. 2). In addition to biostratigraphic datums, carbon isotope chemostratigraphy was included, which has been shown to be a highly accurate correlation tool for the OAE2 stratigraphic interval in oceanic and shelf/epeiric settings ( Tsikos et al. 2004; Jarvis et al. 2006; Takashima et al. 2009). A 2-3‰ positive  $\delta^{13}\text{C}$  excursion that identifies OAE2 and the Cenomanian-Turonian boundary was recognized across all sites, and where possible its characteristic shape was used to subdivide and provide an approximate timescale based on the work of Sageman et al. (2006), Meyers et al. (2012), and Ogg and Hinnov (2012). Macrofossil and microfossil biostratigraphy were also used to indicate the placement of the Cenomanian-Turonian boundary where  $\delta^{13}\text{C}$  records are lower resolution. Using the placement of this excursion and macrofossil zonations within the revised 2012 Geologic Timescale (Ogg and Hinnov 2012) the optimum sequence of nannofossil bioevents and carbon isotope values from the GSSP at Pueblo Colorado are plotted together as an idealized bio-chemostratigraphic framework for OAE2. This framework allows for a robust correlation of changes in

calcareous nannofossil assemblages and organic content between the different OAE2 successions.

New data from sites in the central and southern WIB were compared to published information from the WIB, the mid-latitude European reference section in Wunstorf, Germany, and the tropical site of Demerara Rise. Correlations between these datasets are based on calcareous nannofossil biostratigraphy and carbon isotope chemostratigraphy. Calcareous nannofossil markers recognized in many OAE2 sections provide additional biostratigraphic age control. The bio-chemostratigraphic information of each site is plotted with TOC and relative abundances of key nannofossil fertility taxa in Figure 4.

## 5. Results

In poorly preserved Cretaceous material *Watznauria* is known to dominate nannofossil assemblages (Hill 1975; Roth and Krumbach 1986; Williams and Bralower 1995). A plot of the relative abundances of *Watznaueria* versus species richness (i.e. simple diversity) can be used to estimate if high numbers of *Watznaueria* are the result of selective dissolution. Analysis of *Watznaueria* versus richness for the new datasets presented here reveals no correlation (Fig. 3), suggesting that despite relatively poor preservation in many samples the nannofossil assemblage data are representative of the original burial assemblage. For a more robust assessment of preservation nannofossil abundances are plotted against Shannon diversity (Fig. 4). Diversity is believed to increase during periods of oligotrophy, therefore a decrease in diversity with an increase in the dissolution resistant *Watznaueria* could be seen as evidence of its preferential

preservation and an assemblage affected by diagenesis. Drops in Shannon diversity do parallel a few peaks in *Watznaueria* within the likely OAE2 interval at Mesa Verde and in the Fasken core. These analyses reveal that while most of the samples are representative of the original burial assemblage some intervals during OAE2 are likely impacted by diagenesis, which are highlighted on Figure 4. The upper interval in the lower part of the Bridge Creek Member at Mesa Verde contains a high abundance (>25%) of *Biscutum*, suggesting less of an impact on the assemblage by diagenesis here.

Total organic content and high fertility nannofossils are relatively abundant prior to and in the initial A interval of OAE2 in the WIB. Total organic carbon values are high (from 2-8% TOC) in the Western Interior Seaway (Fig. 4), especially in the subbasins and submarine plateaus of southern Texas. *Biscutum* makes up ~15-60% of the assemblages in the Graneros Member at Mesa Verde and Hartland Member at Cuba in the central WIB. In the lower Eagle Ford Formation in Texas nannofossil assemblages are composed of ~10-25% *Biscutum* in the Fasken Core and up to 54% in the ACC#1 Core. *Biscutum* continues to be fairly abundant through the onset of OAE2 into Pratt and Threlkeld's (1984) A interval.

By the B interval of OAE2, corresponding to the second increase in carbon isotope values, *Biscutum* declines to more than half its pre-excursion values and TOC decreases, while calcareous nannofossil populations become dominated by *Watznaueria*. *Biscutum* decreases to an average of ~12% relative abundance in the basal Bridge Creek Member of the Mancos Shale at Mesa Verde and an average of ~7% within the upper Eagle Ford Formation in the Fasken "A" Core (Fig. 4). Peaks in *Watznaueria* coincide

with lower Shannon Diversity and Eutrophic species at Mesa Verde and in the Fasken core, which may indicate a diagenetic signal. This data may still reflect the original assemblages as values of *Biscutum* and *Zeugrhabdotus* were low prior to and following these intervals where Shannon Diversity is higher. Results from Cuba are something of an exception where *Biscutum* increases slightly in abundance during the onset of OAE2 within an overall decreasing trend into the lower Turonian. The new data are fairly consistent with previous publications showing a sharp drop in the relative abundance of *Biscutum* across mid-latitude sites during OAE2 (Burns and Bralower 1998; Erba 2004; Elson and Bralower 2005; Linnert et al. 2010, 2011; Melinte-Dobrinescu and Bojar 2008; Tantawy 2008).

Following the shift to an assemblage of calcareous nannofossils reflecting oligotrophic conditions, during the B and C intervals of OAE2, there are several short episodes of elevated TOC. In the Hartland Member at Cuba and in the correlative lower Bridge Creek Member within the Rebecca Bounds core TOC increases to 6-10% (Dean and Arthur 1998; Bowman and Bralower 2005). There are also one or two brief intervals where the relative abundance of the eutrophic species *Zeugrhabdotus* increases to 10-20% in the WIB, despite the consistently low numbers of *Biscutum*. At Mesa Verde *Zeugrhabdotus* increases to nearly 10%, while at Cuba and in the Fasken Core it reaches almost 18% in abundance. None of the high TOC events coincide with the peaks in *Zeugrhabdotus* and *Biscutum* remains a small component to nannofossil assemblages.

During the return of the carbon isotope record to more negative values following the C interval and Cenomanian-Turonian boundary calcareous nannofossil assemblages

also return to the pre-excursion assemblages dominated by high fertility *Biscutum* (Fig. 4). In the lower Turonian at Mesa Verde and in the Fasken Core *Biscutum* increases to 20-40% relative abundance. Oceanic anoxic event 2 is interpreted as missing in the ACC#1 Core (Corbett et al. in review), but portions of the lower to middle Turonian are preserved. In the South Bosque Member *Biscutum* also comprises ~16-34% of the assemblage. Total organic carbon remains low at 2% or less in the central WIB and 2-4% or less across Texas.

## 6. Discussion

Multiple analyses of upper Cenomanian through lower Turonian sediments of the Greenhorn Formation in the central Western Interior have concluded that the patterns of carbonate production and fossil abundance changes were linked to interactions between freshened Boreal waters, warmer saline Tethyan currents, and fresh-water runoff (Watkins 1989, 1986; Burns and Bralower 1998; Leckie et al., 1998; Meyers et al. 2001; Eleson and Bralower 2005; Sageman et al. 2006). Sageman (1985) argued that the greatest anoxia and carbon burial occurred during transgressive periods when Tethyan waters entered the WIB from the south, shifting terrestrial run-off in a landward direction. More detailed cyclostratigraphic analysis by Meyers et al. (2001) and study of terrigenous detrital flux substantiate this hypothesis, showing a decrease in detrital elements delivered into the basin with the initiation of Bridge Creek deposition. Slingerland et al. (1996) modeled water mass movement and argued that Tethyan and

Boreal waters would have been drawn into the Western Interior Seaway as a counterclockwise gyre during late transgression in the latest Cenomanian to early Turonian. This is supported by previous analyses of calcareous nannofossil and foraminiferanl assemblages (Watkins 1986; Leckie et al. 1998; West et al. 1998; Elson and Bralower 2005).

The incursion of Tethyan waters in the WIB is signaled by the abrupt appearance of a diverse foraminiferal “Benthonic Zone” at the contact between the Hartland and Bridge Creek members of the Greenhorn Formation (Eicher and Worstell, 1970; Frush and Eicher, 1975; Eicher and Diner, 1985; Leckie et al., 1998). At Rock Canyon and Mesa Verde, this was followed by a short-lived dominance of the epifaunal taxa *Gavelinella* that was quickly replaced by a low diversity assemblage of infaunal *Neobulimina*, implying more anoxic conditions above the sediment water interface as OAE2 became established in the WIB (Leckie et al., 1998). A barren benthic interval and recovery following OAE2 is observed in the southern Western Interior by Lowery et al. (in review), and stepwise changes in benthic communities are recorded in successions in the United Kingdom and Italy by Keller et al. (2001) and Parente et al. (2008), respectively.

Analysis of nannofossil populations across the central WIB also reveals distinct changes during OAE2. An 8-9% turnover of calcareous nannofossil species is observed through the upper Cenomanian and lower Turonian (Fig. 2). At least 9 speciation and 4 extinction events occurred between the second peak in the OAE2 excursion (interval B) and the base of the Turonian (interval C), which indicates a high rate of faunal turnover

in less than ~20 kyr. This implies paleoceanographic changes during this interval generated significant environmental stresses on marine phytoplankton (Leckie et al. 2002, Corbett et al. in review). These changes are also reflected in the relative abundance of specific nannofossil genera (*Watznaueria*, *Biscutum*, *Zeugrhabdotus*) indicating significant shifts in surface water fertility through OAE2.

Watkins (1986) demonstrated that nannofossil assemblages were influenced by northern Boreal waters and a southern Tethyan influx at the base of the Bridge Creek Member and argued the interaction between these water masses would have caused density stratification across the seaway. Additional analysis by Burns and Bralower (1998) and Elson and Bralower (2005) between Kansas and Colorado show that taxa associated with high surface water fertility, *Biscutum* and *Zeugrhabdotus*, decrease in abundance through the Bridge Creek Member. This is inconsistent with the leading explanation that higher primary productivity is responsible for the global increase in carbon burial (Erba 2004; Friedrich 2006; Tantawy 2008; Hetzel et al. 2009; Jenkyns 2010).

The Cretaceous genera *Watznaueria*, *Biscutum* and *Zeugrhabdotus* are thought to indicate a range of oligotrophic to eutrophic fertility levels depending on peaks in relative abundance between the species. *Biscutum* species and small *Zeugrhabdotus* species are thought to be indicative of high surface water fertility. Many studies reveal greater abundance of these taxa in areas of upwelling and elevated organic matter burial (Roth 1981, 1986, 1989; Roth and Bowdler 1981; Roth and Krumbach 1986; Watkins 1986, 1989; Premoli Silva et al. 1989; Erba 1992; Erba et al. 1992; Watkins et al. 2005; Hadas

and Mutterlose 2007) with *Zeugrhabdotus* possibly favoring more eutrophic conditions (Erba 1992; Erba et al. 1992; Haras and Mutterlose 2007). The nannofossil *Watznaueria barnesiae* is generally cited as preferring oligotrophic, low fertility waters, although this may be an artifact of its dominance in the paucity of r-selected taxa under oligotrophic conditions (Roth and Krumbach 1986; Erba et al. 1992; Williams and Bralower 1995; Herrle 2002; Herrle 2003; Watkins et al. 2005; Hardas and Mutterlose 2007). These taxa are often used to calculate a qualitative “Nutrient Index” (high fertility species/low + high fertility species) (e.g., Gale et al. 2000). High ratios of *Zeugrhabdotus* and *Biscutum* to *Watznaueria* should coincide with intervals of elevated primary productivity during OAE2 and should correspond to high TOC in associated sediments.

Use of *Watznaueria*, *Biscutum*, and *Zeugrhabdotus* as proxies for surface water fertility reveals diverging interpretations for the litho-, chemo-, and biostratigraphic response to OAE2 for ODP Site 1258 at the tropical Demerara Rise versus mid-latitude shallow shelf or epicontinental settings in the WIB and Europe. Takashima et al. (2009) suggest that robust correlations between TOC content, proxies of anoxia, and paleontological productivity trends to the  $\delta^{13}\text{C}$  excursion should be noted in sites that reflect the strongest direct correlation to the global organic carbon burial rate. These changes in calcareous nannofossil assemblages are accompanied by significant increases of TOC up to 20-35% total weight at Demerara Rise and 15-20% in Morocco, indicating that surface productivity in these tropical oceanic settings resulted in anoxia and carbon sequestration (Kolonic et al. 2005; Hetzel et al. 2009).

Comparable studies of the shallow, boreal sites yield excellent integrated analyses of successions through OAE2, but suggest more oligotrophic or less anoxic conditions than in the Tethyan tropics. *Watznaueria* tends to dominate, while *Biscutum* and *Zeugrhabdotus* are diminished (<5-10% relative abundance), at sites in the central WIB, the New Jersey coastal plain, the United Kingdom, and Europe (Eleson and Bralower 2005; Linnert et al. 2010, 2011). Results from these successions call upon regional effects to explain the lack of productivity indicators and diachronous deposition of organic rich intervals (Gale et al. 2000; Tsikos et al. 2004; Takashima et al. 2009; Jarvis et al. 2011).

A transition to lower TOC in the WIB implies a decoupling between organic matter burial and surface water fertility at the onset of OAE2 (the A interval) in the mid-latitudes. *Biscutum* is relatively high through this interval, which coincides with the “benthonic zone” observed in many benthic foraminiferal records and the Plenus Cold Event in the midlatitudes (Jarvis et al. 2011). The “benthonic zone” was first recognized by Eicher and Worstell (1970) and Frush and Eicher (1975) as a high diversity interval in benthic foraminiferal populations in the WIB and coincides with high planktic foraminiferal diversity at Rock Canyon Anticline near Pueblo, CO and at Mesa Verde (Leckie 1985; Leckie et al. 1998). This interval is also recognized by Elderbak et al. (2013) at Cuba, KS, while Lowery et al. (submitted) record a higher abundance of benthic foraminifera just below the OAE2 excursion in the Fasken “A” Core. Geochemical proxies for sea-surface temperatures (SSTs) indicate fluctuations in the early stages of OAE2 (A and B intervals) as global carbon burial and associated cooling

in the midlatitudes overcame volcanic outgassing for a short period (the onset of A). The foraminiferal trends are thought to indicate increasing influence of warm, better oxygenated Tethyan waters as relative sea-level reached peak transgression during the latest Cenomanian-early Turonian (Leckie 1985; Leckie et al. 1998; West et al. 1998; Elderbak et al. 2013; Lowery et al., submitted). A Tethyan incursion driven by shifts in SSTs, and associated mixing and oxygenation of the water column, could explain the decrease in the preservation of organic matter despite high surface water productivity.

A shift to oligotrophic surface waters in the B interval is coincident with the end of the “benthonic zone” and peaks over several short episodes in TOC concentrations in the WIB, suggesting oxygenation of the seafloor was inconsistent (Fig. 4). Meyers et al. (2001) argued that anoxia could not have been permanent, citing very low levels of molybdenum, an element typically associated with sulfidic/anoxic depositional environments, through most of the Bridge Creek Member of the Greenhorn Formation. This notion is corroborated by Desmares et al. (2007) who linked the bioturbated limestones in the Bridge Creek Member with high fossil diversity to more oxic conditions.

Gradual changes in benthic foraminiferal assemblages also suggest increasing dysoxia or anoxia in the WIB in the latter stages of OAE2. Leckie et al. (1998) tracked major planktic and benthic foraminiferan shifts and elevated TOC to the incursion of a Tethyan warm water mass. The greater abundance of infaunal benthics and small biserial planktics (e.g., *Heterohelix*) is cited as indicating increased organic flux into the sediments, deep water anoxia, and poor surface water conditions (Leckie et al. 1998).

The high fertility calcareous nannofossils remain a small portion of assemblages through OAE2 and have no observed relationship to increased carbon burial (Fig. 4). *Zeugrhabdotus* and *Biscutum* remain a small component to nannofossil assemblages in the B and C intervals, even in other mid-latitude localities (Burns and Bralower 1998; Eleson and Bralower 2005; Linnert et al. 2010, 2011; Tantawy 2008). Peaks in the abundance of *Zeugrhabdotus* have no correlation to increases in TOC, indicating this species may flourish in environments not exclusive to high surface water productivity. These maxima in *Zeugrhabdotus* are also diachronous between the central WIB and similar intervals observed in Texas and Europe (Fig. 4, 5). Based on the results of Shannon Diversity vs. *Watznaueria* abundance it is likely diagenesis has affected some samples analyzed prior to and following the B and C intervals at Mesa Verde and the Fasken core. Some of these intervals (Fig. 4) correspond to periods of low abundance in *Zeugrhabdotus* and *Biscutum*, which may have been preferentially dissolved. Despite the evidence of diagenesis some samples reflect low surface productivity and higher diversity during OAE2. This is especially true at Mesa Verde where low abundances of high fertility taxa are consistent throughout the latest Cenomanian and earliest Turonian (Fig. 4). Assuming that these intervals are more indicative of OAE2, particularly the B and C intervals, this implies an oligotrophic surface water signal. This oligotrophic signal observed in the WIB and other mid-latitude sites rule out the involvement of phytoplankton productivity with anoxia and elevated organic carbon burial. Stratification of the water column is thought to have occurred as early as the middle-to-late Cenomanian when the Western Interior Seaway first became connected between the arctic and Gulf of Mexico, which could have resulted in deep water anoxia (Watkins

1986; Fisher and Arthur 2002). A study of nannofossil diversity across the WIB by Watkins (1986) revealed biofacies thought to reflect surface waters influenced by northern and southern components. The interaction of the cooler boreal currents and fresh water runoff with warmer, normal marine Tethyan waters from the south would have most likely resulted in vertical stratification (Fig. 6a). This is supported by the work of Fisher and Arthur (2002) who analyzed stable isotope values of planktic and benthic foraminifera from Montana and Wyoming and interpret a strong vertical gradient in  $\delta^{18}\text{O}$  values as indicating freshened, warmer water at the surface and more saline, colder waters at depth. To explain elevated organic matter burial and high fertility calcareous nannofossil assemblages observed by Fisher and Hay (1999) during the mid-to-late Cenomanian Fisher and Arthur (2002) suggest that mixing must have occurred periodically to bring nutrients to the surface. Nannofossil assemblages indicating oligotrophic conditions during OAE2 suggest a strengthened thermal and/or salinity gradient suppressed this mixing with the surface waters.

It's possible that enhanced water column stratification resulted in the periodic formation of a stagnant deep water mass during OAE2, though it is unclear exactly how this separation would have occurred. This can be explained, in part, by a circulation model developed by Slingerland et al. (1996), which indicates Tethyan waters would have been drawn in northward as an eastern coastal jet while Boreal waters flowed south along its western border simultaneously with freshwater runoff similar to estuarine circulation. Water column stratification is typically thermally or salinity driven. At the time of Cenomanian-Turonian boundary the Comanche Platform was situated at

approximately 30° paleolatitude, within the Desert belt (Blakey, 2012). Evaporation in this shallow environment and in the tropics would have made the Tethyan influx much more saline and dense. This is thought to have occurred in the North Atlantic where a dense, saline Tethyan water mass formed a bottom current in the tropics, possibly resulting in the upwelling of deeper nutrient rich waters and high productivity at Demerara Rise (Martin et al. 2012). As sea level continued to rise through the latest Cenomanian in the WIB and SSTs increased in the midlatitudes (Jarvis et al. 2011), a lighter, freshened Boreal water mass could have separated the photic zone from the denser Tethyan current from the Gulf (Fig. 6b). This would prevent mixing of nutrients with the surface waters and result in oligotrophic conditions and inconsistent deep water anoxia during OAE2. Mesotrophic conditions likely return in the early Turonian as the abundance of *Biscutum* gradually increases, though TOC remains low (Fig. 6). In the southern portions of the seaway the carbonate platform sill could have imparted a lacuna during transgression where strong currents may have enhanced mixing and oxygenation of deeper water (Fig. 6c; Slingerland et al. 1996). The lower TOC here and evidence of bioturbation in the lower Turonian suggest a prolonged period of oxygenated bottom water (Donovan et al. 2012). In the central WIB, fertility also increased in the Turonian. Benthic foraminifera also remain abundant at Mesa Verde and in the Fasken “A” core, though not at Rock Canyon, suggesting relatively oxic/dysoxic conditions following OAE2 at these sites and the return to mesotrophic surface waters (Leckie et al. 1998; Lowery et al., submitted). A breakdown in stratification through the WIB may have allowed for mixing of nutrients to the surface and oxygen to deeper water, preventing long term anoxia despite elevated productivity (Fig. 6c).

The exception to this pattern is at Cuba, KS, where assemblages of planktic fossil groups suggest relatively high fertility throughout OAE2. Elson and Bralower (2005) performed a higher resolution study than presented here through this interval and showed a several small abundance increases in *Biscutum* during that may explain our observations. A study of dinoflagellate cyst assemblages by Harris and Tocher (2003) also record evidence of higher surface water productivity in the more eastward sites of a longitudinal transect across the WIB. Work by Elderbak et al. (2013) from Cuba, KS and Sioux City, IA reveal foraminiferal assemblages dominated by planktic taxa and a diminished “benthonic zone”, indicating a shorter period of oxygenated bottom waters than elsewhere in the WIB. These assemblages suggest different periodic mixing may have allowed for continued eutrophic conditions along the shallower western margins of the seaway through OAE2.

## 7. Conclusions

The series of microfossil events summarized here suggest that more complex paleoceanographic changes controlled anoxia and organic matter burial than has been suggested for tropical, oceanic ODP Site 1258 at Demerara Rise and in the WIB across the late Cenomanian-early Turonian transition. Relationships between calcareous nannofossil populations and TOC content suggest that while there was widespread connection between primary productivity and the preservation of organic matter prior to the late Cenomanian  $\delta^{13}\text{C}$  positive excursion they become decoupled during the B and C intervals of OAE2 in the WIB. The persistent dominance of *Watznaueria* shows that primary production was suppressed in the WIB and other mid-latitude shelf and epeiric

sea sections, and that there is no correlation between short episodes of high TOC and increases in the purported eutrophic indicator species *Zeugrhabdotus* (Fig. 4). In contrast, dramatic increases in the relative abundances of *Biscutum* and *Zeugrhabdotus* during the latest Cenomanian in the tropics parallel increases in TOC content (Fig. 5; Hardas and Mutterlose 2007; Hetzel et al. 2009). Disparity between mid-latitude and tropical assemblages supports interpretations that elevated primary production in the latest Cenomanian was limited to the tropics while mid-latitude shelf and epicontinental sea surface waters remained relatively oligotrophic (Fig. 4, 5). As such, an alternative explanation to high productivity is required for the initiation of deep water dyoxia and anoxia and OM preservation in much of the WIB during OAE2.

The decrease in the abundance of high fertility calcareous nannofossil groups through OAE2 has been argued as evidence of oligotrophic conditions driven by enhanced stratification in mid-latitude shelves and epicontinental seas (Eleson and Bralower 2005, Linnert et al. 2010, 2011a, 2011b). This view is supported by new data from the central and southern WIB and together provides robust evidence that surface water productivity played less of a role in the burial of organic matter in mid-latitude shelves and shallow seas. Comparison with biseriate planktic and benthic foraminiferal trends also shows that anoxia at the sediment water interface was decoupled with phytoplankton productivity in the surface waters. The exception is found at Cuba, KS where a suite of planktic fossil groups indicate elevated productivity during OAE2 and suggest periodic mixing may have continued along the eastern margin of the WIB. Additional integrated analysis of nannofossil and foraminiferal data (at Sioux City, IA, etc.) are needed to test

this hypothesis. Subsurface cores from east Texas basins may also be relevant, although bio-chemostratigraphic analysis of outcrops and core around Austin indicate the presence of disconformities through the OAE2 interval (Corbett et al. in review; Lowery et al. submitted).

Comparison of calcareous nannofossil and foraminiferal assemblages between the central and southern WIB reveals similar trends through the upper Cenomanian and lower Turonian (Fig. 4). This implies the southern aperture of the Western Interior Seaway, from the Comanche Platform into the surrounding submarine plateaus, had more in common with the central WIB (except for Cuba, KS) than the tropical oceanic sites. Surface water fertility was potentially driven by similar forcings, though it's likely that the seaway was much shallower through much of the Cenomanian and was influenced by greater terrestrial runoff. The Comanche Carbonate Platform would have served as a barrier or sill between Boreal waters to the north and Tethyan waters towards the Gulf of Mexico (Slingerland et al. 1996). The evidence of high surface water fertility and elevated TOC show that mesotrophy was common following communication was established between the northern and southern openings of the Western Interior Seaway. Total organic carbon is much higher before OAE2 in the central WIB and across Texas (7% or more), where the primary shale gas source/reservoir tends to be found in the upper Cenomanian lower Eagle Ford Formation (Donovan et al. 2012). This supports the hypothesis of periodic mixing of surface and deeper water by Fisher and Arthur (2002), which could have driven higher productivity and expansion of the oxygen minimum zone at that time.

Salinity stratification may have been driven by climate changes associated with warming by outgassing of CO<sub>2</sub> from the formation of the Caribbean Large Igneous Province (LIP), which is claimed to be the triggering mechanism for enhanced greenhouse conditions and sea-level rise in the latest Cenomanian and early Turonian (Erbacher et al. 2001; Erba 2004). As a result of this CO<sub>2</sub> induced global warmth, a rapid incursion of warm, saline waters from the tropics could have resulted in a well-stratified water column in the WIB that limited the mixing of nutrients into the surface waters more common in the earlier mid-late Cenomanian (Fig. 6). This would explain the brief foraminiferal “benthonic zone” and high fertility nannofossil assemblage during interval A and the dominance of oligotrophic taxa and periodic deep water anoxia during intervals B and C (Fig. 6).

### **Acknowledgements**

This study was completed in partial fulfillment of a PhD dissertation and supported by a research assistantship with the North America Gas division of BP America and the University of Nebraska-Lincoln. We would like to thank Scott Staerker and Art Donovan for their support and advice through the course of this research. Thanks also go to Tracy Frank and David Harwood, who provided helpful discussion and revisions. We would also like to thank R. Mark Leckie for providing samples of his collection from Mesa Verde National Park, CO and to Chris Lowery for his partnership in the field and use of his preliminary data from the Fasken “A” core.

### **References**

- Adkins, W.S., and Lozo, F.E., 1951. Stratigraphy of the Woodbine and Eagle Ford, Waco area, Texas. In: Lozo, F.E., Ed., The Woodbine and adjacent strata of the Waco area of central Texas; a symposium. *Fondren Science Series no. 4*, 101-164.
- Andruleit, H., Rogalla, U., and Stäger, S., 2004. From living communities to fossil assemblages: origin and fate of coccolithophores in the northern Arabian Sea. *Micropalaeontology* 50, supplement no. 1, 5-21.
- Arthur, M. A., Dean, W.A., and Pratt, L.M., 1988. Geochemical and climatic effects of increased marine organic burial at the Cenomanian/Turonian boundary. *Nature* 335, 714-717.
- Blakey, R., 2012. Paleogeography of North America. *Colorado Plateau Geosystems, Inc.*, DVD.
- Bowman, A.R., and Bralower, T.J., 2005. Paleoceanographic significance of high-resolution carbon isotope records across the Cenomanian-Turonian boundary in the Western Interior and New Jersey coastal plain, USA. *Marine Geology* 217, 305-321.
- Bralower, T.J. and Bergen, J.A., 1998. Cenomanian-Santonian Calcareous Nannofossil Biostratigraphy of a Transect of Cores Drilled Across the Western Interior Seaway. In: Dean, W.E., and Arthur, M.A., (Eds.), Stratigraphy and Paleoenvironments of the Cretaceous Western Interior Seaway, USA. *SEPM Concepts in Sedimentology and Paleontology No. 6*, 101-126.

- Brown, C.W., 1995. Global Distribution of Coccolithophore Blooms. *Oceanography* 8 (2), 59-60.
- Burnett, J.A. (with contributions from Gallagher, L.T. and Hampton, M.J.), 1998. Upper Cretaceous. In: Bown, P.R., (Ed.), *Calcareous Nannofossil Biostratigraphy, British Micropalaeontological Society Publications Series*. London: Chapman and Hall/Kluwer Academic Publishers. 132-199.
- Burns, C.E., and Bralower, T.J., 1998. Upper Cretaceous Nannofossil Assemblages Across the Western Interior Seaway: Implications for the Origins of Lithologic Cycles in the Greenhorn and Niobrara Formations. In: Dean, W.E., and Arthur, M.A., (Eds.), *Stratigraphy and Paleoenvironments of the Cretaceous Western Interior Seaway, USA. SEPM Concepts in Sedimentology and Paleontology No. 6*, 101-126.
- Cobban, W.A., Hook, S.C., and McKinney, K.C., 2008. Upper Cretaceous molluscan record along a transect from Virden, New Mexico, to Del Rio, Texas. *New Mexico Geology* 30 (3), 75-92.
- Corbett, M.J., and Watkins, D.K. in review, Cenomanian through basal Coniacian Calcareous Nannofossil biostratigraphy of the Mancos Shale reference section, Mesa Verde, CO.

- Corbett, M.J., and Watkins, D.K., submitted. World Data Center-A,  
<http://www.ncdc.noaa.gov/paleo/data.html>. Boulder, Colorado.
- Corbett, M.J., Watkins, D.K., and Pospichal, J.J., in review, A Quantitative Analysis of Calcareous Nannofossil Bioevents of the Late Cretaceous (Late Cenomanian-Coniacian) Western Interior Seaway and their Reliability in Established Zonation Schemes.
- Dean, W.E., and Arthur, M.A., 1998. Western Interior Seaway Drilling Project Data. *IGBP Pages/World Data Center-A for Paleoclimatology Data Contribution Series # 1998-027*. NOAA/NGDC Paleoclimatology Program, Boulder CO, USA.
- Desmares, D., Grosheny, D., Beaudoin, B., Gardin, S., and Gauthier-Lafaye, F., 2007. High resolution stratigraphic record constrained by volcanic ash beds at the Cenomanian-Turonian boundary in the Western Interior Basin, USA. *Cretaceous Research* 28, 561-582.
- Donovan, A.D., Staerker, T.S., Pramudito, A., Weiguo, L., Corbett, M.J., Lowery, C.M., Miceli Romero, A., and Gardner, R., 2012. The Eagle Ford outcrops of West Texas: A laboratory for understanding heterogeneities within unconventional mudstone reservoirs. *GCAGS Journal* 1, 162-185.
- Eicher, D.L., and Worstell, P., 1970. Cenomanian and Turonian Foraminifera from the Great Plains, United States. *Micropaleontology* 16 (3), 269-324.

- Elderbak, K., Leckie, R.M., and Tibert, N.E., 2013. Paleoenvironmental and Paleooceanographic Changes Across the Cenomanian-Turonian Boundary Event (Oceanic Anoxic Event 2) as Indicated by Foraminiferal Assemblages from the Eastern Margin of the Cretaceous Western Interior Seaway. *Geologic Problems Solving with Microfossils 3 Program with Abstracts*, North American Micropaleontological Society, 43-44.
- Eleson, J.W., and Bralower, T.J., 2005. Evidence of changes in the surface water temperature and productivity at the Cenomanian/Turonian Boundary. *Micropaleontology* 51 (4), 319-332.
- Erba, E., 1992. Calcareous nannofossil distribution in pelagic rhythmic sediments (Aptian-Albian Piobbico core, central Italy). *Rivista italiana di paleontologia e stratigrafia* 97, 455-484.
- Erba, E., Castradori, D., Guasti, G., and Ripepe, M., 1992. Calcareous nannofossils and Milankovitch cycles: the example of the Albian Gault Clay Formation (Southern England). *Palaeogeography, Palaeoclimatology, Palaeoecology* 93, 47-69.
- Erba, E., 2004. Calcareous nannofossils and Mesozoic oceanic anoxic events. *Marine Micropaleontology* 52, 85-106.
- Erbacher, J., Huber, B.T., Norris, R.D., and Markey, M., 2001. Increased thermohaline stratification as a possible cause for an ocean anoxic event in the Cretaceous period. *Nature* 409, 325-327.

- Erbacher, J., Freidrich, O., Wilson, P.A., Birch, H., and Mutterlose, J., 2005. Stable organic carbon isotope stratigraphy across Oceanic Anoxic Event 2 of Demerara Rise, western tropical Atlantic. *Geochemistry, Geophysics, Geosystems* 6 (6), Q06010, 9 p.
- Fisher, C.G., and Arthur, M.A., 2002. Water mass characteristics in the Cenomanian US Western Interior seaway as indicated by stable isotopes of calcareous organisms. *Palaeogeography, Palaeoclimatology, Palaeoecology* 188, 189-213.
- Fisher, C.G., and Hay, W.W., 1999. Calcareous nannofossils as indicators of mid-Cretaceous paleofertility along and ocean front, U.S. Western Interior. In: Barrera, E. and Johnson, C.C., Eds., Evolution of the Cretaceous Ocean-Climate System. *Geological Society of America Special Paper* 332, 161-180.
- Forester, A., Schouten, S., Baas, M., and Sinninghe Damsté, J.S., 2007. Mid-Cretaceous (Albian-Santonian) sea surface temperature record of the tropical Atlantic Ocean. *Geology* 35, 919-922.
- Friedrich, O., Erbacher, J., and Mutterlose, J., 2006. Paleoenvironmental changes across the Cenomanian/Turonian Boundary Event (Oceanic Anoxic Event 2) as indicated by benthic foraminifera from the Demerara Rise (ODP Leg 207). *Revue de micropaleontology* 49, 121-139.
- Frush, M.P., and Eicher, D.L., 1975. Cenomanian and Turonian foraminifera and paleoenvironments in the Big Bend region of Texas and Mexico. In: Caldwell,

- W.G.E., Ed., The Cretaceous System in the Western Interior of North America. *Geological Association of Canada Special Paper 13*, 277-301.
- Gale, A.S., Smith, A.B., Monks, N.E.A., Young, J.A., Howard, J.A., Wray, D.S., and Huggett, J.M., 2000. Marine biodiversity through the Late Cenomanian-Early Turonian: palaeoceanographic controls and sequence stratigraphic biases. *Journal of the Geological Society, London* 157, 745-757.
- Geisen, M., Bollman, J., Herrle, J.O., Mutterlose, J. and Young, J.R., 1999. Calibration of the random settling technique for calculation of absolute abundances of calcareous nannoplankton. *Micropaleontology* 45, 437-442.
- Goldhammer, R.K., and Johnson, C.A., 2002. Middle Jurassic-Upper Cretaceous Paleogeographic Evolution and Sequence-stratigraphic Framework of the Northwest Gulf of Mexico Rim. In: Bartolini, C., Buffer, R.T., and Cantú-Chapa, A., (Eds.), The western Gulf of Mexico Basin: Tectonics, sedimentary basins, and petroleum systems. *AAPG Memoir 75*, 45-81.
- Grabowski, G.J., 1995. Organic-rich chalks and calcareous mudstones of the Austin Chalk and Eagleford Formation, south-central Texas, USA. In: Katz, B.J., (Ed.), *Petroleum Source Rocks*. Springer-Verlag, Berlin, 205–234.
- Hancock, J.M., and Walaszczyk, I., 2004. Mid-Turonian to Coniacian changes of sea level around Dallas, Texas. *Cretaceous Research* 25, 459-471.

- Hardas, P., and Mutterlose, J., 2006. Calcareous nannofossil biostratigraphy of the Cenomanian/Turonian boundary interval of ODP Leg 207 at the Demerara Rise. *Revue de micropaleontology* 49, 165-179.
- 2007. Calcareous nannofossil assemblages of Oceanic Anoxic Event 2 in the equatorial Atlantic: Evidence of an eutrophication event. *Marine Micropaleontology* 66, 52-69.
- Hattin, D.E., 1975. Stratigraphy and Depositional Environment of Greenhorn Limestone (Upper Cretaceous) of Kansas. *Kansas Geological Survey Bulletin* 209, 128 p.
- Hattin, D.E., 1985. Distribution and Significance of Widespread, Time-Parallel Pelagic Limestone Beds in the Greenhorn Limestone (Upper Cretaceous) of the Central Great Plains and Southern Rocky Mountains. In: Pratt, L.M. , Kauffman, E.G., and Zelt, F.B., (Eds.), *Fine-Grained Deposits and Biofacies of the Cretaceous Western Interior Seaway: Evidence of Cyclic Sedimentary Processes, SEPM Field Trip Guidebook No. 4*, 28-37.
- Herrle, J.O., 2002. Mid-Cretaceous paleoceanographic and paleoclimatic implications on black shale formation of the Vocontian Basin and Atlantic: Evidence from calcareous nannofossils and stable isotopes. *Tübinger Mikropaläont Mitt* 15, 181 p.
- Herrle, J.O., 2003. Reconstructing nutricline dynamics of mid-Cretaceous oceans: evidence from calcareous nannofossils from the Niveau Paquier black shale (SE France). *Marine Micropaleontology* 47, 307-321.

- Hetzl, A., Böttcher, M.E., Wortmann, U.G., and Brumsack, H.-J., 2009. Paleo-redox conditions during OAE2 reflected in Demerara Rise sediment geochemistry (ODP Leg 207). *Palaeogeography, Palaeoclimatology, Palaeoecology* 273, 302-328.
- Hill, M.E., 1975. Selective dissolution of mid-Cretaceous (Cenomanian) calcareous nannofossils. *Micropaleontology* 21 (2), 227-235.
- Huber, B.T., Leckie, R.M., Norris, R.D., Bralower, T.J., and CoBabe, E., 1999. Foraminiferal assemblage and stable isotopic change across the Cenomanian-Turonian boundary in the subtropical North Atlantic. *Journal of Foraminiferal Research*, 29, 392-417.
- Jarvis, I., Gale, A.S., Jenkyns, H.C., and Pearce, M.A., 2006. Secular variation in Late Cretaceous carbon isotopes: a new  $\delta^{13}\text{C}$  carbonate reference curve for the Cenomanian-Campanian (99.6-70.6 Ma). *Geological Magazine* 143 (5), 561-608.
- Jarvis, I., Lignum, J.S., Gröcke, D.R., Jenkyns, H.C., and Pearce, M.A., 2011. Black shale deposition, atmospheric CO<sub>2</sub> drawdown, and cooling during the Cenomanian-Turonian Oceanic Anoxic Event. *Paleoceanography* 26 (PA3201), 17 p.
- Jenkyns, H.C., 1980. Cretaceous anoxic events: from continents to oceans. *Journal of the Geological Society, London* 137, 171-188.
- Jenkyns, H.C., 2010. Geochemistry of oceanic anoxic events. *Geochemistry, Geophysics, Geosystems* 11, Q03003.

- Jiang, M.-J., 1989. Biostratigraphy and geochronology of the Eagle Ford shale, Austin chalk, and lower Taylor marl in Texas based on calcareous nannofossils. (Volumes I and II). *Texas A&M University Dissertation*, 496 p.
- Jones, C., and Jenkyns, H.C., 2001. Seawater Strontium Isotopes, Oceanic Anoxic Events, and Seafloor Hydrothermal Activity in the Jurassic and Cretaceous. *American Journal of Science* 301, 112-149.
- Kauffman, E.G., 1985. Depositional History of the Graneros Shale (Cenomanian), Rock Canyon Anticline. In: Pratt, L.M., Kauffman, E.G., Zelt, F.B., (Eds.), *Fine-grained Deposits and Biofacies of the Cretaceous Western Interior Seaway: Evidence of Cyclic Sedimentary Processes: SEPM Field Trip Guidebook No. 4*, 90-99.
- Keller, G., Han, Q., Adatte, T., and Burns, S.J., 2001. Palaeoenvironment of the Cenomanian-Turonian transition at Eastbourne, England. *Cretaceous Research* 22, 391-422.
- Kerr, A.C., 1998. Oceanic plateau formation: a cause of mass extinction and black shale deposition around the Cenomanian-Turonian boundary? *Journal of the Geological Society, London* 155, 619-626.
- Kolonic, S., Wagner, T., Forster, A., Sinninghe Damsté, J.S., Walsworth-Bell, B., Erba, E., Turgeon, S., Brumsack, H.-J., Chellai, E.H., Tsikos, H., Kuhnt, W., and Kuypers, M.M.M., 2005. Black shale deposition on the northwest African Shelf

during the Cenomanian/Turonian oceanic anoxic event: Climate coupling and global organic carbon burial. *Paleoceanography* 20, PA1006, 18 p.

Kuroda, J., Ogawa, N.O., Tanimizu, M., Coffin, M.F., Tokuyama, H., Kitazato, H., and Ohkouchi, N., 2007. Contemporaneous massive subaerial volcanism and Late Cretaceous Oceanic Anoxic Event 2. *Earth and Planetary Science Letters* 256, 211-223.

Leckie, R.M., 1985. Foraminifera of the Cenomanian-Turonian Boundary Interval, Greenhorn Formation, Rock Canyon Anticline, Pueblo, Colorado. In: Pratt, L.M., Kauffman, E.G., Zelt, F.B., (Eds.), *Fine-grained Deposits and Biofacies of the Cretaceous Western Interior Seaway: Evidence of Cyclic Sedimentary Processes: SEPM Field Trip Guidebook No. 4*, 139-149.

Leckie, R.M., Kirkland, J.I., and Elder, W.P., 1997. Stratigraphic Framework and Correlation of a Principal Reference Section of the Mancos Shale (Upper Cretaceous), Mesa Verde, Colorado. *New Mexico Geological Society Guidebook, 48<sup>th</sup> Field Conference, Mesozoic Geology and Paleontology of the Four Corners Region*, 163-216

Leckie, R.M., Yuretich, R.F., West, O.L.O., Finkelstein, D., and Schmidt, M., 1998. Paleooceanography of the Southwestern Western Interior Sea During the Time of the Cenomanian-Turonian Boundary (Late Cretaceous). In: Dean, W.E., and Arthur, M.A., (Eds.), *Stratigraphy and Paleoenvironments of the Cretaceous*

Western Interior Seaway, USA. *SEPM Concepts in Sedimentology and Paleontology* No. 6, 101-126.

Leckie, R.M., Bralower, T.J., and Cashman, R., 2002. Oceanic anoxic events and plankton evolution: Biotic response to tectonic forcing during the mid-Cretaceous. *Paleoceanography* 17 (3), 1-29.

Linnert, C., Mutterlose, J. and Erbacher, J., 2010. Calcareous nannofossils of the Cenomanian/Turonian boundary interval from the Boreal Realm (Wunstorf, northwest Germany). *Marine Micropaleontology* 74, 38-58.

Linnert, C., Mutterlose, J., and Mortimore, R., 2011a. Calcareous nannofossils from Eastbourne (Southeastern England) and the Paleooceanography of the Cenomanian-Turonian boundary interval. *Palaios* 26, 298-313.

Linnert, C., Mutterlose, J., Herrle, J.O., 2011b. Late Cretaceous (Cenomanian-Maastrichtian) calcareous nannofossils from Goban Spur (DSDP Sites 549, 551): Implications for the palaeoceanography of the proto North Atlantic. *Palaeogeography, Palaeoclimatology, Palaeoecology* 299, 507-528.

Lowery, C.M., Corbett, M.J., Leckie, R.M., Watkins, D.K., Staerker, T.S., Donovan, A., submitted, Foraminiferal Evidence of Paleooceanographic Transitions in the Cenomanian-Turonian Eagle Ford Shale Across Southern Texas.

- Mattioli, E., 1997. Nannoplankton productivity and diagenesis in the rhythmically bedded Toarcian-Aalenian Fiuminata section (Umbria-Marche Apennine, central Italy). *Palaeogeography, Palaeoclimatology, Palaeoecology*, 130, 113-133.
- Melinte-Dobrinescu, M.C., and Bojar, A.-V., 2008. Biostratigraphic and isotopic record of the Cenomanian-Turonian deposits in the Ohaba-Ponor section (SW Hațeg, Romania). *Cretaceous Research* 29, 1024-1034.
- Meyers, S.R., Sageman, B.B., and Hinnov, L.A., 2001. Integrated Quantitative Stratigraphy of the Cenomanian-Turonian Bridge Creek Limestone Member Using Evolutive Harmonic Analysis and Stratigraphic Modeling. *Journal of Sedimentary research* 71 (4), 628-644.
- Meyers, S.R., Sageman, B.B., Arthur, M.A., 2012. Obliquity forcing of organic matter accumulation during Oceanic Anoxic Event 2. *Paleoceanography* 27, PA3212, 19 p.
- Miller, K.G., Kominz, M.A., Browning, J.V., Wright, J.D., Mountain, G.S., Katz, M.E., Sugarman, P.J., Cramer, B.S., Christie-Blick, N., and Pekar, S.F., 2005. *The Phanerozoic Record of Sea-Level Change*. *Science* 310, 1293-1298.
- Norris, R.D., Bice, K.L., Magno, E. A., and Wilson, P.A., 2002. Jiggling the tropical thermostat in the Cretaceous hothouse. *Geology* 30 (4), 299-302.
- Ocean Drilling Stratigraphic Network (ODSN), 2011. Plate Tectonic Reconstruction Service, <http://www.odsn.de/odsn/services/paleomap/paleomap.html>.

- Ogg, J.G., and Hinnov, L.A. (contributions by C. Huang), 2012. Cretaceous. In:  
Gradstein, F.M., Ogg, J.G., Schmitz, M., and Ogg, G., (Eds.) *The Geologic Time  
Scale 2012*. Elsevier, Amsterdam.
- Parente, M., Frijia, G., Lucia, M.D., Jenkyns, H.C., Woodfine, R.G., and Baroncini, F.,  
2008. Stepwise extinction of larger foraminifers at the Cenomanian-Turonian  
boundary: A shallow-water perspective on nutrient fluctuations during Oceanic  
Anoxic Event 2 (Bonarelli Event). *Geology* 36 (9), 715-718.
- Perch-Nielsen, K., 1985. Mesozoic calcareous nannofossils. In: H.M. Bolli, J.B. Saunders,  
K. Perch-Nielsen, (Eds.), *Plankton Stratigraphy* 1, 329-426.
- Pessagno, E. A., 1967, Upper Cretaceous Foraminifera from the Western Gulf Coastal  
Plain, *Paleontographica Americana* 5 (37), 245-445.
- Pratt, L.M., and Threlkeld, C.N., 1984. Stratigraphic significance of  $^{12}\text{C}/^{13}\text{C}$  ratios in  
mid-Cretaceous rocks of the Western Interior, U.S.A. In: Stott, D.F., and Glass,  
D.J., eds., *The Mesozoic of middle North America: Canadian Society of  
Petroleum Geology* 9, 305-312.
- Premoli Silva, I., Erba, E., and Tornaghi, M.E., 1989. Paleoenvironmental signals and  
changes in surface fertility in Mid-Cretaceous Corg-rich pelagic facies of the  
Furoid Marls (central Italy). *Geobios, Mémoires Spécial* 11, 225-236.

- Roth, P.H., 1981. Mid-Cretaceous calcareous nannoplankton from the central Pacific: implication for paleoceanography. In: Thiede, J., Vallier, T.L., et al., *Initial Reports, DSDP 62*, 471-489.
- Roth, P.H., 1986. Mesozoic palaeoceanography of the North Atlantic and Tethys Ocean. In: Summerhayes, C.P., and Shackleton, N.J., (Eds.), North Atlantic Palaeoceanography, *Geological Society Special Publication, London 21*, 299-320.
- Roth, P.H., 1989. Ocean circulation and calcareous nannoplankton evolution during the Jurassic and cretaceous. *Palaeogeography, Palaeoclimatology, Palaeoecology 74*, 111-126.
- Roth, P.H., and Bowdler, J.L., 1981. Middle Cretaceous Nannoplankton biogeography and oceanography of the Atlantic Ocean. In: J.E. Warme, R.G. Douglas, and E.I. Winterer, (Eds.), The Deep Sea Drilling Project: A Decade of Progress. *SEPM Special Publication 32*, 517-546.
- Roth, P.H., and Krumbach, K.R., 1986. Middle Cretaceous calcareous nannofossil biogeography and preservation in the Atlantic and Indian Oceans: implications for paleoceanography. *Marine Micropaleontology 10*, 235-266.
- Sageman, B.B., 1985. High-Resolution Stratigraphy and Paleobiology of the Hartland Shale Member: Analysis of an Oxygen-Deficient Epicontinental Sea. In: Pratt, L.M., Kauffman, E.G., Zelt, F.B., (Eds.), *Fine-grained Deposits and Biofacies of the Cretaceous Western Interior Seaway: Evidence of Cyclic Sedimentary Processes: SEPM Field Trip Guidebook No. 4*, 110-121.

- Sageman, B.B., Meyers, S.R., and Arthur, M.A., 2006. Orbital time scale and new C-isotope record for Cenomanian-Turonian boundary stratotype. *Geology* 34 (2), 125-128.
- Samtleben, C., Schäfer, P., Andruleit, H., Baumann, A., Baumann, K.-H., Kohly, A., Matthiessen, J., Schröder-Ritzrau, and “Synpal” Working Group, 1995. Plankton in the Norwegian-Greenland Sea: from living communities to sediment assemblages – an actualistic approach. *International Journal of Earth Sciences (Geologische Rundschau)* 84 (1), 108-136.
- Schlanger, S.O., and Jenkyns, H.C., 1976. Cretaceous Oceanic Anoxic Events: Causes and Consequences. *Geologie en Mijnbouw* 55 (3-4), 179-184.
- Scott, R.W., Franks, P.C., Evetts, M.J., Bergen, J.A., and Stein, J.A., 1998. Timing of Mid-Cretaceous Relative Sea Level Changes in the Western Interior: Amoco No. 1 Bounds Core. In: Dean, W.E., and Arthur, M.A., (Eds.), Stratigraphy and Paleoenvironments of the Cretaceous Western Interior Seaway, USA. *SEPM Concepts in Sedimentology and Paleontology No. 6*, 11-34.
- Sinninghe Damsté, J.S., van Bentum, E.C., Reichart, G.-J., Pross, J., and Schouten, S., 2010. A CO<sub>2</sub> decrease-driven cooling and increased latitudinal temperature gradient during the mid-Cretaceous Oceanic Anoxic Event 2. *Earth and Planetary Science Letters* 293, 97-103.

- Slingerland, R., Kump, L.R., Arthur, M.A., Fawcett, P.J., Sageman, B.B., and Barron, E.J., 1996. Estuarine circulation in the Turonian Western Interior seaway. *GSA Bulletin* 108 (7), 941-952.
- Smith, C.C., 1981. Calcareous Nannoplankton and Stratigraphy of Late Turonian, Coniacian, and early Santonian Age of the Eagle Ford and Austin Groups of Texas. *Geological Survey Professional Paper 1075*, 98 p.
- Snow, L.J., and Duncan, R.A., 2005. Trace element abundances in the Rock Canyon Anticline, Pueblo, Colorado, marine sedimentary section and their relationship to Caribbean plateau construction and oxygen anoxic event 2. *Paleoceanography* 20, PA3005, 14 p.
- Styzen, M.J., 1997. Cascading counts of nannofossil abundance. *Journal of Nannoplankton Research* 19 (1), 49.
- Takashima, R., Nishi, H., Hayashi, K., Okada, H., Kawahata, H., Yamanaka, T., Fernando, A.G., and Mampuku, M., 2009. Litho-, bio- and chemostratigraphy across the Cenomanian-Turonian boundary (OAE2) in the Vocontian Basin of southeastern France. *Palaeogeography, Palaeoclimatology, Palaeoecology* 272, 61-74.
- Tantawy, A.A., 2008. Calcareous nannofossil biostratigraphy and paleoecology of the Cenomanian-Turonian transition in the Tarfaya Basin, southern Morocco. *Cretaceous Research* 29, 995-1007.

- Thierstein, H.R., 1981. Late Cretaceous nannoplankton and the change at the Cretaceous-Tertiary boundary. In: Warme, J.E., Douglas, R.G., and Winterer, E.I., Eds. The Deep Sea Drilling Project: A Decade of Progress. *SEPM Special Publication 32*, 355-394.
- Tsikos, H., Jenkyns, H.C., Walsworth-Bell, B., Petrizzo, M.R., Forster, A., Kolonic, S., Erba, E., Premoli Silva, I., Baas, M., and Wagner, T., 2004. Carbon-isotope stratigraphy recorded by the Cenomanian-Turonian Oceanic Anoxic Event: correlation and implications based on three key localities. *Journal of the Geological Society, London* 161, 711-719.
- Turgeon, S.C., and Creaser, R.A., 2008. Cretaceous oceanic anoxic event 2 triggered by massive magmatic episode. *Nature* 454, 323-326.
- Voigt, S., Erbacher, J., Mutterlose, J., Weiss, W., Westerhold, T., Wiese, F., Wilmsen, M., and Wonik, T., 2008. The Cenomanian-Turonian of the Wunstorf section (North Germany): global stratigraphic reference section and new orbital time scale for Oceanic Anoxic Event 2. *Newsletters on Stratigraphy* 43 (1), 65-89.
- Watkins, D.K., 1986. Calcareous nannofossil paleoceanography of the Cretaceous Greenhorn Sea. *GSA Bulletin* 97, 1239-1249.
- Watkins, D.K., 1989. Nannoplankton productivity fluctuations and rhythmically-bedded pelagic carbonates of the Greenhorn Limestone (upper Cretaceous). *Palaeogeography, Palaeoclimatology, Palaeoecology* 74, 75-86.

- Watkins, D.K. and Bergen, J.A., 2003. Late Albian adaptive radiation in the calcareous nannofossil genus *Eiffellithus*. *Micropaleontology* 49, 231-252.
- Watkins, D.K., Cooper, M.J., and Wilson, P.A., 2005. Calcareous nannoplankton response to the late Albian oceanic anoxic event 1d in the western North Atlantic. *Paleoceanography* 20, PA2010, 14 p.
- West, O.L.O., Leckie, R.M., and Schmidt, M., 1998. Foraminiferal Paleoecology and Paleoceanography of the Greenhorn Cycle Along the Southwestern Margin of the Western Interior Sea. In: Dean, W.E. and Arthur, M.A. Stratigraphy and Paleoenvironments of the Cretaceous Western Interior Seaway. *SEPM Concepts in Sedimentology and Paleontology No. 6*, 79-99.
- Wignall, P.B., 2001. Large igneous provinces and mass extinctions. *Earth-Science Reviews* 53, 1-33.
- Williams, J.R., and Bralower, T.J., 1995. Nannofossil assemblages, fine fraction stable isotopes, and the paleoceanography of the Valanginian-Barremian (Early Cretaceous) North Sea Basin. *Paleoceanography* 10 (4), 815-839.
- Wilson, P.A., and Norris, R.D., 2001. Warm tropical ocean surface and global anoxia during the mid-Cretaceous period. *Nature* 412, 425-429.
- Young, J.R., Geisen, M., and Probert, I., 2005. A Review of Selected Aspects of Coccolithophore Biology with Implications for the Paleodiversity Estimation. *Micropaleontology* 51 (4), 267-288.

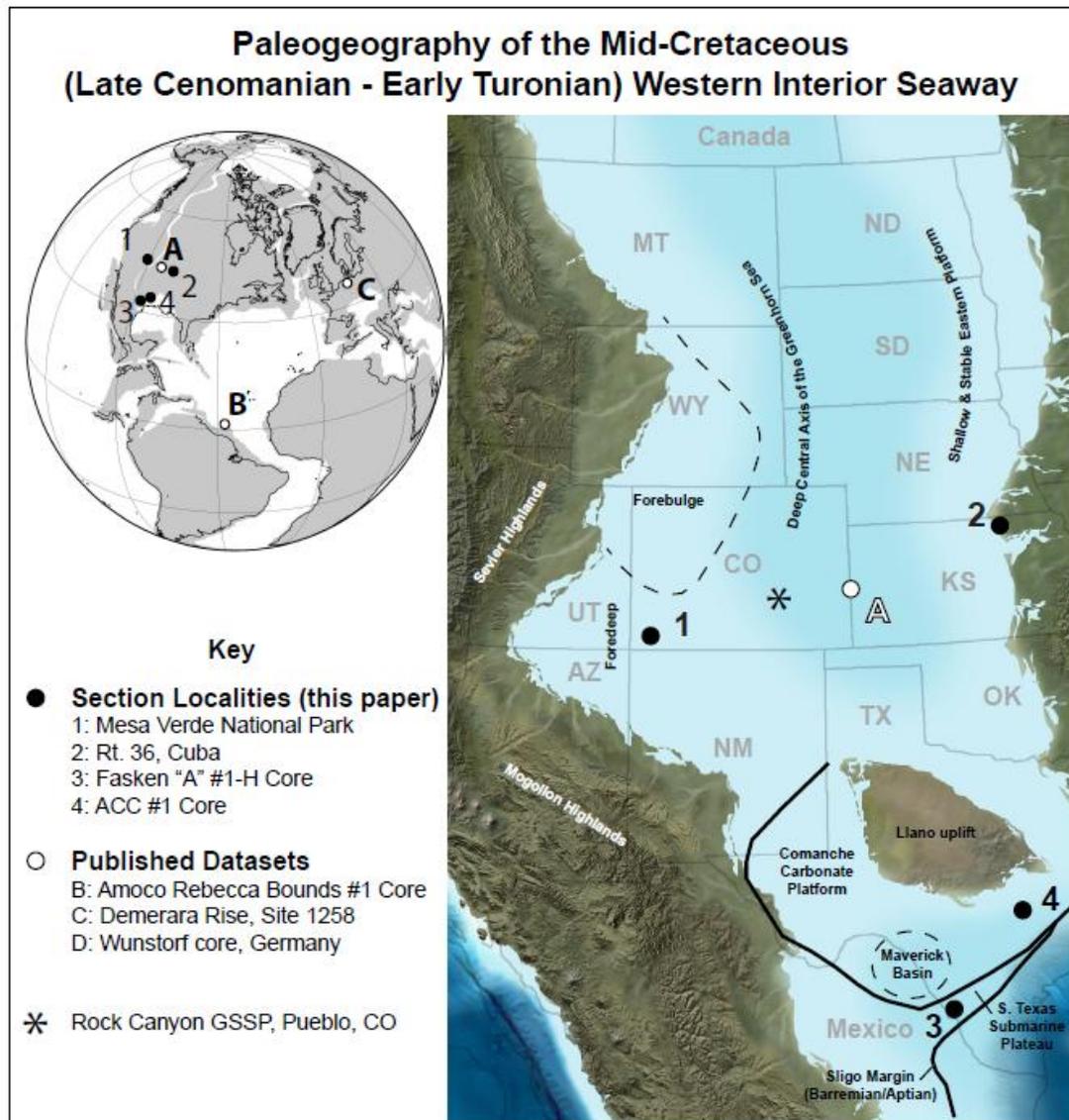


Figure 1

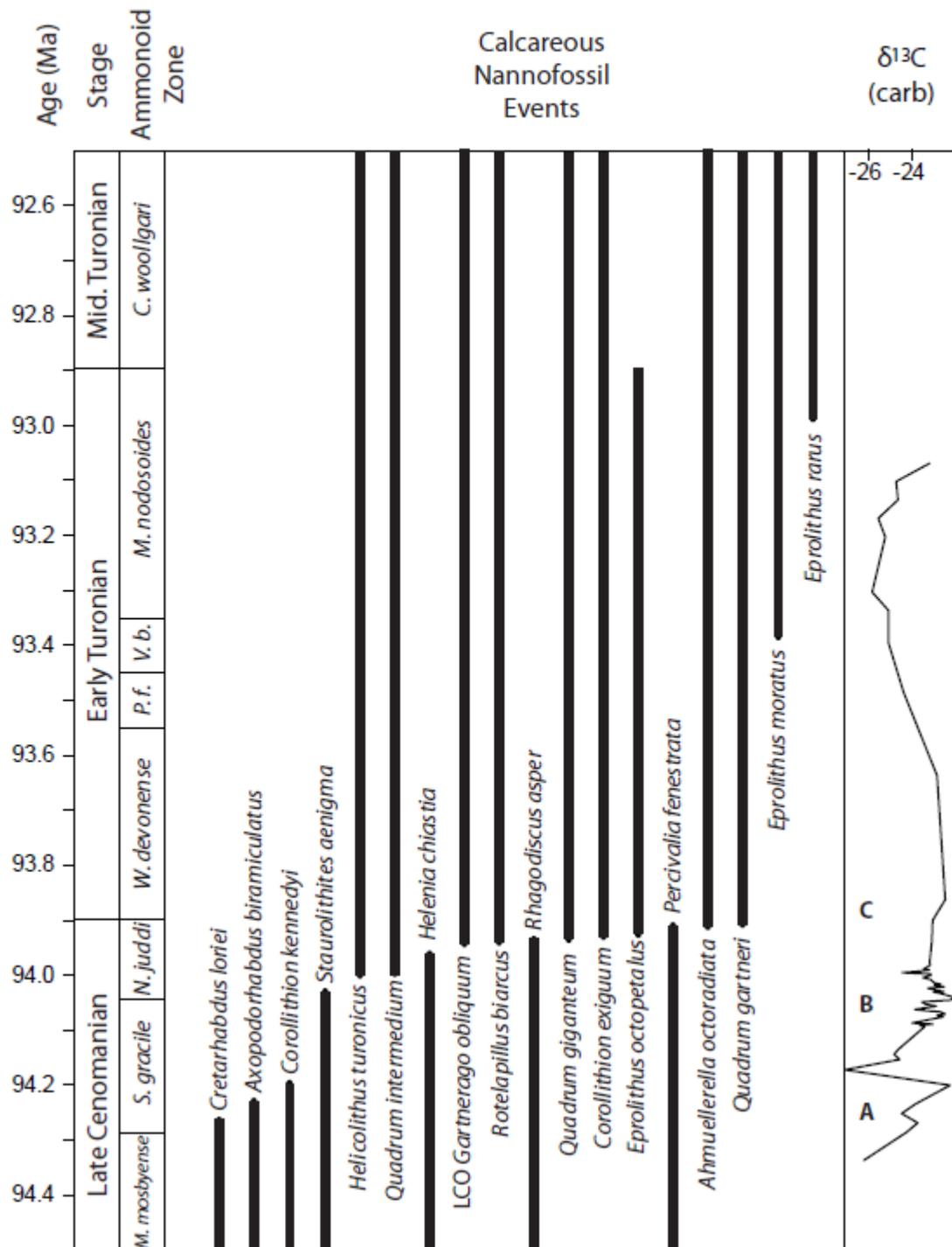


Figure 2

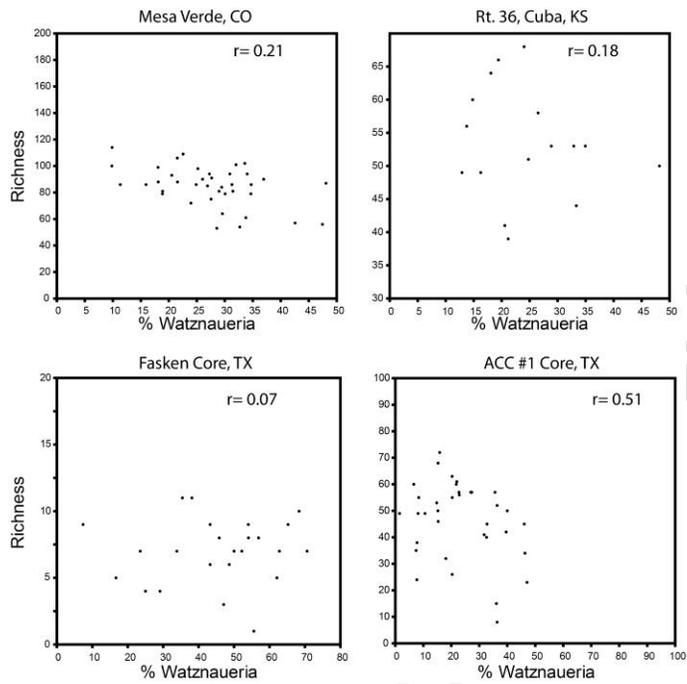


Figure 3

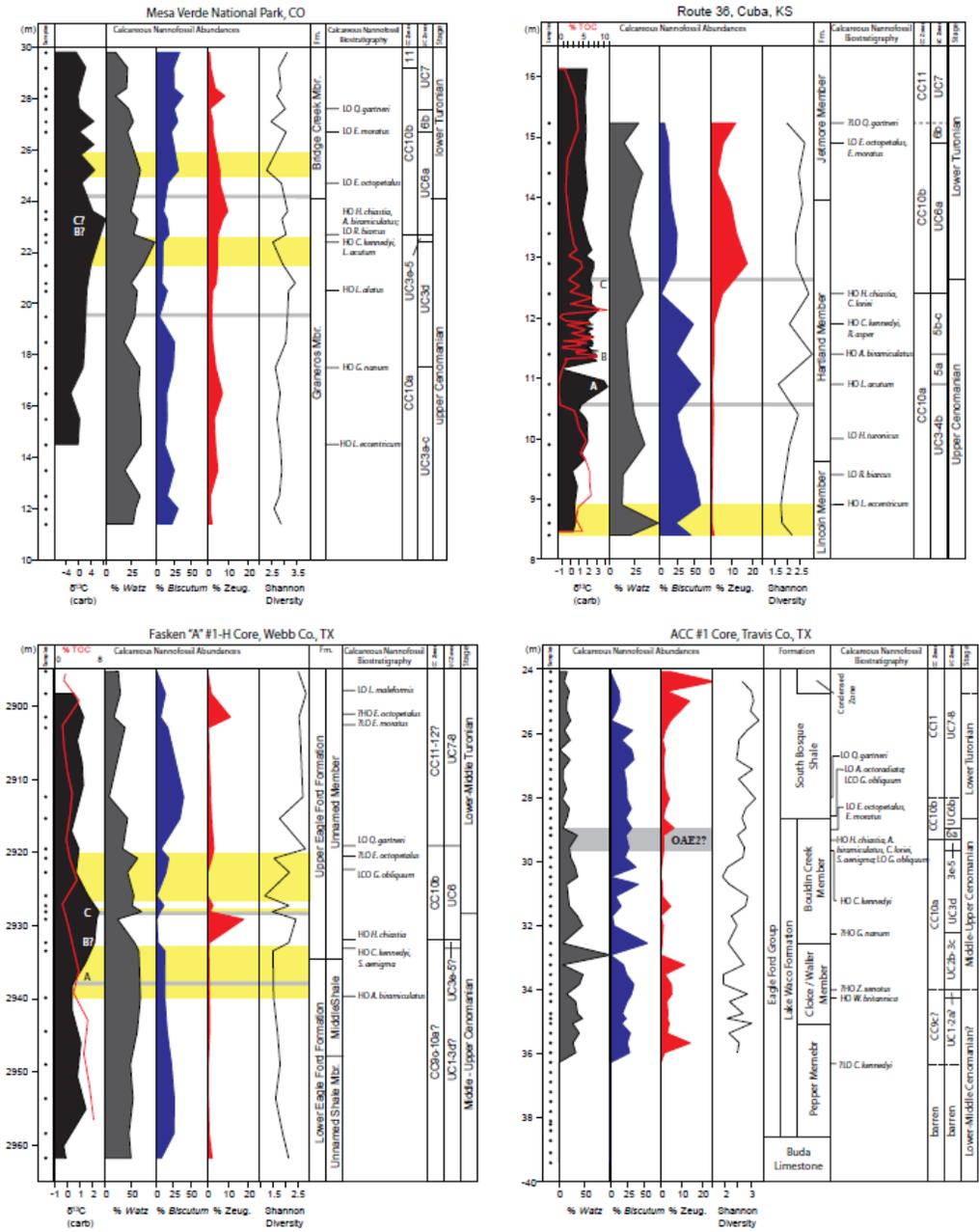


Figure 4

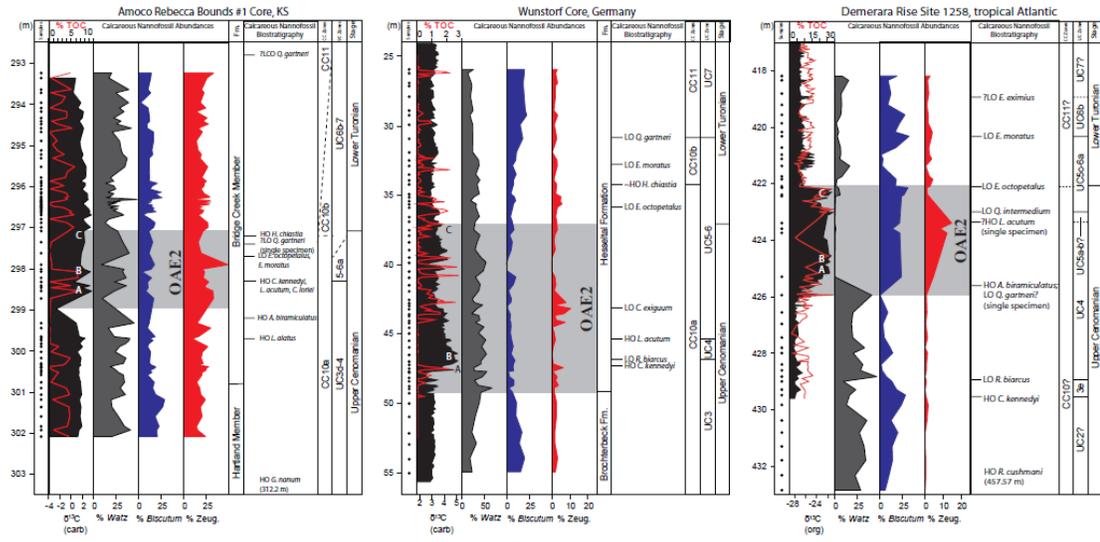


Figure 5

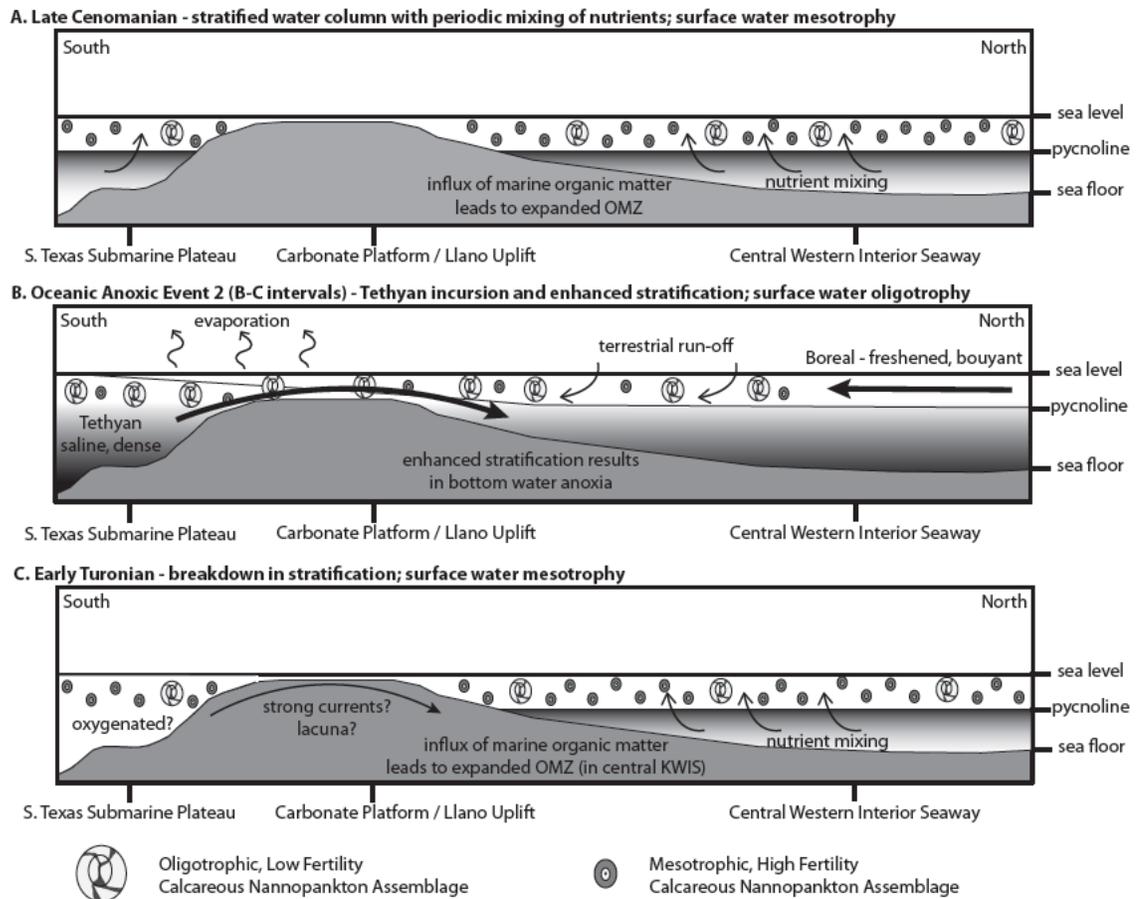


Figure 6

**Figure 1:**

Paleogeographic reconstruction of the Late Cenomanian-Early Turonian OAE2 period showing the location of materials used in this study (black points) and sites from previously published datasets (white points). Paleooceanographic features from the central and southern regions of the seaway are reconstructed from Leckie et al. (1998) and Donovan et al. (2012), respectively (Modified from Blakey, 2012). Black outlines in inset map indicate position of the modern shoreline (Created with the ODSN Plate Tectonic Reconstruction Service, 2011).

**Figure 2:**

An idealized bio-chemostratigraphic framework for OAE2 summarizing the relationship of the Late Cenomanian-Early Turonian quantitatively derived optimum sequence of nannofossil biostratigraphic events from Corbett et al. (in review) with carbon isotope values (Bowman and Bralower 2005) and macrofossil zonations (Kennedy et al. 2005) from the Rock Canyon Anticline near Pueblo, CO. Spacing on an absolute timescale is based on the age model from the 2012 Geologic Timescale (Ogg and Hinnov 2012).

**Figure 3:**

Plots of the percent relative abundance of the nannofossil species *Watznaueria barnesiae* versus species richness for each of the four sites analyzed in this paper. There is no negative correlation between richness and greater % *Watznaueria*, suggesting nannofossil populations are not biased by preservational effects.

**Figure 4:**

Carbon isotope records and total organic carbon (TOC) plotted against calcareous nannofossil biostratigraphy, Shannon Diversity, and relative abundance of key taxa used to interpret fertility of the surface waters for sites analyzed in the Western Interior Basin. *Watznaueria* are generally dominant during periods of oligotrophy, while *Biscutum* and *Zeugrhabdotus* are believed to thrive in meso-eutrophic conditions (see text 2.2 for discussion). The interval from the beginning of OAE2 to the base of the Turonian is bracketed by the grey lines and indicated by a carbon isotope excursion (except for the ACC #1 core). The A, B, and C intervals of the carbon isotope excursion as defined by Pratt and Threlkeld (1984) are labeled alongside  $\delta^{13}\text{C}$  values. Yellow shaded intervals indicate periods where low diversity corresponds to higher abundance of *Watznaueria*, suggesting a diagenetic signal within the assemblage. Carbon isotopes and TOC for Cuba from Bowman and Bralower (2005), for the Fasken core from Donovan et al. (2012), and for Mesa Verde from Corbett and Watkins (submitted b). Biostratigraphy from Corbett and Watkins (in review) and Corbett et al. (in review).

**Figure 5:**

Carbon isotope records and total organic carbon (TOC) plotted against calcareous nannofossil biostratigraphy and relative abundance of key taxa used to interpret paleoecology of the surface waters for sites from previously published datasets. The OAE2 interval is highlighted by the grey bar and A, B, and C intervals of the carbon isotope excursion as defined by Pratt and Threlkeld (1984) are labeled alongside  $\delta^{13}\text{C}$  values.. Carbon isotopes and TOC for the Bounds core from Dean and Arthur (1998), for Demerara Rise Site 1258 from Erbacher et al. (2005), and for the Wunstorf core from

Voight et al. (2008). Calcareous nannofossil biostratigraphy and assemblage data for these sites from Burns and Bralower (1998) and Bralower and Bergen (1998), Hardas and Mutterlose (2006, 2007), and Linnert et al. (2010), respectively. Nannofossil zonations have been modified based on the author's interpretations.

**Figure 6:**

Model of calcareous nannofossil surface water fertility and paleoceanographic conditions across the southern to central Western Interior Seaway during the Late Cenomanian through Early Turonian: A. Late Cenomanian, B. OAE2 (Latest Cenomanian – Earliest Turonian), C. Early Turonian. Diagrams not to scale. Discussed in text (6.-7.).

**Highlights**

Nannofossils in Cretaceous Western Interior compared to other global sites

*Watznaueria*, *Biscutum*, and *Zeugrhabdotus* % abundance reveal surface water fertility

Conditions are mesotrophic before and after, but oligotrophic during, OAE2

Implies productivity was less important to anoxia/organic carbon burial during OAE2

Salinity stratification, not productivity, likely controlled bottom water anoxia