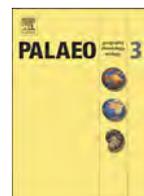




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## Paleoenvironmental and paleoceanographic changes across the Cenomanian–Turonian Boundary Event (Oceanic Anoxic Event 2) as indicated by foraminiferal assemblages from the eastern margin of the Cretaceous Western Interior Sea

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## ARTICLE INFO

## Article history:

Received 28 June 2013

Received in revised form 30 June 2014

Accepted 2 July 2014

Available online xxx

## Keywords:

Cretaceous

Oceanic Anoxic Event 2

## ABSTRACT

Two sites near the eastern margin of the Cretaceous Western Interior Sea (WIS) were investigated. The section at Cuba, Kansas (CK) is ~630 km east of the GSSP for the Cenomanian/Turonian boundary at Rock Canyon, Colorado (RC), and the section near Sioux City, Iowa (SCI) is ~315 km northeast of the Cuba site. Surprisingly, planktic foraminifera dominate all the studied samples despite the relative proximity of the sites to the paleo-shoreline and presumed neritic water depths. Such dominance suggests inhospitable benthic environments, and benthic foraminiferal assemblages indicate that seafloor oxygen in the WIS decreased eastward. Therefore, the hypothesis of an influx of freshwater into the WIS from the western margin forming a fresh water cap that diminished eastward is not supported. Benthic foraminifera are scarce in most studied samples and species diversity is low. In the CK section, diversity and abundance increase abruptly in the uppermost Cenomanian Benthonic Zone at the initiation of the  $\delta^{13}\text{C}_{\text{org}}$  positive excursion marking the onset of Oceanic Anoxic Event (OAE 2). In the SCI section, however, the Benthonic Zone is recognized only by presence of *Nodosaria bighornensis* that has a stratigraphic range restricted to this interval; other benthic taxa are very rare or absent. The favorable conditions of the Benthonic Zone were short-lived. While relatively diverse planktic foraminiferal assemblages, including keeled species, characterize the initial  $\delta^{13}\text{C}$  excursion at the CK site, dwarfed specimens of *Heterohelix* and *Hedbergella* dominate the assemblages at the more proximal Sioux City site. Furthermore, most of the biostratigraphic events recognized in the basin center RC section can be traced into the CK section, but not into the SCI section, including the *Rotalipora* spp. and *Globigerinelloides bentonensis* extinctions, the *Heterohelix* shift event, and the brief benthic recovery event. Correlation between eastern WIS sites shows that the SCI section is thicker, suggesting a major sediment source to the east. This may explain the inhospitable benthic conditions and development of a 'dead zone' (seasonal hypoxia) analogous to the modern shelf of the northern Gulf of Mexico proximal to active discharge of the Mississippi River. Development of estuarine circulation in the WIS provided the eastern part of the basin with input of calcareous plankton from the south including planktic foraminifera. Foraminiferal assemblages, total organic carbon (TOC), and  $\delta^{13}\text{C}$  data of the studied sections suggest a two-fold history of Greenhorn transgression and OAE 2 development. The initial phase is a global signal characterized by a positive  $\delta^{13}\text{C}$  excursion, low TOC values, and high foraminiferal species diversity. The second phase is characterized by overprinting by local conditions in the WIS, including high fluvial input, relatively high TOC values, and low foraminiferal species diversity. These findings suggest that the eastern margin records unique depositional and biotic environments further revealing the dynamic and complex nature of the WIS and its sedimentary cycles.

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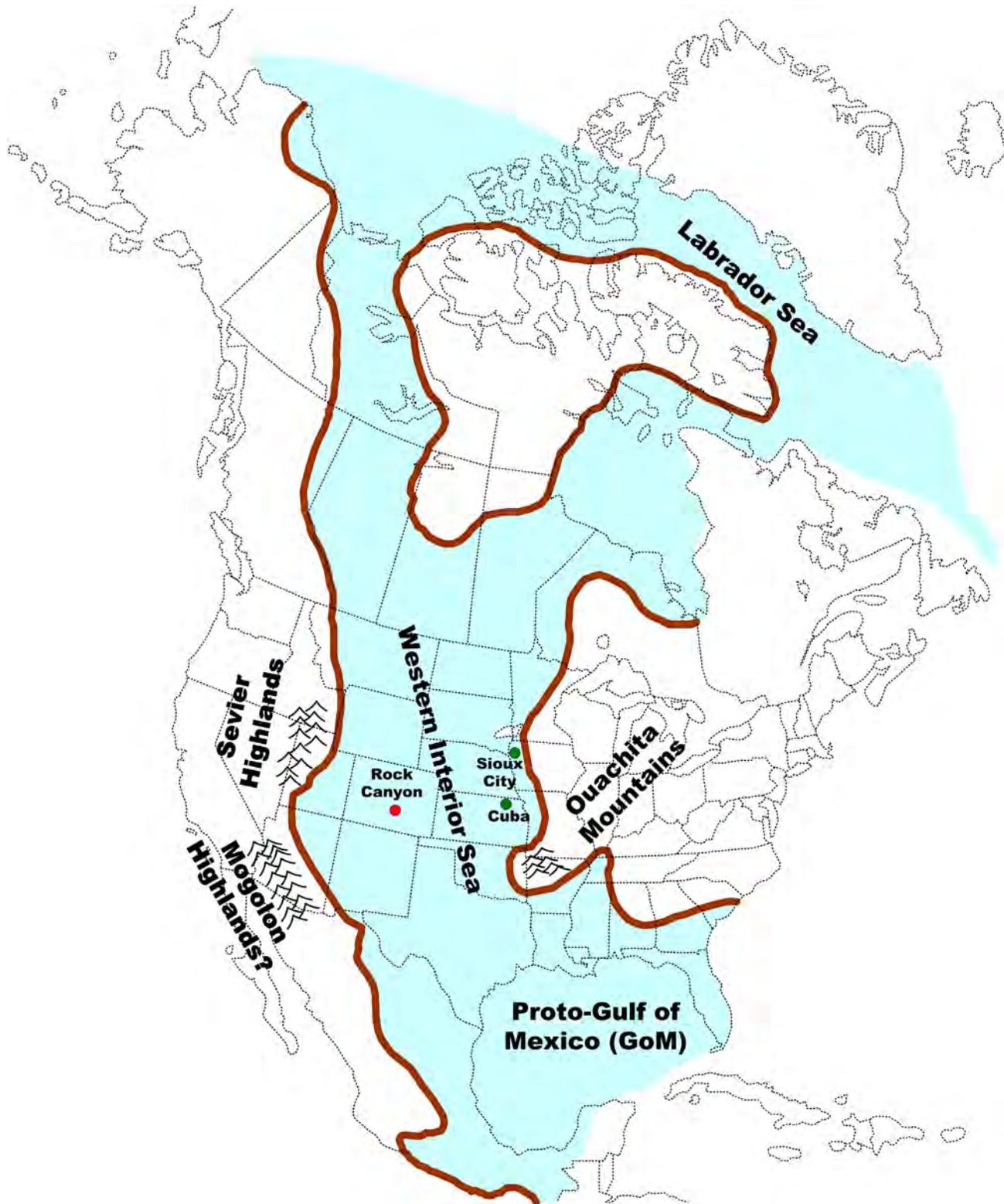
## 1. Introduction

Cretaceous rocks deposited in the Western Interior Sea (WIS) form a wedge of strata that greatly diminishes in thickness eastward from the

foreland basin created by the Sevier Orogeny (Price, 1973; Jordan, 1981; Kauffman, 1988). During the late Cenomanian and early Turonian, the Greenhorn transgression flooded the North American foreland basin to form a relatively shallow seaway (Fig. 1). This allowed for the deposition of rhythmically bedded sequences, including organic-rich strata of the Greenhorn Formation and its equivalents. Planktic and benthic foraminiferal assemblages have been effectively utilized to interpret

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**Fig. 1.** Map of the Western Interior Sea during Greenhorn maximum transgression in the early Turonian connecting the Boreal Sea and the Proto-Gulf of Mexico. The map also shows the position of paleo-shoreline to the studied sections (green circles) and their relative positions to the GSSP section at Rock Canyon (RC), CO (red circle).

Cenomanian–Turonian paleoenvironments and paleoceanography of most parts of the WIS (e.g., Eicher, 1967, 1969; Eicher and Worstell, 1970; Frush and Eicher, 1975; McNeil and Caldwell, 1981; Eicher and Diner, 1985, 1989; Leckie, 1985; Fisher et al., 1994; Leckie et al., 1998; West et al., 1998; Fisher and Arthur, 2002; Fisher, 2003). However, there are few such studies from the eastern part of the WIS.

This study addresses the response of foraminiferal assemblages to ecological perturbations around the time of the Cenomanian/Turonian boundary (C/T) on the eastern side of the WIS and establishes a high-resolution biostratigraphic correlation with the Cenomanian–Turonian Global Stratotype Section and Point (GSSP) at the Rock Canyon (RC) section near Pueblo, Colorado. Furthermore, data of this study provide a

greater understanding of the paleoenvironments and paleoceanographic conditions in the WIS.

### 1.1. Geological setting

The eastern side of the WIS is located on a large, low, and flat extension of the stable craton (Reese, 1957) and for most of the Late Cretaceous was not thought to be an important source of sediment to the basin (Weimer, 1970). Consequently, the uppermost Cenomanian–lower Turonian Greenhorn Limestone on the eastern side of the WIS represents accumulation of carbonate-rich sediment (Hattin, 1975). This stable craton is one-third of the width of the WIS and is characterized by low episodic subsidence rates accompanied by slow accumulation of pelagic carbonate, and fine-grained terrigenous clastics in a neritic marine environment of low energy (Kauffman, 1985, 1988). The sediment accumulation of coarser terrigenous clastic sediment is restricted to nearshore facies of the WIS (Kauffman, 1985).

During the early Cenomanian, fluvial and deltaic sedimentation characterized central Kansas (Hattin, 1967) with a principal transport direction toward the southwest (Franks et al., 1959). Further to the northeast, large fluvial meander–belt systems drained the North American craton west of the Appalachians across Iowa and emptied into the WIS (Ludvigson and Bunker, 1979; Brenner et al., 1981; Whitley and Brenner, 1981; Witzke and Ludvigson, 1982, 1987, 1994, 1996; Munter et al., 1983; Witzke et al., 1983; Ludvigson et al., 1994; Ravn and Witzke, 1994, 1995). During the late Cenomanian Greenhorn sea-level transgression, the shoreline pushed further eastward, diminishing the influence of the cratonic source area and allowing the deposition of fine sediment including marine biogenic carbonates (Fig. 2; Hattin, 1975; Brenner et al., 1981; Witzke and Ludvigson, 1982).

In the central WIS, the continuity and parallelism of a number of limestone and bentonite beds of the Greenhorn Formation, together with molluscan biostratigraphy, have provided a practical tool for cross-basin correlation (e.g., Hattin, 1971, 1975; Elder, 1991; Desmares et al., 2007). However, the number of limestone beds decreases northeastward across Kansas and become thinner, softer and less resistant (Fig. 3; Hattin, 1971). Therefore, stratigraphic correlation between central and eastern margin sections requires integration of multiple proxies.

### 1.2. The C/T boundary Global Stratotype Section and Point (GSSP)

The section at the Rock Canyon Anticline in central Colorado is the Cenomanian/Turonian boundary Global Stratotype Section and Point

(GSSP) and global reference for Oceanic Anoxic Event (OAE) 2 studies (Fig. 4; Kennedy et al., 2005; Sageman et al., 2006). OAE 2 at the Rock Canyon section spans the uppermost part of the Hartland Shale and the lower Bridge Creek Limestone Member of the Greenhorn Formation (Pratt et al., 1985). This marks much of the late transgressive systems tract of the Greenhorn third-order cycle (Kauffman, 1984b, 1985; Kauffman and Caldwell, 1993; Sageman et al., 1997, 1998; West et al., 1998).

The upper subunit of Hartland Shale is composed of fine and evenly laminated black calcareous shale with sparse zones of microburrowed, marly shale (Pratt, 1984; Sageman, 1989). The overlying Bridge Creek limestone is composed of alternating limestone and calcareous shale beds that have been related to Milankovitch cycles (e.g., Gilbert, 1895; Gale, 1995; Kauffman, 1995; Sageman et al., 1997, 1998, 2006; Meyers et al., 2001; Meyers and Sageman, 2004). Four regionally persistent bentonite beds, labeled A–D, are interbedded in the C/T boundary interval (Figs. 3 and 4; Hattin, 1971, 1985; Elder, 1985, 1988; Desmares et al., 2007) and have provided important radiometric age dates (Obradovich and Cobban, 1975; Obradovich, 1993). A minor global stepwise extinction event among macrofauna characterizes OAE 2, forming regional and global bioevent surfaces for correlations (Kauffman, 1984a, 1988; Elder, 1985, 1991; Elder and Kirkland, 1985; Sageman et al., 1997).

Foraminiferal assemblages of the Bridge Creek Member, spanning the C/T boundary interval at the Rock Canyon section, have been studied extensively (Eicher and Worstell, 1970; Eicher and Diner, 1985; Leckie, 1985; Leckie et al., 1998; Desmares et al., 2003; Caron et al., 2006; Elderbak, 2014). Subsequently, a sequence of foraminiferal events has added biostratigraphic significance to the section (Fig. 4). Furthermore, foraminiferal assemblages of the C/T boundary rocks have contributed significantly to our understanding of the paleoclimate, paleoenvironment, and paleoceanography of the WIS during the Greenhorn transgression.

## 2. Materials and methods

A total of 153 samples from two sections (CK and SCI) were analyzed for foraminifera. The 9 m-thick CK outcrop in northeast Kansas is represented by 79 samples, previously washed and provided by Professor Timothy J. Bralower, Penn State University. Sampling procedure and geographical location for this site can be found in Bowman and Bralower (2005) and detailed lithological descriptions are available in Hattin (1975); section No. 6). Weight percent total organic carbon (wt %TOC), percent calcium carbonate (%CaCO<sub>3</sub>), and carbon isotope

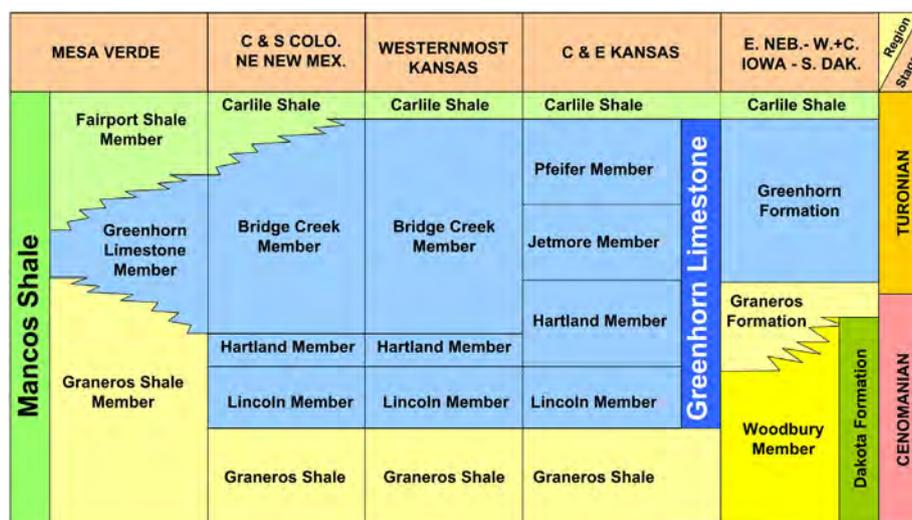


Fig. 2. Stratigraphic nomenclature of Cenomanian–Turonian strata from Mesa Verde National Park on the western side of the seaway to “Tri-State Region” on the eastern margin (modified after Hattin, 1987; Leckie et al., 1997; Brenner et al., 2000).

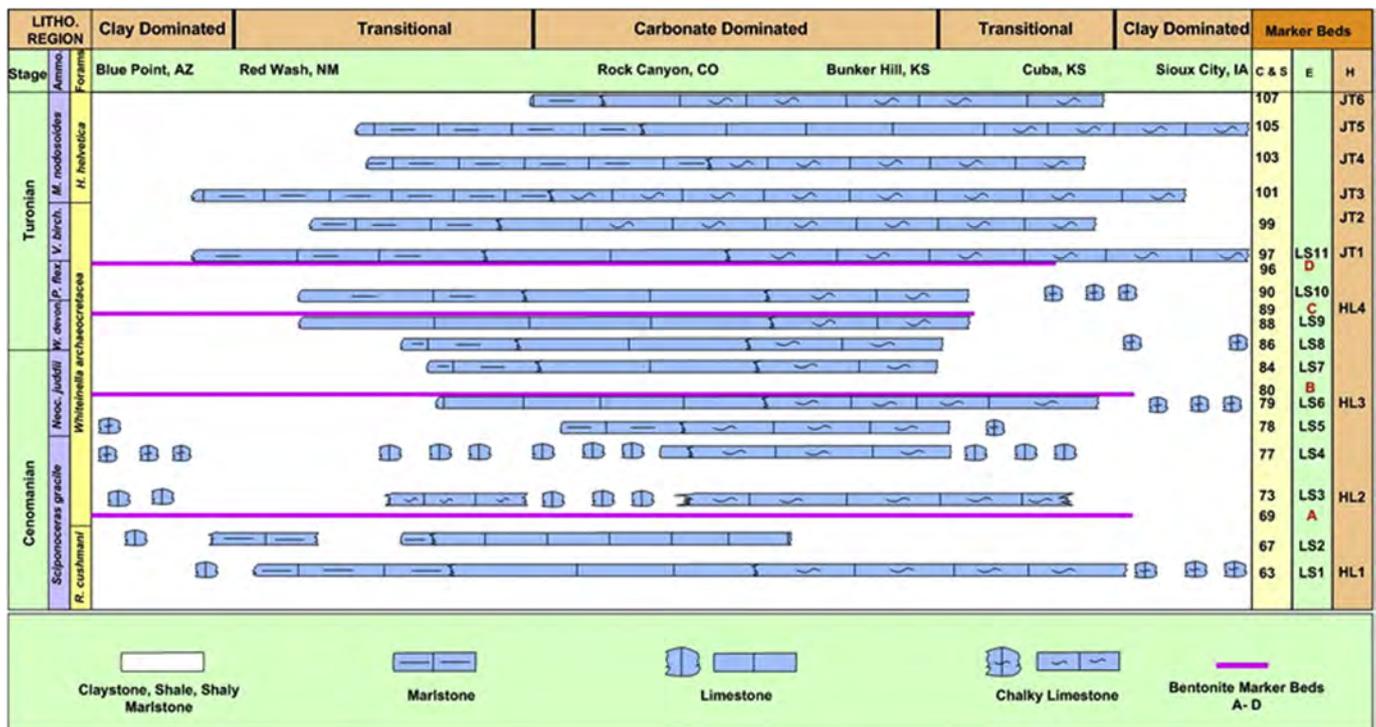


Fig. 3. Transect from Blue Point, Arizona, to Sioux City, Iowa, showing relative stratigraphic placement of limestone and bentonite marker beds (A–D) throughout the Cenomanian–Turonian boundary interval and the geographic distribution of the limestone marker beds and coeval concretion beds in the different lithofacies (LITHO) regions. Numerical numbering of marker beds follow Cobban and Scott, 1972 (C & S), Elder, 1985 (E), and Hattin, 1975 (H). Modified after Elder (1991). The C/T boundary is at the base of Bed 86.

values for both carbonate and organic carbon ( $\delta^{13}\text{C}_{\text{carb}}$  and  $\delta^{13}\text{C}_{\text{org}}$ ) are provided by Bowman and Bralower (2005). Nannofossil data of the upper Cenomanian to lower Turonian strata of the CK section can be found in Watkins (1989), Elson and Bralower (2005), Corbett and Watkins (2013), and Corbett et al. (2014).

The SCI section is located in western Iowa and is exposed on the east side of Highway 12, near the junction with Plymouth County Highway K-18 (Fig. 1). Brenner et al. (1981) provide a detailed description of the lithological and sedimentary features and structures of the 18 m-thick section. The outcrop spans the upper Cenomanian Graneros and lowermost Turonian Greenhorn formations, which are equivalent to the upper Hartland Shale and lower Jetmore Member of the Greenhorn Formation in central and eastern Kansas (Fig. 2; Hattin, 1975; Brenner et al., 2000). Samples were taken every 0.5 m through the lowermost 6 m and uppermost 6 m of the section and every 10 cm in the middle part of the section. A total of 74 samples were washed and sieved following the procedure described by Leckie et al. (1991) and then examined for foraminiferal content.

At least 300 foraminiferal specimens were picked from each sample and a second or third pick sometimes was made on samples with few specimens for population analysis. Miscellaneous components including quartz, fish bone/teeth, pyrite, inoceramid prisms and shell fragments were also counted. Diversity of both planktic and benthic foraminifera was calculated by applying Shannon information function:

$$H(S) = -\sum_{i=1}^S P_i * \ln P_i$$

where  $H(S)$  is diversity;  $S$  is the number of species observed and  $P_i$  the proportion of the  $i$ th species. Foraminiferal test preservation at both sites was moderate to poor and in many cases identification could only be made to the generic level. Taxonomic concepts follow Eicher and Worstell (1970) and Leckie (1985).

### 3. Results

#### 3.1. Planktic foraminifera

##### 3.1.1. Cuba, KS section (CK)

In general, planktic foraminifera are abundant throughout the studied section and dominate the foraminiferal assemblages (Fig. 5). The genus *Heterohelix* dominates the lowermost 1.5 m along with several species of *Hedbergella* and *Whiteinella*. The top of this 1.5 m-thick interval (130–150 cm) is characterized by the first sporadic occurrence of keeled species including *Rotalipora cushmani* and its descendant *Anaticinella planoconvexa*. Throughout this interval, the Shannon–Wiener index ranges from 0.5 to 1.4. Just below the onset of the carbon isotope positive excursion, foraminiferal assemblages are characterized by a brief disappearance of keeled species, an abrupt increase in the proportion of trochospiral morphotypes and first appearance of benthic foraminifera (Fig. 5). Keeled planktic species, including *Praeglobotruncana gibba*, *R. cushmani*, *Rotalipora greenhornensis* and *Anaticinella multiloculata*, as well as planispiral morphotypes *Globigerinelloides bentonensis* and *Globigerinelloides caseyi* appear at the top of this short-lived event. There is also a gradual increase in the Shannon–Wiener index value of planktic foraminifera, with a range from 1.1 to 1.5.

Biserial morphotypes (*Heterohelix*) abruptly become dominant and largely replace trochospiral taxa (mainly, *Hedbergella*) at the positive carbon isotope excursion marking the onset of OAE 2. This influx ended abruptly and diverse assemblages of trochospiral morphotypes (*Hedbergella* and *Whiteinella*) once again dominate the population counts. The highest values of the planktic foraminiferal Shannon–Wiener index characterize this section, with a maximum of 1.7 in bed HL-1 (230 cm). Furthermore, the last occurrences of the planispiral species *Globigerinelloides bentonensis*, as well as rotaliporids (*Rotalipora cushmani* and *Rotalipora greenhornensis*; 220 and 230 cm, respectively) occur in this interval (Fig. 5). Simultaneously, a few double- and single-keeled species (*Dicarinella* and *Praeglobotruncana*) appear, while *Anaticinella*

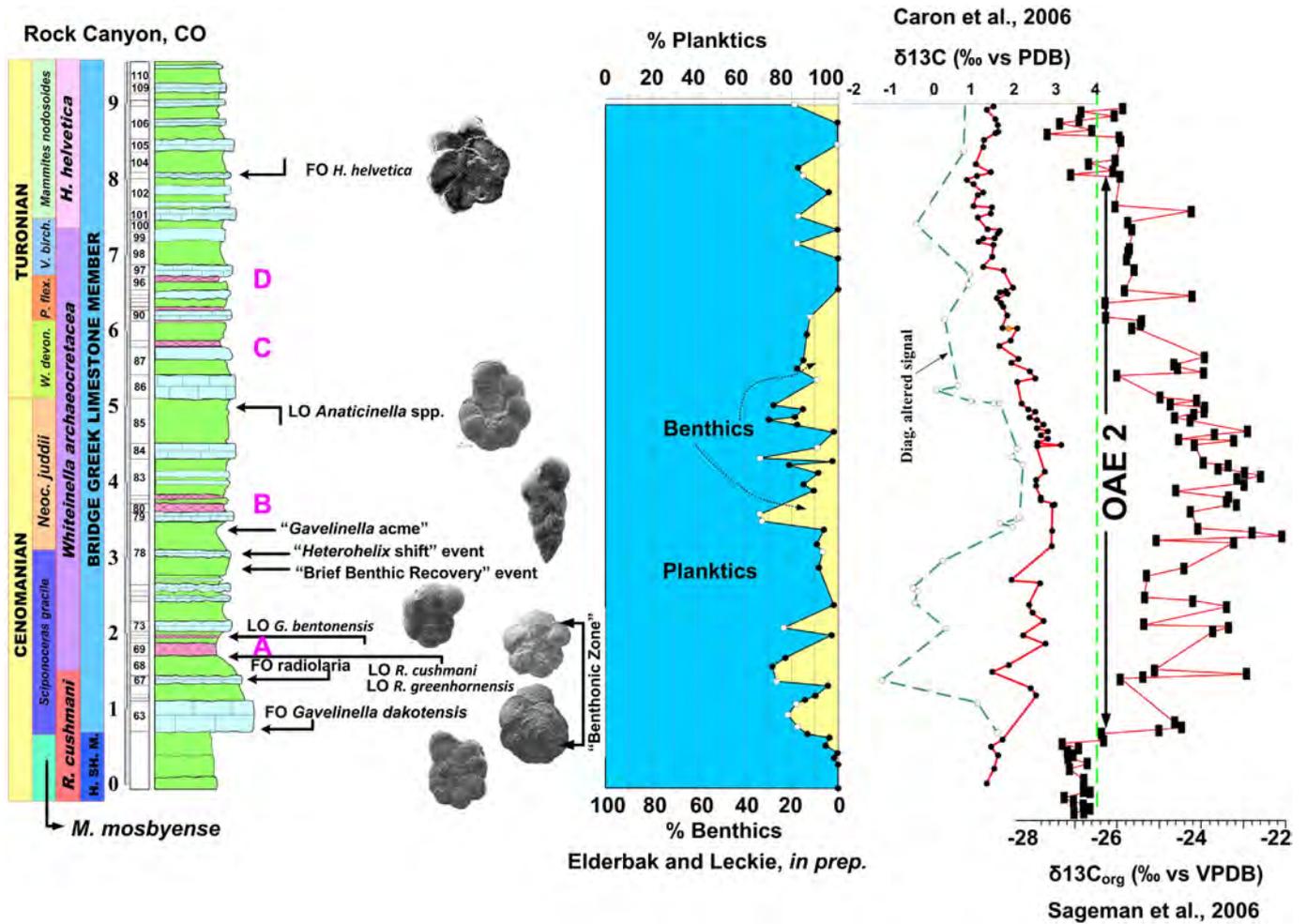


Fig. 4. Stratigraphic section of the Rock Canyon anticline (after Caron et al., 2006), the Cenomanian–Turonian boundary Global Stratotype Section and Point (GSSP) showing the most important foraminiferal bioevents (Leckie, 1985; Leckie et al., 1998; Caron et al., 2006; Elderbak, 2014) and planktic/benthic ratio (Elderbak and Leckie, in prep.) associated with the Oceanic Anoxic Event 2 (OAE 2) as indicated by bulk carbonate carbon isotopes (Caron et al., 2006) and organic carbon isotopes (Sageman et al., 2006). Bed numbering based on Cobban and Scott (1972). Open symbols in the %planktic–%benthic plot are samples from limestones; closed symbols are from marlstones or calcareous shales.

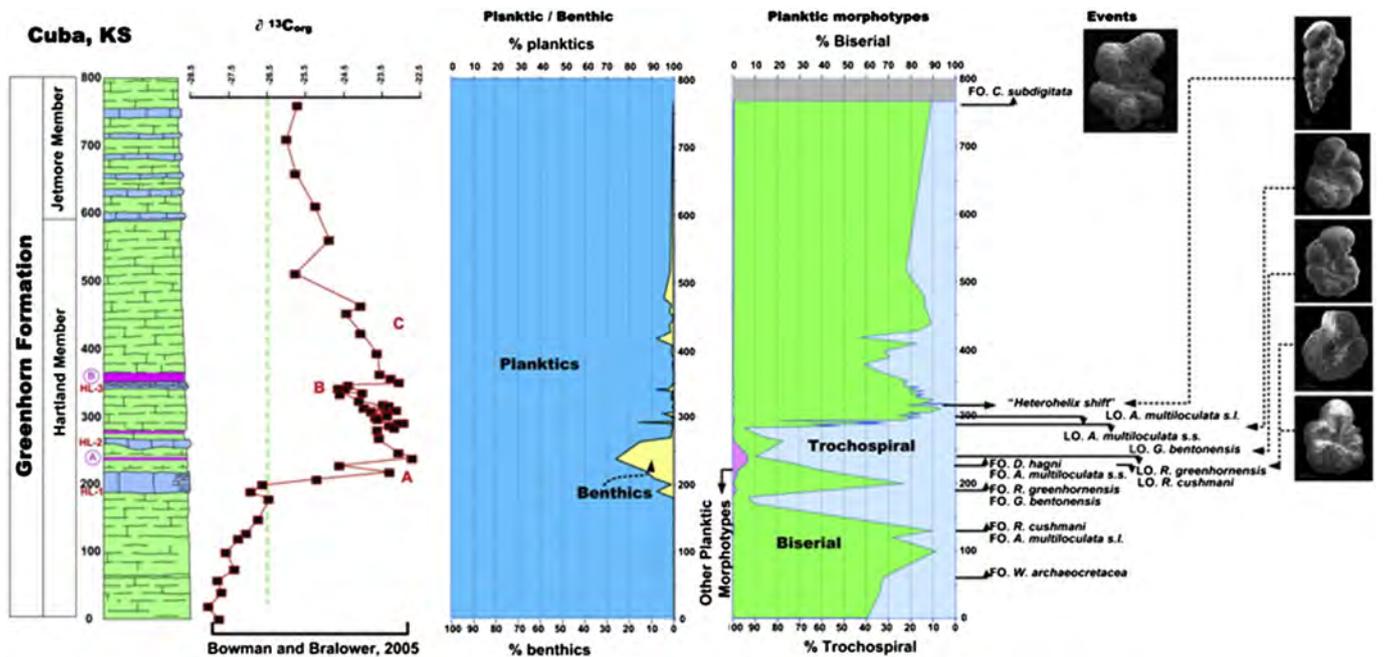


Fig. 5. Foraminiferal assemblages of the Cuba, KS section showing planktic/benthic ratio, the proportion of major planktic foraminiferal morphotypes, and foraminiferal bioevents associated with OAE 2. The  $\delta^{13}C_{org}$  isotope curve is from Bowman and Bralower (2005).

*multiloculata* and *Anaticinella planoconvexa* go extinct at 230 cm. This species turnover occurs within the interval from 220 to 230 cm.

An abrupt increase in *Heterohelix* species at 294.5 cm marks the widespread event known as the “*Heterohelix* shift” of Leckie et al. (1998) that also coincides with planktic species dwarfism (Fig. 5). The uppermost portion of the outcrop, from 294.5 cm to the top of the section, is delineated by an assemblage of abundant *Heterohelix*, common *Hedbergella planispira*, and sporadic occurrence of a few *Whiteinella* species and other taxa of *Hedbergella*. Despite the fluctuations in Shannon–Wiener diversity index from 335.5 to 767 cm, species simple diversity shows a general increase up-section.

The lower Turonian marker species *Helvetoglobotruncana helvetica* was not recovered, although a few specimens of *Helvetoglobotruncana praehelvetica* were found in two samples (230 cm and 767 cm). The First Occurrence (FO) of *Clavhedbergella subdigitata* was also recorded at 767 cm (Fig. 5), as well as coinciding with a return of planktic foraminifer tests of more normal size. In the U.S. Great Plains, the FO of *C. subdigitata* is reported from the upper part of the Bridge Creek Limestone Member and in the equivalent strata of the Jetmore Member of the Greenhorn Formation (Eicher and Worstell, 1970).

3.1.2. Sioux City, IA (SCI)

Surprisingly, planktics dominate the foraminiferal assemblages in all the studied samples of this more proximal site, although the assemblages are dominated by biserial *Heterohelix* taxa. Unlike the CK section, keeled species are absent and trochospiral species are never common. Two shale samples underlying a three meter interval (1.5–4.75 m) of interbedded fine sandstone and shale with flaser or wavy bedding that is barren of foraminifera, contain abundant, but low diversity planktic foraminiferal assemblages. Immediately above this barren sandy interval, abundant planktic foraminifera dominate the assemblage (96% of

total population) with *Heterohelix* spp. comprising 90% of planktic individuals. An abrupt decrease in the proportion of planktic foraminifera (up to 61%) then follows from 5.75–6.0 m an increase in the proportion of trochospiral morphotypes (mainly, *Hedbergella*) in two samples above a concretionary chalky limestone at 5.20 m (Fig. 6). *Heterohelix* spp. continue to dominate planktic foraminiferal assemblages up to an interval of interbedded calcareous shale and chalk (12.8–14.1 m) that lies beneath cyclic massive limestone with thin laminated calcareous shale beds (Fig. 6). Some of shale in this interval (9.0–14.1 m) is barren or contains very few planktic specimens. An abrupt increase in the proportion of trochospiral species coincides with a thick massive limestone bed at the top the studied section (Fig. 6). This also coincides with a short-lived decrease in the proportion of planktic taxa in the total foraminiferal population count and an increase in specimen test size. As in the CK section, the lower Turonian marker species *Helvetoglobotruncana helvetica* is missing at SCI, but a trace of *Helvetoglobotruncana praehelvetica* and few *Clavhedbergella subdigitata* were recovered from the uppermost samples.

3.2. Benthic foraminifera

3.2.1. Cuba, KS section (CK)

Despite proximity of the studied sections to the paleo-shoreline and presumed neritic water depths (<200 m), benthic foraminifera are rare to absent in most samples (Fig. 7). Moreover, benthic assemblages are entirely calcareous except in one sample (230 cm) from which three specimens of the agglutinated species *Textularia rioensis* were recovered. In general, preservation of benthic foraminifera is better than that of the planktic taxa allowing identification to the species level.

The lowermost portion of the study section (0–130 cm) is devoid of benthic foraminifera and planktic species make up 100% of foraminiferal

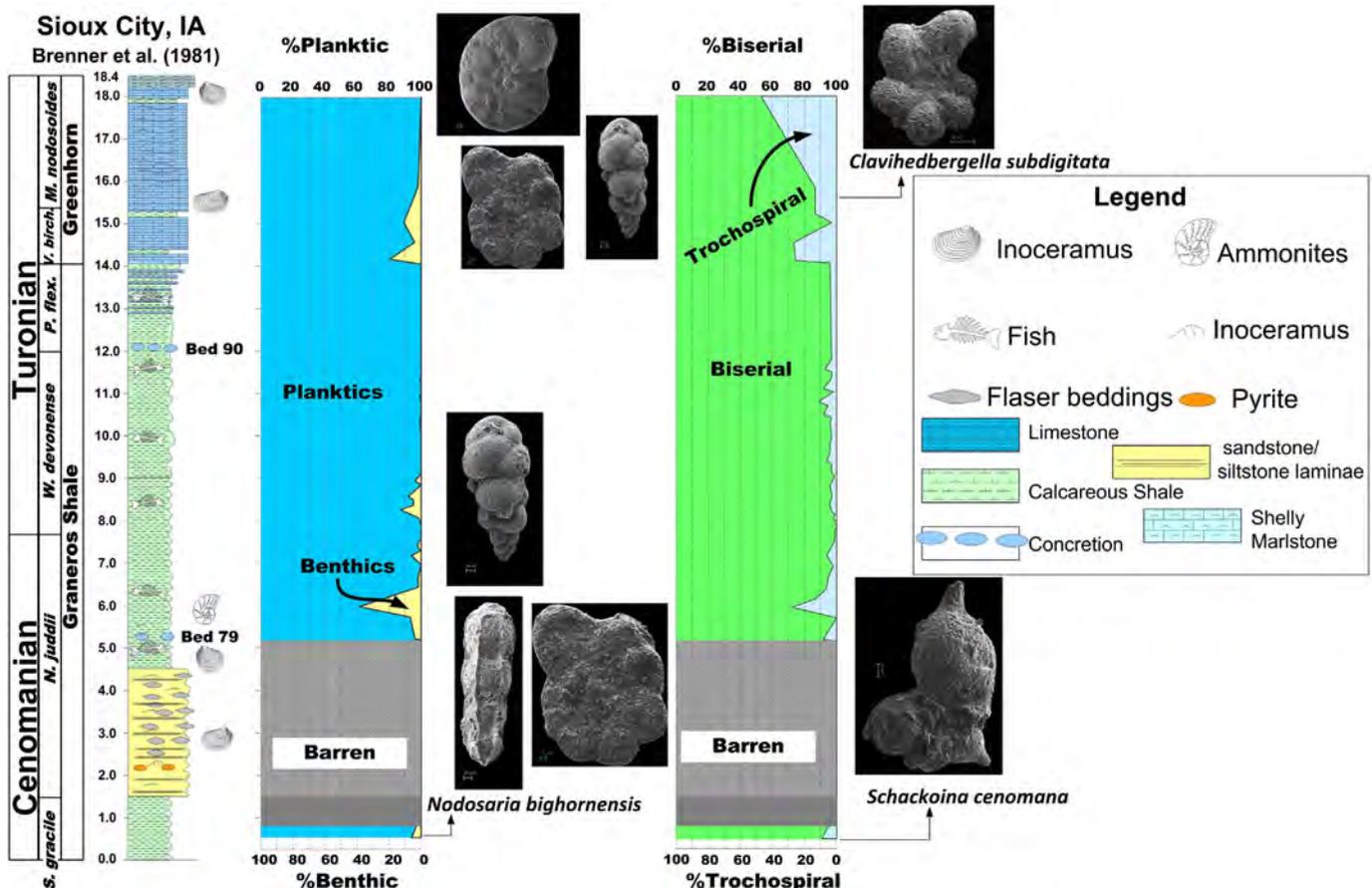


Fig. 6. Foraminiferal assemblage results for the Sioux City, IA section, including planktic/benthic ratio and the proportion of planktic foraminiferal morphotypes.

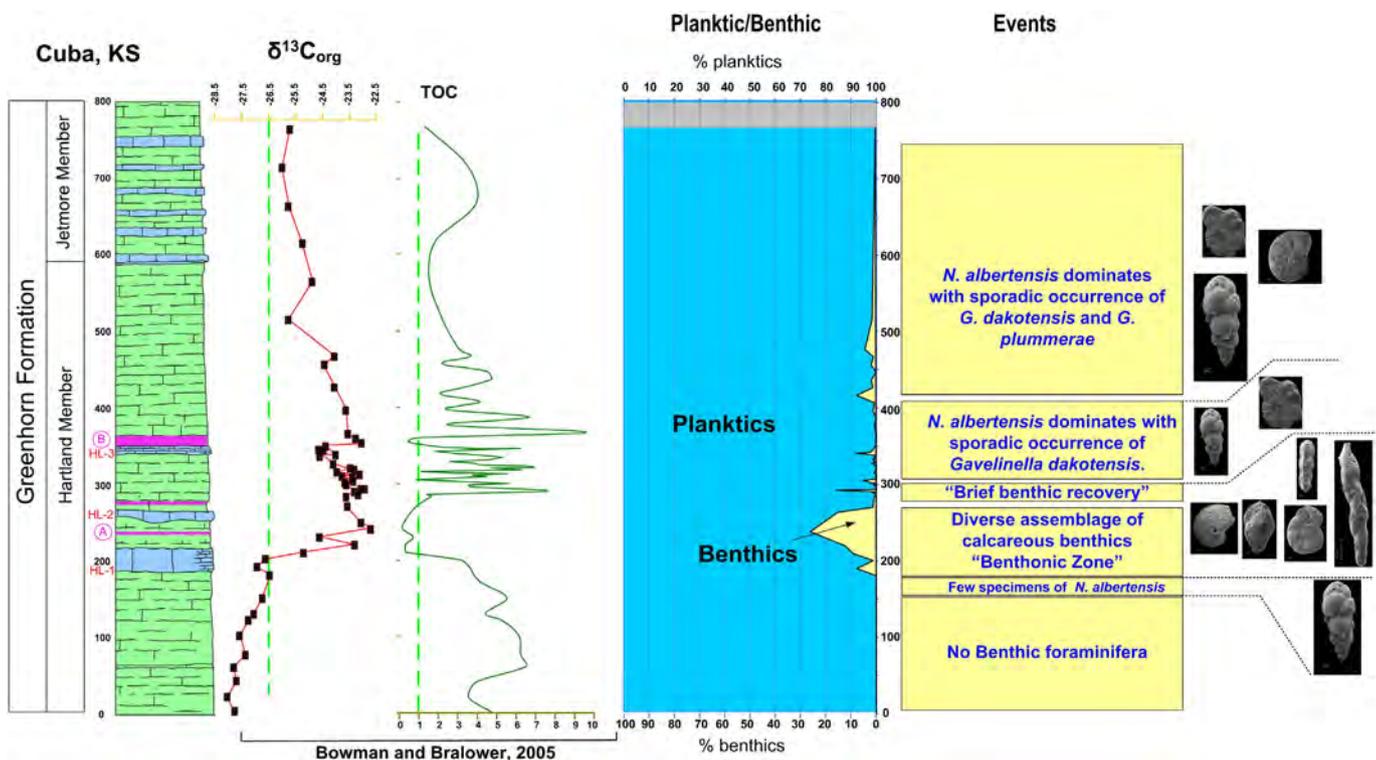


Fig. 7. Stratigraphic section of Cuba, KS showing changes in the composition of benthic foraminiferal assemblages. Weight percent of total organic carbon (wt% TOC) and carbon isotope data from Bowman and Bralower, 2005.

assemblages (Fig. 7). A few specimens of *Neobulimina albertensis* were recovered from the samples preceding the initial positive carbon isotope excursion at 190 cm. This is followed by a rapid increase of benthic foraminiferal species diversity and abundance making up as much as 23% of the foraminiferal assemblages. This 60-cm interval (190–250 cm) marks the “Benthonic Zone” of Eicher and Worstell (1970), which in the CK section is associated with dominance of trochospiral planktic morphotypes over biserial taxa, appearance of keeled planktic species and the lowest TOC values of the 8-m study interval. Most of the species in the CK Benthonic Zone have southern affinities and include *Lenticulina gaultina*, *Buliminella fabilis*, *Gavelinella dakotensis*, *Gavelinella plummerae*, *Lingulogavelinella modesta*, *N. albertensis*, *Pleurostomella nitida*, *Lingulogavelinella asterigerinoides*, *Orithostella viriola*, *Citharina kochii*, *Bullopore laevis*, *Fursenkoina croneisi*, and *Nodosaria bighornensis*. Surprisingly, *Valvulinera loetterlei*, a common species in the Benthonic Zone assemblage of the Great Plains, is very rare at this site.

A marked decline in benthic foraminiferal relative abundance (<2%) marks the top of the Benthonic Zone at 270 cm. Nevertheless, a brief return of diverse and abundant benthic foraminiferal species (15.9%) at 293 cm precedes the planktic “*Heterohelix* shift” event. This benthic event is comparable to the “brief benthic recovery” that Leckie et al. (1998) recognized at the Rock Canyon, Colorado section. Subsequently, the infaunal benthic foraminiferal species *Neobulimina albertensis* dominates most of the samples (294.5–767 cm) along with sporadic occurrences of the epifaunal species *Gavelinella dakotensis*. However, *G. dakotensis*, as well as *Gavelinella plummerae* show a slight increase in relative abundance toward the top of the study section (Fig. 7).

### 3.2.2. Sioux City, IA (SCI)

In comparison to the more distal CK section, relative benthic foraminiferal abundance in this proximal site is much lower, and the benthic assemblage is dominated throughout by shallow infaunal species of *Neobulimina*. Surprisingly, no agglutinated species have been recovered from this site. The lowermost two samples (0.25–0.5 m) contain few and very low diversity calcareous benthic species. Foraminifera

disappear completely in a 3 m interval of interbedded very fine-grained sandstone and shale (Fig. 6). Above this sandy interval, the relative abundance of benthic foraminifera increases rapidly to 39% and 24% in two consecutive samples (5.75 and 6 m), respectively. Dominance by *Neobulimina albertensis* continues in all samples in this section along with sporadic occurrence of *Gavelinella dakotensis*, especially at the base of the carbonate-rich interval at 14.1 m. In general, most of the calcareous benthic species recovered from this site have southern affinities. A single specimen of *Valvulinera loetterlei* occurs at 7.0 m at the base of the middle one-third of the studied section. At other locations across the Great Plains, this species is common in the Benthonic Zone, but rare and sporadic above it (Eicher and Worstell, 1970).

## 4. Discussion

### 4.1. Biostratigraphy and cross basin correlation

Bowman and Bralower (2005) recognized a single limestone bed in the Hartland and Jetmore members of the Greenhorn Formation at the CK section. However, according to Hattin (1975), plate 1) the CK stratigraphic section has several limestone beds: HL-1, the thickest, HL-2, and a limestone bed associated with bentonite marker bed HL-3, and six thin limestone beds of the Jetmore Member (Fig. 5). The single limestone bed depicted by Bowman and Bralower (2005) corresponds to bed HL-3 of Hattin (1975). At the SCI section, two concretionary chalky limestone beds and four massive limestones are recognized. In addition, a large number of bentonite seams characterize the Greenhorn Formation strata, but the number of these bentonites varies from one rock exposure to another (Fig. 3; Hattin, 1975). Moreover, many of these bentonites thin toward the east (Elder, 1988) and are difficult to detect. In our study, for example, three bentonite seams are detected at the CK section (Figs. 5 and 7; Bowman and Bralower, 2005), but none at the SCI section (Fig. 6).

Although with some limitations, isotope profiles of organic and inorganic carbon have proven to be of great value in regional and global

correlation for the C/T interval (Pratt and Threlkeld, 1984; Pratt, 1985; Pratt et al., 1993; Tsikos et al., 2004; Jarvis et al., 2006, 2011; Sageman et al., 2006; Gale et al., 2008). While the initial positive carbon isotope excursion marking the onset of OAE 2 is well defined globally, the so-called “plateau” and termination point of the excursion are masked by local effects (Tsikos et al., 2004). Integration of carbon-isotope stratigraphy and biostratigraphy provides high-resolution correlation among sections globally (e.g., Tsikos et al., 2004; Jarvis et al., 2006, 2011; Sageman et al., 2006; Gale et al., 2008).

Biofacies parameters including punctuated evolutionary events, abundance events, productivity events, ecostratigraphic events, immigration–emigration bioevents, mass mortality events, and mass extinction bioevents are very important in high-resolution cross-basin stratigraphy (Kauffman, 1988). Integration of the carbon-isotope record, lithological marker beds, and foraminiferal assemblage bioevents allows for high-resolution correlation between the study intervals and the GSSP stratotype section at Rock Canyon (RC), Colorado (Fig. 8). Response of planktic and benthic foraminiferal assemblages to the ecological perturbations associated with OAE 2 at the CK and the RC sections shows striking similarities. At the proximal SCI section, however, many of these paleontological events are missing. Several stratigraphically constrained foraminiferal bioevents that characterize C/T strata of the GSSP section at RC have proven to be of a great significance for regional and global correlation (Fig. 8; Leckie, 1985; Leckie et al., 1998; Caron et al., 2006). C/T strata below the OAE 2 positive carbon isotope excursion in the GSSP section contain a diverse planktic foraminiferal assemblage including keeled taxa such as *Rotalipora*, *Praeglobotruncana*, and *Dicarinella*, but lack benthic foraminifera (Fig. 4; Eicher and Worstell, 1970; Eicher and Diner, 1985; Leckie, 1985; Leckie et al., 1998; Caron et al., 2006; Elderbak, 2014). This interval correlates to the upper Cenomanian *Metoicoceras mosbyense* Zone and can be traced into the CK section. However, no keeled species have been recovered from the proximal SCI section.

At the CK section, the appearance of rare specimens of the low-oxygen tolerant infaunal benthic species *Neobulimina albertensis* precedes the initial carbon-isotope excursion. A rapid increase in benthic foraminiferal assemblage diversity and abundance marks the base of the overlying *Sciponoceras gracile* Zone and foraminiferal Benthonic Zone (Figs. 7 and 8). At the proximal SCI section, the occurrence of a few benthic foraminiferal species including *Nodosaria bighornensis* and planktic species *Schackoia cenomana* suggests that the lowermost portion of the section also correlates to the Benthonic Zone and hence the upper Cenomanian *S. gracile* Zone (Fig. 8). Across the Great Plains region, *N. bighornensis* has a short stratigraphic range restricted to the Benthonic Zone (Eicher and Worstell, 1970), and although *S. cenomana* has been reported from both the lower and upper planktic zones (upper Cenomanian and lowermost Turonian), it is most common in the Benthonic Zone (Eicher and Worstell, 1970; Leckie, 1985).

At the reference section in Rock Canyon, the *Sciponoceras gracile* Zone from Bed 63 up to the base of Bed 78 (Fig. 8) is characterized by several foraminiferal bioevents. These include the Benthonic Zone represented here by a diverse and relatively abundant benthic foraminiferal assemblage. The Benthonic Zone appears to represent a synchronous event that has been described from equivalent strata in western and central Kansas, southwestern South Dakota, northern and southern Colorado, northeastern Arizona, south-central Utah and west Texas (Eicher and Worstell, 1970; Frush and Eicher, 1975; Eicher and Diner, 1985; Leckie, 1985; Leckie et al., 1991, 1998; Tibert et al., 2003). Foraminiferal assemblages from northern and western regions of the WIS are characterized by a mix of agglutinated and calcareous benthic species (Eicher and Diner, 1985; Leckie et al., 1991, 1998; West et al., 1998; Tibert et al., 2003), while calcareous benthic foraminifera dominate the assemblages of southern and eastern regions (Frush and Eicher, 1975; Lowery et al., this volume; this study). The lower boundary of the Benthonic Zone is gradational in northern and western parts of the basin, but is abrupt at southern and eastern regions (Eicher and

Worstell, 1970; Frush and Eicher, 1975; Leckie et al., 1998; Lowery et al., this volume; this study). In the SCI section, only a remnant of what appears to be the top of the “Benthonic zone” or the “brief benthic recovery” event of Leckie et al. (1998) is recognized. It is represented by a few benthic foraminiferal species (*Neobulimina albertensis*, *Gavelinella dakotensis*, and *Nodosaria bighornensis*) in the basal samples just below the barren sandy interval from 0.25–0.5 m (Fig. 6).

In addition, a major planktic foraminiferal turnover event occurs within the *Sciponoceras gracile* Zone in the CK section that includes the disappearance of *Rotalipora cushmani*, *Rotalipora greenhornensis*, *Anaticinella multiloculata*, and *Globigerinelloides bentonensis*. However, none of these turnover elements can be traced into the proximal SCI section (Fig. 8). In the RC section, LO of *R. cushmani* precedes the LO of *R. greenhornensis* (Caron et al., 2006), but both species disappear at the same level in the CK section. This may be due to the condensed nature of the CK section or due to the spotty occurrences of these taxa near the end of their ranges (so-called ‘Signor-Lipps effect’; Signor and Lipps, 1982). This is followed shortly up-section by the LO of the planispiral species *G. bentonensis*, just a few centimeters below Bentonite A, which represents a synchronous event at both sections. No specimens of *G. bentonensis* have been observed in the SCI section.

The subsequent “*Heterohelix* shift” event of Leckie et al. (1998) is also well developed at the CK section and roughly coincides with increased TOC values (Fig. 5). In the basin center, this dramatic change in planktic foraminiferal composition is associated with the base of the uppermost Cenomanian *Neocardioceras juddii* Zone (Leckie, 1985; Leckie et al., 1998). At the SCI section, heterohelicids dominate throughout the studied section and hence the event is masked (Fig. 6). A spike of the clay mineral kaolinite at the central and western margin of the basin, generally coincides with the “*Heterohelix* shift”, and is believed to be a result of increased surface runoff into the basin (Leckie et al., 1998). The spike is more pronounced at the RC section (basin center) than at the more proximal western Lohali Point (LP), Arizona locality (Leckie et al., 1998), suggesting an alternative sediment source than the western margin. Therefore, we suggest that the 3 m-thick sandy interval near the base of the SCI section is correlative to the kaolinite spike in the central and western side of the WIS and represents a time of major influx of terrigenous sediment, including kaolinite from the eastern margin of the basin.

Within the *Neocardioceras juddii* Zone in the CK section, a thick bentonite denotes Bed B and an underlying chalky limestone bed represents the HL-3 bed in central and eastern Kansas (Hattin, 1975) and limestone Bed 79 in Colorado and western Kansas (Fig. 3; Cobban and Scott, 1972). At the SCI section, limestone Bed 79 becomes a chalky concretionary bed, but overlying Bentonite B is missing (Figs. 3 and 6). Bentonite B or the top of the underlying limestone is utilized as the datum for cross correlation between our studied sections in the eastern WIS and the RC section in the central WIS (Fig. 8).

By latest Cenomanian time, a roughly synchronous increase in the proportion of *Gavelinella dakotensis* (“*Gavelinella acme*” event) has been reported from three localities in the central and western margin of the WIS (Leckie et al., 1998). Despite very low benthic abundance, this short-lived event can also be traced into the CK section where it is represented by brief dominance of *G. dakotensis* over *Neobulimina albertensis*. At the SCI section, *G. dakotensis* appears sporadically in the lowermost and uppermost portions of the studied section and hence a distinct acme event is missing. It seems that the “*Gavelinella acme*” event is less pronounced and/or diminishes eastward.

At the RC GSSP section, the base of Turonian is placed at the bottom of limestone Bed 86 corresponding to the base of the *Watinoceras devonense* Zone (Kennedy and Cobban, 1991; Kennedy et al., 2005). According to Caron et al. (2006), the most practical marker for the C/T boundary at RC is LO of *Anaticinella planoconvexa* at the top of the bed 85 “precision interval” a few centimeters below bed 86. Previously, the LO of *Anaticinella multiloculata* s.l. (= *A. planoconvexa*) and *A. multiloculata* s.s. were recorded within the Benthonic Zone (Eicher and

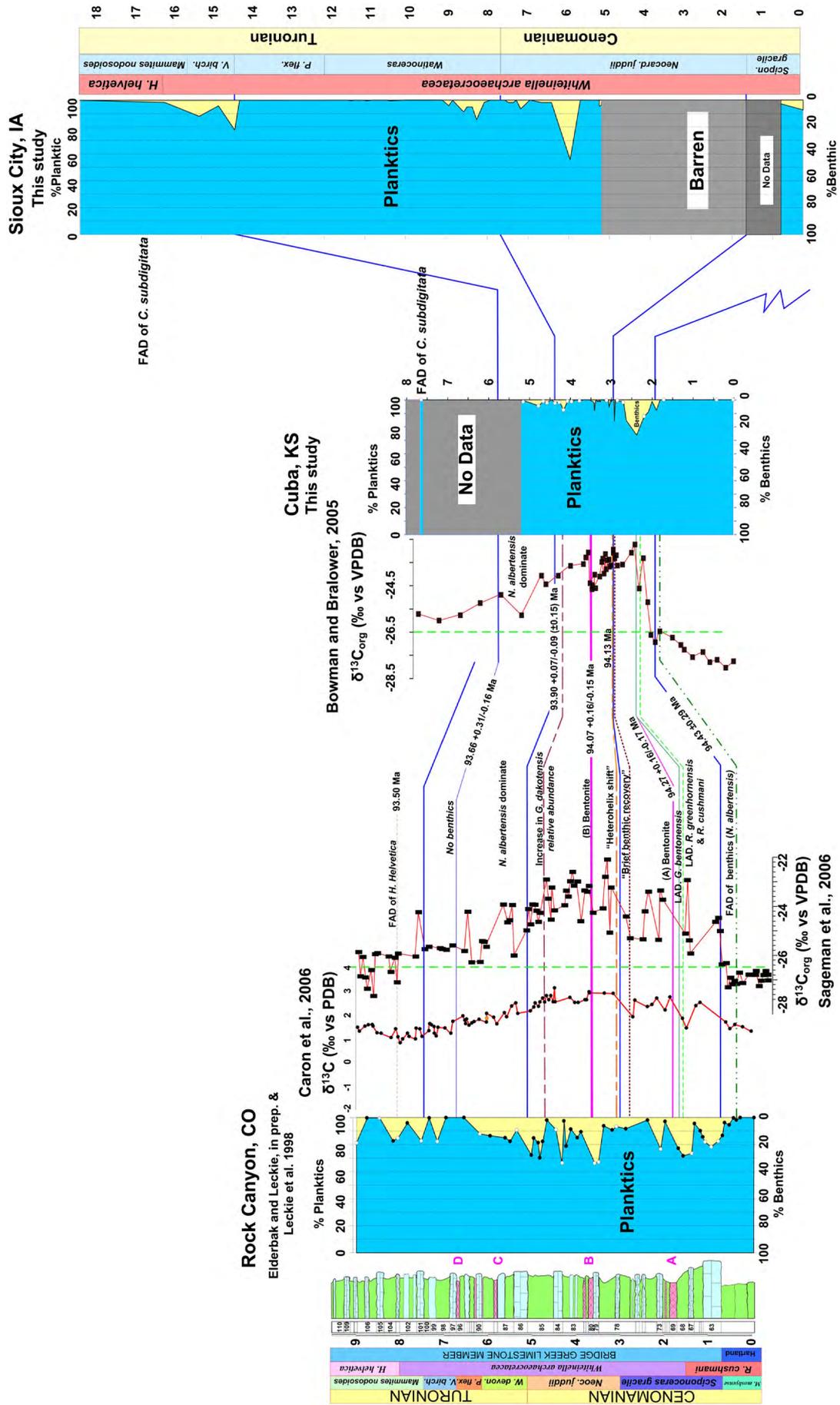


Fig. 8. High-resolution correlation between the studied sections at CK and SCI, and the Cenomanian/Turonian GSSPat RC. Ages are from Meyers et al., 2012.

and Worstell, 1970; Leckie, 1985; Leckie et al., 1998). Higher occurrences of *A. planoconvexa* to Bed 85 (just a few centimeters below C/T) were reported (Desmares et al., 2003, 2007; Caron et al., 2006); however, a thorough investigation of Bed 85 from six samples has shown no occurrence of *A. planoconvexa* (Elderbak, 2014).

Previously, the base of Turonian at the CK section was placed at 300 cm based on the FO of the calcareous nannofossil species *Quadrum gartneri* (Elson and Bralower, 2005) and the carbon isotope stratigraphy (Bowman and Bralower, 2005). However, the base of Turonian should occur above marker limestone HL-3 (= Bed 79 at RC) that is easily recognizable at the CK section (see plate 1 in Hattin, 1975; Bowman and Bralower, 2005) and occurs just below the prominent Bentonite B bed that can be traced across the southern WIS to eastern Kansas (Hattin, 1975; Elder, 1988). Bentonite B lies at 350 cm, 50 cm above the FO of *Q. gartneri* in the CK section. Therefore, we place the base of Turonian at 447 cm based on the following correlative criteria to the RC section: 1) a significant reduction in the proportion of the benthic foraminiferal assemblages and low species diversity in Bed 85; 2) a significant increase in the proportion of *Heterohelix* associated with the termination of the positive  $\delta^{13}\text{C}$  excursion; and 3) according to the stratigraphic section of Hattin (1975), the base of the Turonian must be placed between marker beds HL-3 and JT-1 (350 and 600 cm, respectively).

The base of Turonian is placed at 7.6 m at SCI based on the following criteria: 1) it must be placed between the lower concretionary chalky limestone bed (equivalent to Bed 79 at RC) at 5.25 m and the upper concretionary chalky bed (equivalent to Bed 90) at 12.1 m; and 2) a major reduction in the proportion of the benthic foraminiferal assemblages with low species diversity similar to that in the more distal CK section. In both sections, the early Turonian marker species *Helvetoglobotruncana helvetica* has not been recovered. However, the presence of *Clavhedbergella subdigitata* along with *Helvetoglobotruncana prae-helvetica* in the upper parts of both studied sections confirms an early Turonian age. *Clavhedbergella subdigitata* has been previously reported from equivalent strata (Jetmore Member in central Kansas) across the Great Plains (Eicher and Worstell, 1970).

Integrated sedimentological, paleontological, and geochemical data allowed for a correlation between our studied sections and C/T boundary GSSP at the basin center. Response of foraminifera to the paleoenvironmental and paleoceanographic perturbations associated with OAE 2 provided a number of local, regional, and global correlative chronostratigraphic units of short duration (Fig. 8). The detailed biostratigraphic events observed at the CK and RC sections, especially within the OAE 2 interval, suggest similar paleoenvironmental and paleoceanographic histories at both sites. Dominance of near-shore facies at the SCI section resulted in the absence of many important bioevent datums defined from more distal sections in the WIS. However, integration of lithological and biological data revealed important depositional insights. In addition, geochemical data including organic carbon isotopes and clay mineralogy further added to our understanding of paleoenvironmental and paleoceanographic processes on the eastern side of the WIS.

#### 4.2. Paleoenvironments

Cretaceous rocks on the eastern margin of the WIS provide important insights into sedimentation, paleoceanography, and paleoenvironments in the WIS. During the early Cenomanian, fluvial and deltaic sedimentation characterized central Kansas (Hattin, 1967) for which the principal transport direction was toward the southwest (Franks et al., 1959). Further to the northeast, large fluvial meander-belt systems drained the North American craton west of the Appalachians across Iowa and emptied into the WIS (Brenner et al., 1981; Whitley and Brenner, 1981). During the late Cenomanian Greenhorn transgression, the sea pushed the shoreline further eastward, diminishing the influence of the cratonic source area and allowing the deposition of

fine-grained sediments including marine biogenic carbonates in central Kansas (Hattin, 1975; Brenner et al., 1981; Witzke and Ludvigson, 1982). In western Iowa, the Greenhorn transgression resulted in the replacement of coarse-grained fluvial sediments of the Nishnabotna Member of the Dakota Formation by fine-grained sandstone and mudstone of the Woodbury Member (Fig. 2; Whitley and Brenner, 1981). Only during the later stages of the Greenhorn transgression were the marine Graneros shale and Greenhorn limestone (Equivalent to Hartland, Jetmore, and Pfeifer Members) deposited across western Iowa (Fig. 2; Witzke and Ludvigson, 1994).

In central Kansas, the deposition of the Hartland Shale is associated with a major change in the composition of foraminiferal assemblages from an entirely planktic makeup to a mix of planktic and benthic taxa (Eicher and Worstell, 1970; Hattin, 1975). In the lowermost portion of the CK section (Hartland Shale) below the positive carbon isotope excursion, low diversity planktic foraminiferal assemblages dominate. At the basin center, however, more distal conditions allowed for proliferation of slightly more diverse and robust planktic foraminiferal assemblages (Eicher and Worstell, 1970; Eicher and Diner, 1985; Elderbak, 2014). The CK site is more proximal to the paleo-shoreline of the eastern margin of the WIS and hence planktic assemblages may have been affected by paleobathymetry and/or terrigenous clastic influx. It is therefore not surprising that planktic foraminiferal assemblages at this site are dominated by *Heterohelix*; a genus characteristic of epicontinental seas (Leckie, 1985, 1987; Leckie et al., 1998). *Heterohelids* are one of the most abundant and widely distributed groups in the WIS during the Greenhorn transgression (Eicher, 1969; McNeil and Caldwell, 1981). Isotopic data suggest that Cenomanian–Turonian heterohelids were near-surface dwellers (Fisher and Arthur, 2002; Bornemann and Norris, 2007; Wendler et al., 2013). Increased abundance in eurytopic *Heterohelix* has been related to low oxygen marine environments, reduced salinity of surface waters, and/or elevated productivity (Leckie, 1985; Hart and Ball, 1986; Boersma and Premoli Silva, 1989, 1991; Leckie et al., 1991, 1998; Elderbak, 2014).

Study samples from the upper Cenomanian *Metioceras* Zone are completely devoid of benthic foraminifera, suggesting inhospitable environmental conditions on the seafloor (Fig. 9). Similar conditions prevailed in Kansas and eastern Colorado (Eicher and Worstell, 1970), as well as in the Big Bend region of Texas (Frush and Eicher, 1975). Low oxygen levels at/or below the sediment–water interface have been suggested as an explanation for paucity of benthic foraminifera in this interval (Eicher and Worstell, 1970; Frush and Eicher, 1975; Eicher and Diner, 1985). Indeed, high TOC values up to 6.5 wt% in the lower ~2 m of the CK section also indicate hypoxic bottom conditions resulting in better preservation of organic matter. However, some modern studies indicate that certain benthic foraminifera can tolerate very low oxygen levels and are found living in essentially anoxic sediments (Smith, 1964; Phleger and Soutar, 1973; Boltovskoy and Wright, 1976; Bernhard, 1989; Bernhard and Sen Gupta, 1999). Equivalent strata at the RC section are characterized by very low values (<1.0 wt%) of TOC, but still lack benthic foraminifera (Eicher and Worstell, 1970; Caron et al., 2006; Elderbak, 2014). Surface runoff from the eastern margin provided the basin with terrestrial organic matter and enhanced water column stratification due to a low-density hyposaline cap (estuarine environment) (Fig. 9). Furthermore, accumulation of organic detritus resulted in anaerobic conditions beneath the sediment–water interface and production of toxic  $\text{H}_2\text{S}$  further amplifying unfavorable conditions for benthic organisms and establishing a “dead zone”. Low oxygen levels and development of hypoxia conditions characterize several modern shallow marine environments receiving high freshwater input. The excess nutrients being discharged from the Mississippi River into the northern Gulf of Mexico, for example, enhance surface water primary productivity and eutrophication leading to severe hypoxia and/or anoxia in the bottom water (e.g., Osterman et al., 2005, 2008, 2009; Platon et al., 2005; Diaz and Rosenberg, 2008). A subsequent major sea-level transgression brought warm, oxygenated,

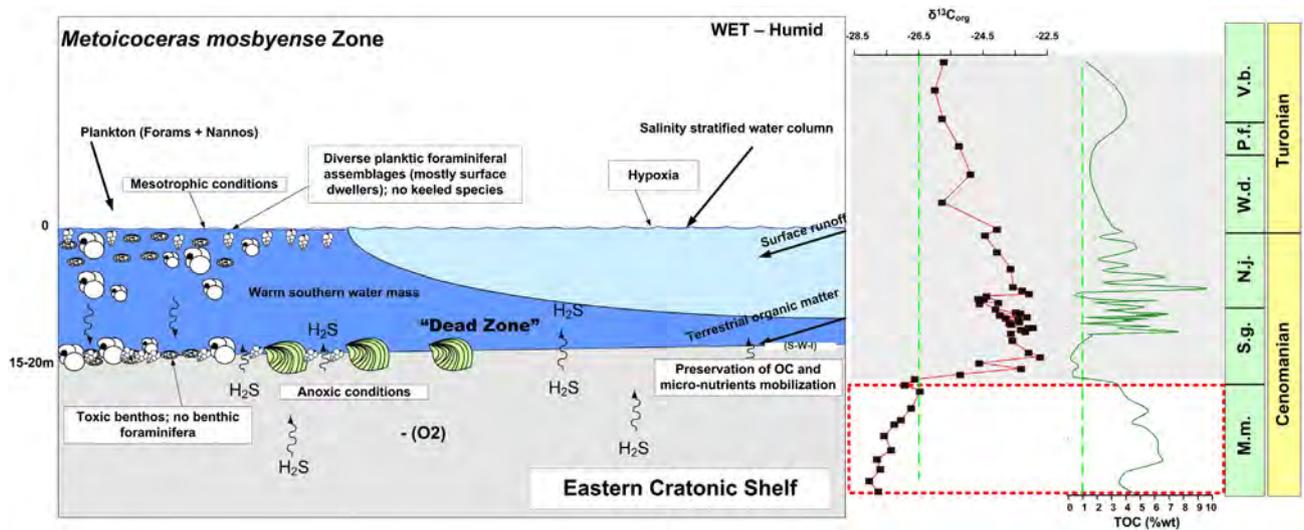


Fig. 9. Paleoenvironmental interpretation for late Cenomanian time *Mammites mosbyense* Zone, at the eastern margin of the WIS as indicated by foraminiferal assemblages and carbon isotope and organic carbon data.

normal salinity southern waters into the basin creating favorable conditions for the development of diverse and abundant microfossil and macrofaunal assemblages of the upper Cenomanian *Scipionoceras gracile* Zone (Kauffman, 1984a,b). The onset of this transgression is also associated with the deposition of the Hartland Shale limestone bed HL-1 (= Bed 63 at RC), which coincides with the initial positive  $\delta^{13}\text{C}$  excursion marking the onset of OAE 2 (Fig. 10). A rapid increase in the proportion of benthic foraminifera (Benthonic Zone) marks a major change in substrate and bottom water conditions (Sageman et al., 1997). This benthic oxygenation event has been recorded from the Big Bend region of Texas in the south to the Black Hills of South Dakota in the north (Eicher and Worstell, 1970; Frush and Eicher, 1975; Eicher and Diner, 1985) and from Lohali Point of Arizona in the southwest to CK in the eastern WIS (Leckie et al., 1991, 1998; this study). While northern and western regions were characterized by near equal abundance of agglutinated and calcareous benthic species, calcareous benthic species dominate the assemblages of the eastern regions, reflecting the influence of different water masses. The Benthonic Zone represents a synchronous

event throughout the basin (Eicher and Worstell, 1970; Eicher and Diner, 1985).

At the CK section, the Benthonic Zone is represented by 18 species of foraminifera, most of which are calcareous and with southern affinities. This assemblage has lower diversity and abundance than assemblages recovered from equivalent strata at the basin center. This eastward decrease in abundance and diversity is paralleled by an eastward increase in TOC values suggesting increasing dysoxic bottom-water conditions to the east. According to the dilution model, however, the eastern side of the WIS should be more oxygenated than the western side adjacent to the main source of terrigenous detritus and surface runoff. Despite major species turnover, planktic foraminiferal assemblages at this time attained maximum diversity and abundance indicating normal marine conditions. The disappearance of the keeled genus *Rotalipora* may have been due to break down of the water column stratification, or due to development and/or expansion of an oxygen minimum zone (e.g., Leckie, 1985; Leckie et al., 1998). During the oxic *Scipionoceras gracile* Zone, dry climatic conditions along the eastern side of the WIS (van Helmond

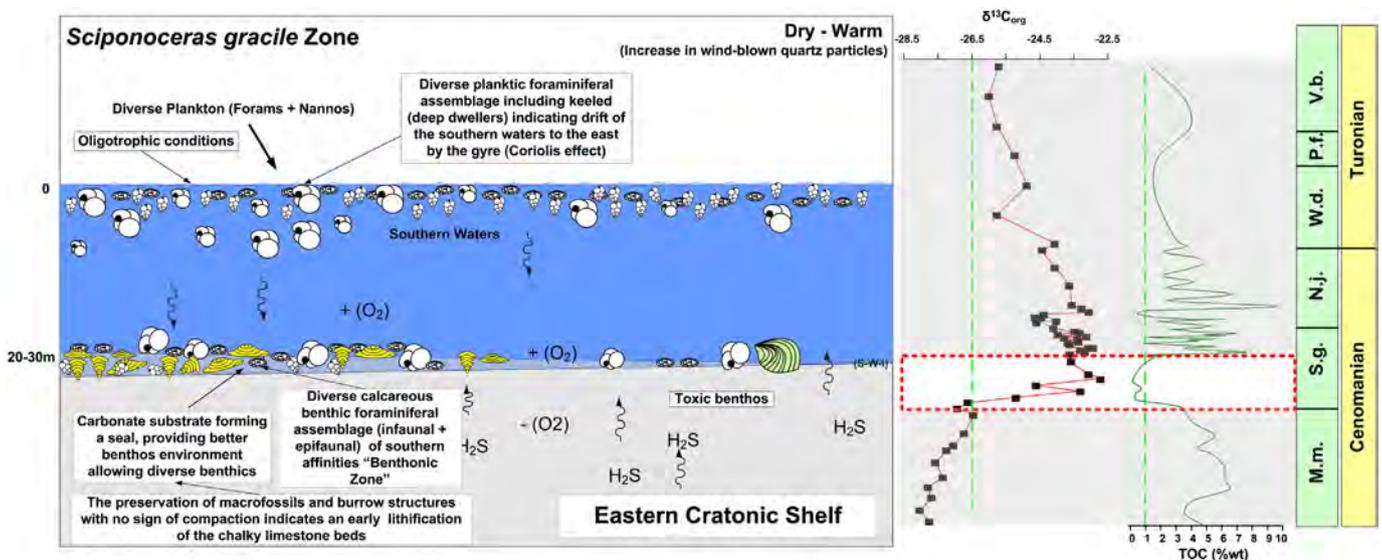


Fig. 10. Paleoenvironmental interpretation for late Cenomanian time *Scipionoceras gracile* Zone, at the eastern margin of the WIS as indicated by foraminiferal assemblages and carbon isotope and organic carbon data.

et al., 2014) accompanied by rapid sea-level transgression resulted in a cutoff or reduction of freshwater input into the basin (Fig. 10). Subsequent break down of the water column stratification resulted in a well-oxygenated seafloor. Relative abundance of nannoplankton species such as *Biscutum constans* and *Prediscosphaera* spp., indicative of high primary productivity, significantly decreased in this interval suggesting oligotrophic conditions (Eleson and Bralower, 2005). A marked decrease in TOC values (<1.0 wt%) may also indicate reduced influx of organic matter to, and/or a poorer preservational environment at the seafloor. Abundant and diverse foraminiferal assemblages, including deep-water dwelling keeled species suggest relatively optimum marine conditions in the WIS. Increased influx of biogenic carbonate to the seafloor associated with the incursion of a warm southern water mass may have created a significant change in the nature of the substrate allowing diverse benthic foraminiferal assemblages to thrive. The preservation of mineral-filled feeding burrows in pure chalky limestones of the Bridge Creek Member and equivalents suggests early lithification of firm substrates (Hattin, 1971, 1975, 1985, 1986). Early lithification of carbonate-rich strata, as indicated by lack of compaction, may have provided a seal for upward degassed toxic H<sub>2</sub>S, further enhancing favorable conditions for the benthos.

By latest Cenomanian time (*Neocardioceras juddii* Zone), a dramatic environmental change occurred and created a stressed habitat for both planktic and benthic communities. This zone is associated with a depauperate ammonite fauna in the central and eastern parts of the basin related to development of a hyposaline cap on the WIS; however, equivalent strata in Arizona, Utah, and Montana contain a relatively diverse and abundant ammonite fauna (Elder, 1985). We suggest that wetter climatic conditions at the eastern side of the WIS resulted in increased fluvial/deltaic outflow to the WIS at this time (Fig. 11). At the Sioux City site, this facies change is denoted by a coarsening upward sequence of interbedded sandstone and siltstone with flaser and wavy bedding (Fig. 12). A 1.5 m-thick shale containing abundant, but low diversity planktic foraminifera and a few benthic species is overlain by a 3 m-thick barren interval, delineating a progressively stressful paleoecology. The sedimentary structures associated with this progradational event suggest a high-energy shallow marine environment influenced by tidal currents (Fig. 12). Oxygen isotope data from the basin center record an abrupt negative shift at the base of the *N. juddii* Zone indicating a major flux of freshwater into the basin (Barron et al., 1985; Pratt, 1985; Pratt et al., 1993). At the CK section, this coincides with the widespread “*Heterohelix* shift” event that has been linked to a major drop in the  $\delta^{18}\text{O}$  value at the basin center (Leckie, 1985; Leckie et al., 1998). In addition, a spike in kaolinite at the central and western margin of the basin generally coincides with the “*Heterohelix* shift” event, the result of increased surface runoff into the basin (Leckie et al., 1998). Moreover, a remarkable drop in the diversity of benthic foraminiferal assemblages is recorded at the CK section. *Neobulimina albertensis*, a presumed infaunal benthic species, dominates the benthic assemblages at both studied sections. At the SCI section, the proportion of *N. albertensis* increases up to 39% (Fig. 6). A comparable trend has been recorded in the western and central parts of the WIS and denotes impingement of an oxygen minimum zone (OMZ) from the south (Leckie et al., 1998).

At the top of the *Neocardioceras juddii* zone, the “*Gavelinella acme*” recorded in western and central parts of the basin and has been interpreted as productivity event (Leckie et al., 1998), but it is less pronounced on the eastern cratonic shelf. Leckie et al. (1998) suggested that upwelling of cool nutrient-rich northern waters, flowing southward along the WIS western's margin on a “forebulge” topographic-high stimulated primary productivity that resulted in increased flux delivery of organic matter to the seafloor. At the CK section, TOC values increased significantly up to 9.65 wt% suggesting favorable conditions for organic matter preservation. Increased nutrient discharge from rivers and upwelling of nutrient-rich waters over topographic highs on the eastern shelf may have also stimulated primary productivity and increased flux of organic matter to the seafloor (Fig. 11). Development of a

“dead zone” due to hypoxia near the coast completely excluded benthic foraminiferal assemblages at the SCI site and significantly reduced benthic abundance and diversity at the CK location. Therefore, we suggest that benthos along the eastern margin of the WIS was more controlled by dissolved oxygen content than by food availability.

By earliest Turonian time (lowermost *Watinoceras devonense* Zone), upper water column conditions deteriorated at the more proximal SCI section due to the influence of freshwater influx from the eastern margin and only a few specimens of dwarfed *Heterohelix* and *Hedbergella planispira* were recovered. In contrast, at the more distal CK section, *Heterohelix* remains abundant throughout the interval. At both sites, bottom water conditions were much stressed as indicated by recovery of only a few specimens of *Neobulimina albertensis*. This biofacies may have been associated with the expansion of the intermediate dysoxic southern waters into the area with continued rising sea level (Fig. 13). However, TOC values gradually decreased as the plateau of positive  $\delta^{13}\text{C}$  values begins to drop.

The deposition of limestone of the Jetmore Member in Kansas and equivalent strata of the Greenhorn Formation in Iowa mark a subsequent slight improvement in the paleoecology of upper water column reflected in increased species diversity of planktic foraminifera, especially at the more proximal SCI site. The lowest ten limestone beds of Jetmore Member in Kansas can be traced from northeastern Kansas westward to the San Juan Basin attesting to the uniformity of conditions across the WIS (Hattin, 1971, 1975, 1985, 1986; Elder, 1985). Unfortunately, only one sample from the Jetmore Member was available at the CK section at (767 cm; Fig. 8). This sample contains the most diverse planktic foraminiferal assemblage of the CK section including the keeled *Helvetoglobotruncana praeahelvetica*. Specimens exhibit a more normal (larger) size distribution relative to underlying intervals. Although these changes indicate a return of normal marine conditions in the surface water, the presence of planktic foraminifera with radially elongated chambers such as *Clavohedbergella subdigitata* also suggests some lingering dysoxic conditions in the upper water column (Figs. 8 and 15; Verga and Premoli silva, 2002; Coccioni et al., 2006; Coxall et al., 2007). The time of the *Mammites nodosoides* Zone in the early Turonian coincides with peak transgression during which the WIS may have reached its maximum depth and width (Elder and Kirkland, 1993; Leithold, 1994; Sageman et al., 1997; West et al., 1998). The low-oxygen tolerant, infaunal *Neobulimina albertensis* continued to dominate benthic foraminiferal assemblages with sporadic occurrence of epifaunal *Gavelinella dakotensis* suggesting dysoxic organic-rich conditions at the seafloor.

#### 4.3. Paleooceanography

In the WIS, the late Cenomanian to early Turonian Greenhorn Cyclothem records a peak sea level transgression and highstand during which the WIS reached its maximum extent and depth (Fig. 1; Williams and Stelck, 1975; Kauffman, 1977, 1984b; Molenaar, 1983; Cobban and Hook, 1984; Leckie et al., 1991, 1998; Slingerland et al., 1996; Hardenbol et al., 1998; West et al., 1998). Changes in global climate undoubtedly influenced the depositional record of the WIS during C/T time, but effects of regional tectonics and oceanography were also important (Hay et al., 1993; Slingerland et al., 1996; Leckie et al., 1998). Utilization of sedimentological, paleontological, and geochemical data, as well as numerical models, have indicated the complexity climatic and oceanographic conditions of the mid-Cretaceous WIS (e.g., Frush and Eicher, 1975; Lloyd, 1982; Parrish et al., 1984; Eicher and Diner, 1985; Erickson and Slingerland, 1990; Leckie et al., 1991, 1998; Hay et al., 1993; Jewell, 1993; Fisher et al., 1994, 2003; Fisher, 1995; Slingerland et al., 1996; Sageman et al., 1997, 1998, 2006; West et al., 1998; Meyers and Sageman, 2004; Floegel et al., 2005). These studies have suggested that the central part of the WIS was characterized by a warm and humid subtropical climate with varying distribution and interactions of water masses (Fig. 14).

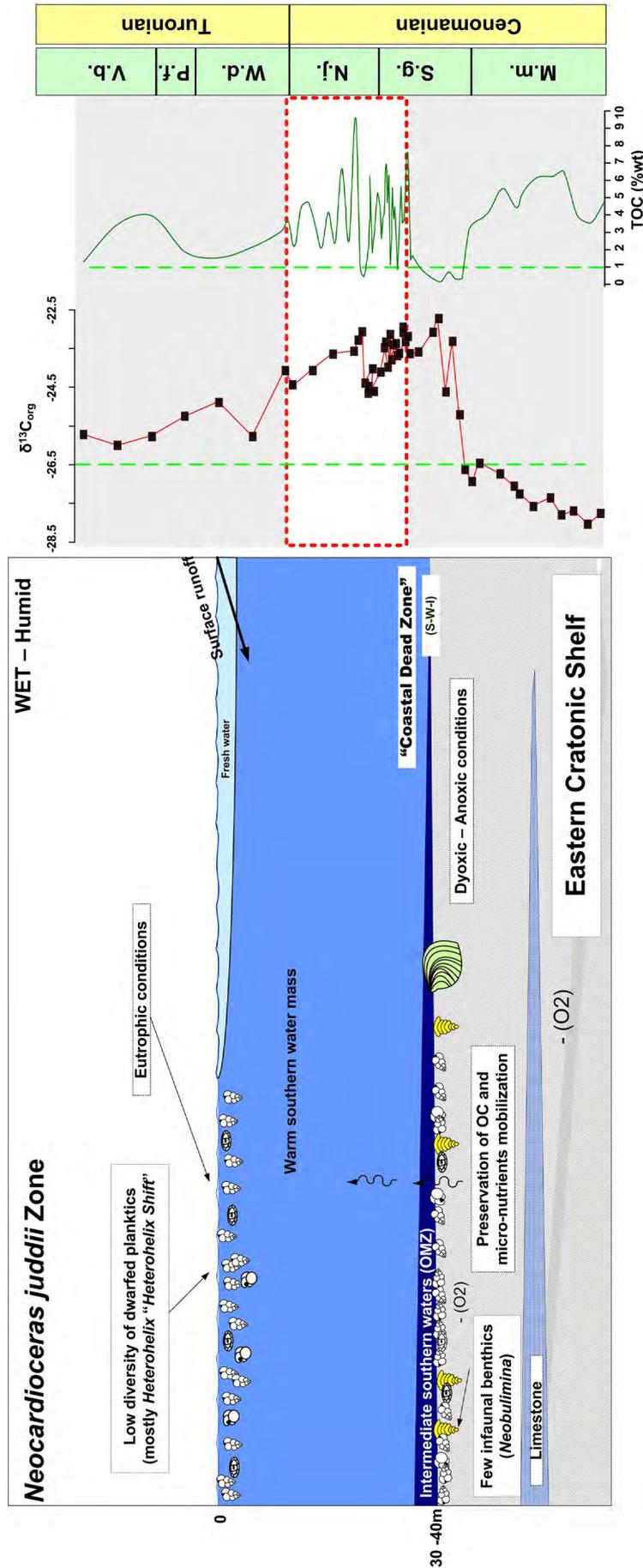


Fig. 11. Paleoenvironmental interpretation for latest Cenomanian time, *Neocardioceras juddii* Zone, at the eastern margin of the WIS as indicated by foraminiferal assemblages and carbon isotope and organic carbon data.

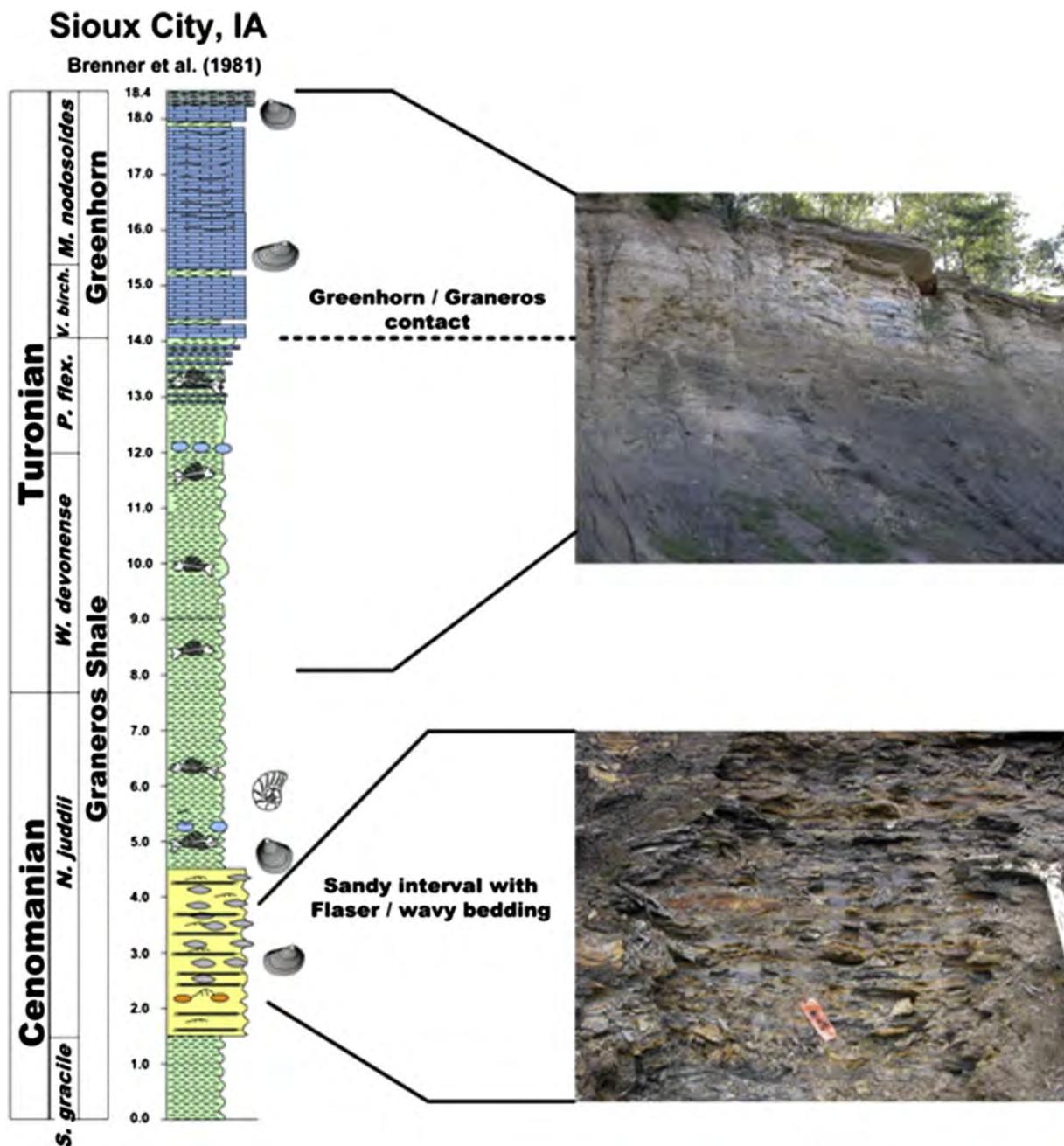


Fig. 12. Stratigraphic section of the Graneros and Greenhorn formations at Sioux City, IA showing sedimentary structures associated with the 3 m-thick sandy interval in the lower part of the section, as well as the contact between the Graneros and the overlying Greenhorn Formations.

For example, Hay et al. (1993) proposed three scenarios for the mixing of southern and northern water masses. One such scenario is the convergence of the two water masses along an oceanic front that results in the formation of a third denser water mass that sinks and flows out of the WIS and toward the open ocean (Fig. 14-A). Utilizing constraints from atmospheric general circulation models, Slingerland et al. (1996) suggested a quasi-estuarine circulation for the early Turonian WIS with a counterclockwise gyre (Fig. 14-C). Surface runoff from both margins of the WIS created a surface water gradient inclined toward the basin center allowing a pathway for fresh waters. The Coriolis force deflected currents to the right resulting in the formation of coastal currents moving northward and southward along the eastern and western margins of the basin, respectively. Subsequently, Tethyan and Boreal surface waters met and mixed to form a denser third water mass that sank and returned to the open ocean. The strength of the gyre was controlled by the difference between the amount of precipitation and

evaporation, as well as by changes in the sill depth at both ends of the WIS. Under constant insolation values, the two strongest driving forces of this type of gyre circulation are the magnitude of fluvial/deltaic runoff and meridional temperature gradients (Kump and Slingerland, 1999). Changes in the amount of surface runoff during the precession cycle (Floegel et al., 2005) and/or changes in insolation (Glancy et al., 1993) may have significantly affected climate and the sedimentation patterns in the WIS. The Slingerland et al. (1996) model explains the mechanism by which Tethyan water mass advanced into WIS, but failed to produce widespread organic-rich strata or water-column stratification because of rapid mixing of the water column (Fisher, 2003).

Leckie et al. (1998) proposed a paleoceanographic circulation model for the WIS based on detailed study of foraminifera and clay mineralogy of shale and marl intervals from three localities representing a transect across the southwestern side of the WIS (Fig. 14-D). According to their model, southern and northern waters met along an oceanic front that

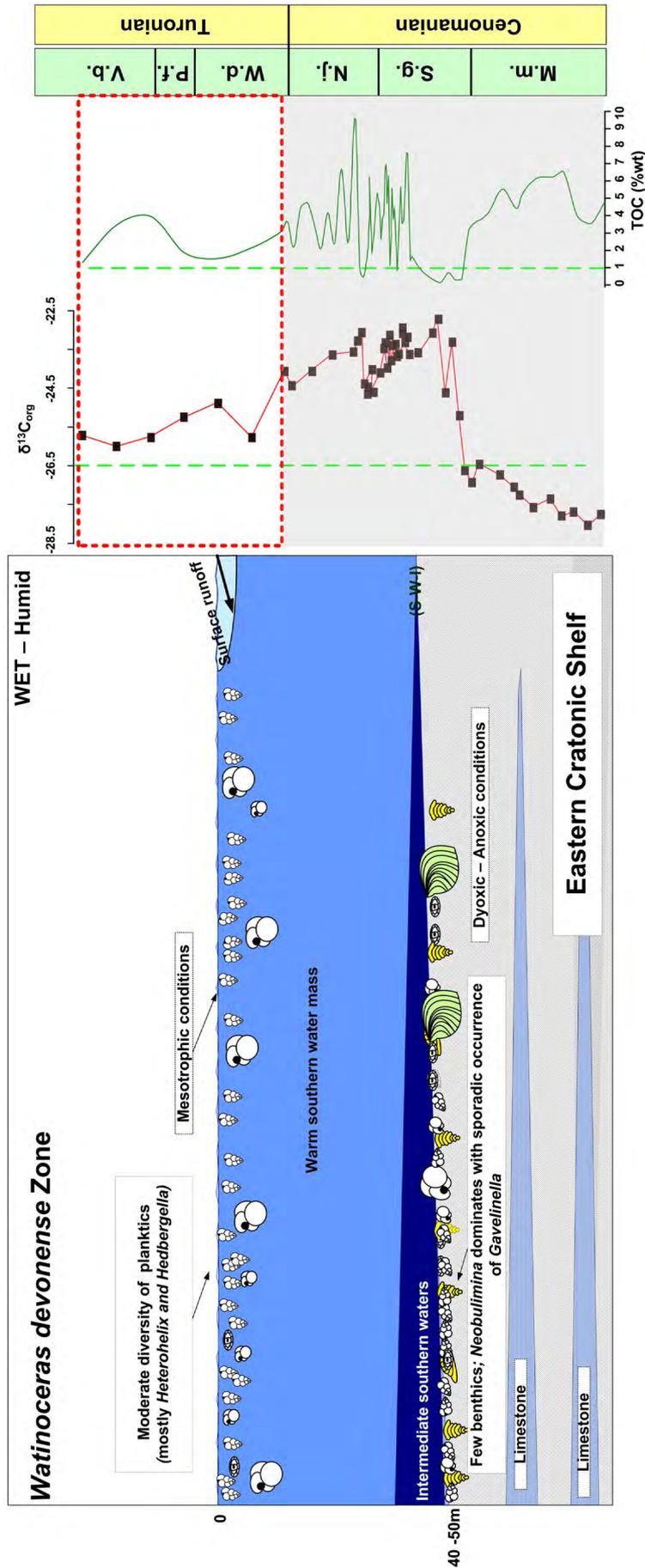
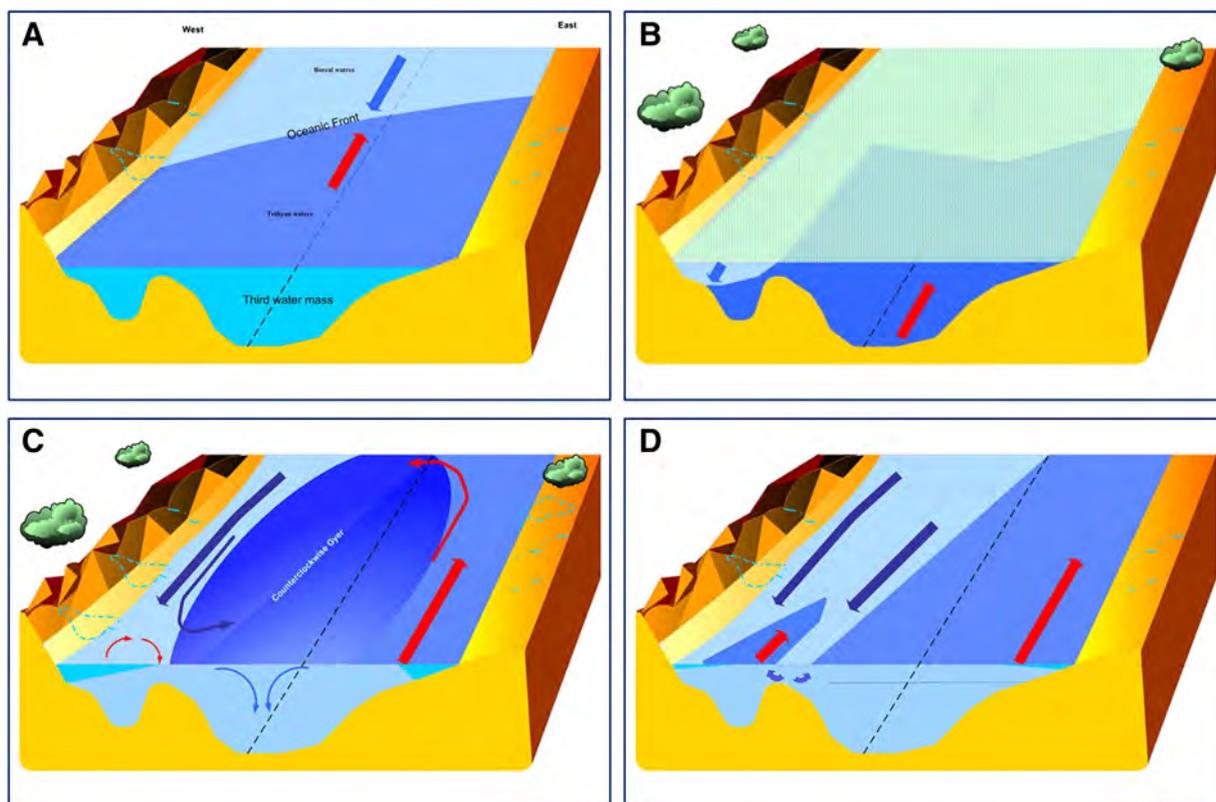


Fig. 13. Paleoenvironmental interpretation for early Turonian time *Watinoceras devonense* Zone, at the eastern margin of the WIS as indicated by foraminiferal assemblages and carbon isotope and organic carbon data.



**Fig. 14.** A number of proposed paleoceanographic models of the Cretaceous WIS including A) Caballing model (Hay et al., 1993; Fisher, 1995); B) Fresh-water lid model of (e.g., Jewell, 1993); C) Estuarine model (Slingerland et al., 1996); D) Topographic high model (Leckie et al., 1998).

may have been influenced by a forebulge along the tectonically active western margin of the foreland basin. Warm, normal salinity water mass dominated the southern and eastern parts of the WIS and a cool, relatively low salinity water mass dominated the northern and western parts of the WIS with topographically induced upwelling along the trend of the forebulge.

Foraminiferal assemblages of the sections studied here indicate that the eastern side of the WIS was influenced by a southern Tethyan water mass during late Cenomanian to early Turonian time. Foraminiferal assemblages present a striking similarity between the Cuba, Kansas section and the GSSP section at Rock Canyon, Colorado indicating similar paleoenvironmental and paleoceanographic conditions and processes. Planktic foraminifera from below the OAE 2 carbon isotope excursion in both sections are relatively diverse and indicate normal marine conditions, but the eastern cratonic shelf of the WIS may not have been deep enough at this time to support deep dwellers such as keeled planktic taxa. Proximity of the site to the paleo-shoreline and fluvial input into the basin from the eastern margin may also have contributed to the increased abundance of the genus *Heterohelix* to the east (Fig. 15-A). The elevated values of TOC at this stage and absence of benthic foraminiferal assemblages indicate hypoxic bottom water conditions that may have been due to a combination of increased organic matter (marine and terrestrial) influx and a stratified water column due to runoff from the cratonic interior (Fig. 15-A). This coincided with increased relative abundance (~30%) of the mesotrophic to eutrophic nannofossil species *Biscutum constans* (Eleson and Bralower, 2005). Moreover, northward flowing southern waters along the eastern margin brought nutrients and an extra input of calcareous plankton into the basin. Upwelling around structural and paleotopographic highs stimulated primary productivity and increased organic flux to the seafloor (Fig. 15-A).

Sea-level rise and rapid transgression during deposition of the *Sciponoceras gracile* Zone brought warm, and well-oxygenated southern

waters into the basin along with diverse and abundant macrofauna and calcareous plankton (Fig. 15-B). This zone has the most diverse fossil assemblages of the Greenhorn rocks of Kansas (Cobban and Reeside, 1952; Hattin, 1975). Oligotrophic conditions are indicated by nanoplankton assemblages (Eleson and Bralower, 2005) and diverse planktic foraminiferal taxa. In addition, normal salinity and well-oxygenated conditions at the seafloor resulted in development of a diverse assemblage of infaunal and epifaunal benthic foraminifera ("Benthonic Zone" of Eicher and Worstell, 1970).

Deposition of coarsening-upward sequence of interbedded sandstone and mudstone with high energy sedimentary structures at the proximal SCI site indicates high river sediment discharge during the latest Cenomanian (*Neocardioceras juddii* Zone). This increased fluvial runoff from the eastern margin of the WIS enhanced water column stratification. Based on our biostratigraphic interpretations, the *N. juddii* Zone at the Sioux City, IA section is about five-times thicker than at the Cuba, KS section, and about three-times that of Rock Canyon, CO section (Fig. 8). Increased nutrient discharge from rivers and upwelling of nutrient-rich bottom waters over topographic highs stimulated primary productivity and increased organic matter flux to the seafloor. Development of a "dead zone" in coastal waters completely excluded benthic foraminiferal assemblage at the SCI section and significantly reduced benthic abundance and diversity at the CK section. Incursion of low-oxygen intermediate Tethyan waters added to the paleoecologic stress on the benthos especially at the central and southern parts of the basin (Fig. 15-C).

By earliest Turonian time (*Watinoceras devonense* Zone), upwelling was reduced due to increased paleobathymetry over topographic highs as sea-level continued to rise (Fig. 15-D). In addition, retreat of the shoreline reduced the influx of freshwater and terrestrial nutrients to the study area. In response, Tethyan intermediate water and an OMZ expanded northward along the eastern margin. Planktic foraminiferal

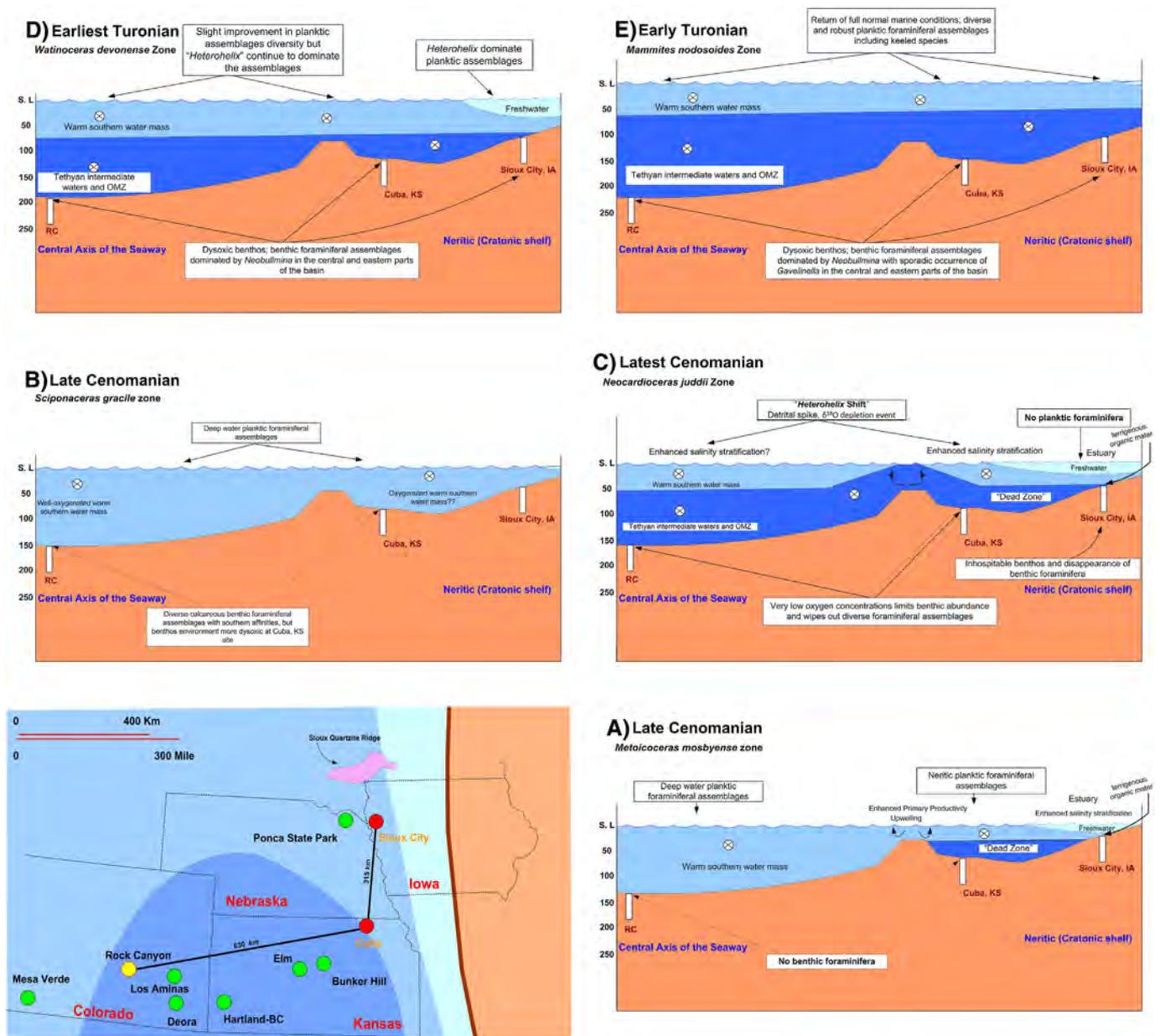


Fig. 15. A sequence of illustrations (A–E) showing paleoceanographic developments from late Cenomanian to early Turonian along the eastern margin of the WIS.

assemblages indicate a return to somewhat more normal marine conditions in the upper water column, but benthic foraminifera indicate continued hypoxia on the seafloor and *Neobulimina albertensis* dominates the benthic foraminiferal assemblages in the central and eastern parts of the WIS.

The Greenhorn transgression peaked during the early Turonian (*Mammites nodosoides* Zone) as the WIS reached its maximum extent and depth (e.g., Elder and Kirkland, 1994; Leithold, 1994; Sageman et al., 1997; Arthur and Sageman, 2005). At this time, fully normal marine conditions were widespread even at the most proximal part of the basin (Sioux City site) and alternating limestone and shale couplets were deposited. Good recovery of planktic and benthic foraminiferal assemblages characterize both limestone and shale samples (Fig. 15-E), but diversity of benthic assemblages is higher in the shale layers than in adjacent limestone beds. Similar abundance and diversity trends characterize alternating limestone and marlstone beds of the Bridge Creek Limestone at the basin center (Elderbak, 2014). These bio- and lithofacies may be explained by an oceanographic circulation that combines the models of Slingerland et al. (1996) and Leckie et al. (1998).

## 5. Conclusions

1. Late Cenomanian–early Turonian foraminiferal assemblages from northeastern Kansas (Cuba; CK) and western Iowa (Sioux City; SCI) indicate that the eastern cratonic shelf and central axis basin of the Western Interior Sea were influenced by the same warm, southern water mass.
2. The eastern margin was a major source of sediment and fresh water into the basin. Topographic highs (e.g., Sioux Ridge and horst and graben structures) restricted circulation and enhanced stagnation, as well as stimulating upwelling and increasing productivity and facilitating the creation of dead zones along the eastern margin.
3. A shallow redox boundary and production of toxic  $H_2S$  eliminated benthic foraminifera during deposition of the lowermost portion of the study interval that corresponds to the upper Cenomanian *Mammites mosbyense* Zone.
4. During the time of the *Sciponoceras gracile* Zone in the late Cenomanian, increased pelagic sedimentation and early lithification of sediments provided a seal for toxic  $H_2S$  allowing a diverse

- benthic foraminiferal assemblage to flourish. Yet, more dysoxic benthic conditions persisted at the eastern localities corresponding to the eastward thinning of the basal limestone bed.
- The initial positive  $\delta^{13}\text{C}$  excursion marking the onset of Oceanic Anoxic Event 2 coincides with the time of establishment of a well-oxygenated seafloor marked by diverse benthics and low TOC values in the WIS. This event is correlative with European sections thereby indicating a synchronous onset of OAE 2 around the globe.
  - The presence of deep-dwelling planktic foraminiferal species such as *Rotalipora greenhornensis*, *Rotalipora cushmani* and *Globigerinelloides bentonensis* in the relatively shallow environment of the eastern margin indicates that these species were brought to this part of the basin by gyre circulation from the south.
  - Planktic and benthic foraminiferal assemblages of Cenomanian/Turonian strata provide a sequence of synchronous bioevents based upon correlation of the studied sections to the marker bentonite and limestone beds at the Rock Canyon GSSP section.
  - By latest Cenomanian time (*Neocardioceras juddii* Zone), the incursion of a southern intermediate water mass combined with topographic induced upwelling and coastal zone hypoxia eliminated benthic foraminifera from the eastern cratonic shelf.
  - Dysoxic to anoxic benthic conditions allowed for the preservation of organic matter and mobilization of nutrients that enhanced surface primary productivity, as denoted by the carbon isotope data.
  - By early Turonian time (*Watinoceras devonense* Zone), an increase in planktic foraminiferal diversity indicates more normal marine surface water conditions, including reduced fluvial/deltaic outflow from the east, and marking the gradual termination of the global carbon-isotope excursion associated with OAE 2.
  - Integration of planktic and benthic foraminiferal bioevents with chemostratigraphic data and marker beds allowed for high-resolution stratigraphic correlation between eastern WIS sections and the C/T GSSP reference section at Rock Canyon, Colorado.
  - Foraminiferal assemblages present a striking similarity between the Cuba, Kansas section and the GSSP outcrop at Rock Canyon, Colorado indicating that both sites represent similar paleoenvironmental and paleoceanographic conditions, whereas the Sioux City, Iowa section denotes the long-term influence of fluvial/deltaic outflow and nutrient influx from the eastern craton and development of persistent hypoxia along the eastern margin of the Western Interior Sea.

## Acknowledgments

We are grateful to Timothy J. Bralower (Penn State University) for providing washed and bulk samples of the Cuba, Kansas section. Khalifa Elderbak would like to acknowledge the generous fund received from the General People's Committee of Libya. We thank the reviewers Paul Sikora (Anadarko Petroleum) and Anthony Gary (Chevron) for carefully reading our manuscript and for giving detailed comments and suggestions that have been helpful to improve the manuscript. Discussions with Steve Nathan, Andy Fraass, Chris Lowery, Kendra Clark, and Serena Dameron greatly benefited the results.

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