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# Biotic effects of the Chicxulub impact, K–T catastrophe and sea level change in Texas

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ABSTRACT

Biotic effects of the Chicxulub impact, the K–T event and sea level change upon planktic foraminifera were evaluated in a new core and outcrops along the Brazos River, Texas, about 1000 km from the Chicxulub impact crater on Yucatan, Mexico. Sediment deposition occurred in a middle neritic environment that shallowed to inner neritic depths near the end of the Maastrichtian. The sea level fall scoured submarine channels, which were infilled by a sandstone complex with reworked Chicxulub impact spherules and clasts with spherules near the base. The original Chicxulub impact ejecta layer was discovered 45–60 cm below the sandstone complex, and predates the K–T mass extinction by about 300,000 years.

Results show that the Chicxulub impact caused no species extinctions or any other significant biotic effects. The subsequent sea level fall to inner neritic depth resulted in the disappearance of all larger (>150 μm) deeper dwelling species creating a pseudo-mass extinction and a survivor assemblage of small surface dwellers and low oxygen tolerant taxa. The K–T boundary and mass extinction was identified 40–80 cm above the sandstone complex where all but some heterohelicids, hedbergellids and the disaster opportunistic guembelitrids went extinct, coincident with the evolution of first Danian species and the global $\delta^{13}C$ shift. These data reveal that sea level changes profoundly influenced marine assemblages in near shore environments, that the Chicxulub impact and K–T mass extinction are two separate and unrelated events, and that the biotic effects of this impact have been vastly overestimated.

## 1. Introduction

Biotic effects of the Cretaceous–Tertiary (K–T) catastrophe are well known primarily from the extinction of dinosaurs, ammonites and other invertebrates, planktic foraminifera and nannofossils (reviews in MacLeod et al., 1997; Keller, 2001; Twitchett, 2006). Among these only planktic foraminifera suffered a dramatic and sudden mass extinction at the K–T boundary. The Chicxulub impact is commonly believed to be the single cause despite the gradual extinction patterns, associated climate changes, sea level fluctuations and volcanism preceding the mass extinction. The K–T age for this impact is based on the controversial interpretation of a sandstone complex with reworked Chicxulub impact spherules at the base as impact generated tsunami deposits in NE Mexico and Texas (e.g., Bourgeois et al., 1988; Smit et al., 1992, 1996, 2004; Schulte et al., 2006; Kring, 2007; Schulte et al., 2008). Such geologically instantaneous deposition is required to bridge the stratigraphic separation between the K–T boundary and Chicxulub spherule ejecta layer. But multiple burrowing horizons within the sandstone complex in Mexico and Texas are incompatible with tsunami deposition (Ekdale and Stinnesbeck, 1998; Keller et al., 2003a; Gale, 2006). Recent discoveries of an older and apparently the original Chicxulub spherule ejecta layer 4–9 m below the sandstone complex in two sections in NE Mexico and 45–60 cm below in Texas indicate that this impact predates the K–T boundary by about 300,000 years (Keller et al., 2003a, 2007a).

Brazos River sections have long been known to contain a complete K–T transition comparable to the El Kef stratotype section in Tunisia (Jiang and Gartner, 1986; Keller, 1989a,b; Barrera and Keller, 1990), but with the added advantage of a sandstone complex with Chicxulub spherules up to 1.6 m below the K–T boundary (Keller et al., 2007a, 2008a). Nevertheless, Schulte et al. (2006, 2008) placed the K–T boundary at the base of the sandstone complex arguing that the Chicxulub impact defines the K–T boundary. With the recent discovery of the original Chicxulub spherule ejecta layer in undisturbed claystones below the sandstone complex (Keller et al., 2007a), the Brazos sections have also become the most unique in their preservation of these three stratigraphically well-separated events that represent the Chicxulub impact, sea level fall and K–T mass extinction. These sections thus provide an unprecedented opportunity to unravel the history of events leading up to the K–T mass extinction in a marginal continental shelf environment.

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The first and only previous attempt to use quantitative planktic foraminiferal studies and stable isotopes to understand the K–T transition at Brazos was about 20 years ago and prior to the discovery of the Chicxulub impact crater (Keller, 1989a,b; Barrera and Keller, 1990). Since that time, hundreds of K–T sections have been analyzed globally and the biotic and environmental changes are much better understood, which warrants a comprehensive analysis of new Brazos sections and drill cores. In this study, the main objectives are to quantitatively document the faunal changes in planktic foraminifera in order to evaluate the biotic and environmental effects of the Chicxulub impact, the sea-level fall and the K–T boundary event and reconstruct the history leading up to the end-Cretaceous mass extinction.

## 2. Location, materials and methods

The Brazos K–T transitions are found in central Texas along a 3 km stretch extending from Highway 413 south along the Brazos River of Falls County and its tributaries the Cottonmouth and Darting Minnow Creeks (Fig. 1; Yancey, 1996). These sections have long been the focus of numerous studies evaluating the K–T mass extinction by focusing on a prominent sandstone complex as link to the Chixulub impact (e.g., Jiang and Gartner, 1986; Hansen et al., 1987; Bourgeois et al., 1988; Hansen et al., 1993; Smit et al., 1996; Heymann et al., 1998; Schulte et al., 2006, 2008), or alternatively to a sea-level fall (Yancey, 1996; Keller, 1998a; Gale, 2006; Keller et al., 2007a, 2008a).

Here we report on a new core Mullinax-1 (Mull-1), which was drilled by DOSEC (Drilling, Observation and Sampling of Earths Continental Crust) on a meadow about 370 m downstream from the Hwy 413 Bridge (GPS Location 31° 07′53. 00″N, 96° 49′30. 14″W) at the same location as the older cores KT1 and KT2 reported by Schulte et al. (2006, Fig. 1). A new outcrop was also sampled in Cottonmouth Creek about 1.8 km to the south from Mull-1. At this locality the K–T transition was first sampled in two segments at 10 m (CMA) and 30 m (CMB) from a small waterfall over the sandstone complex. Subsequently, heavy rains collapsed the steep creek walls and exposed the sections at the waterfall (CMW), which was also collected and analyzed (Fig. 2). The only difference between CMA and CMW is the 15 cm greater thickness between the sandstone complex and the yellow clay layer at the waterfall due to variable erosion at the base of the sandstone complex; these two sections are therefore combined as CMAW.

Outcrops and core Mull-1 were measured, described, photographed and sampled at an average of 5–10 cm intervals with 1–2 cm spacing through the K–T transition. Planktic foraminifera were processed using standard techniques (Keller et al., 1995). Core sample size was generally restricted to 3–5 $cm^3$, except for intervals where too few specimens were recovered for quantitative analysis and therefore sample size was doubled. Much larger samples were collected and processed from the outcrops, which significantly improved the chances of finding rare species.

Samples were washed through three sieve sizes (38–63 μm, 63–150 μm and >150 μm) to recover very small, small and large planktic foraminifera. Quantitative analyses was done on the 63–150 μm and >150 μm size fractions to get a better representation of the small and very common heterohelicids, globigerinelloids, hedbergellids, and guembelitrids and document in detail the less common larger globotruncanids and heterohelicids, which are good markers of environmental variability. For each sample in the two size fractions an aliquot of 250–300 specimens was picked, mounted on micro-slides and identified. Benthic specimens were also counted in the same aliquots of the >63 μm size fraction to evaluate the P/B ratio as basic indicator of sea level change. The remaining residues were examined for rare species and these were noted for species range

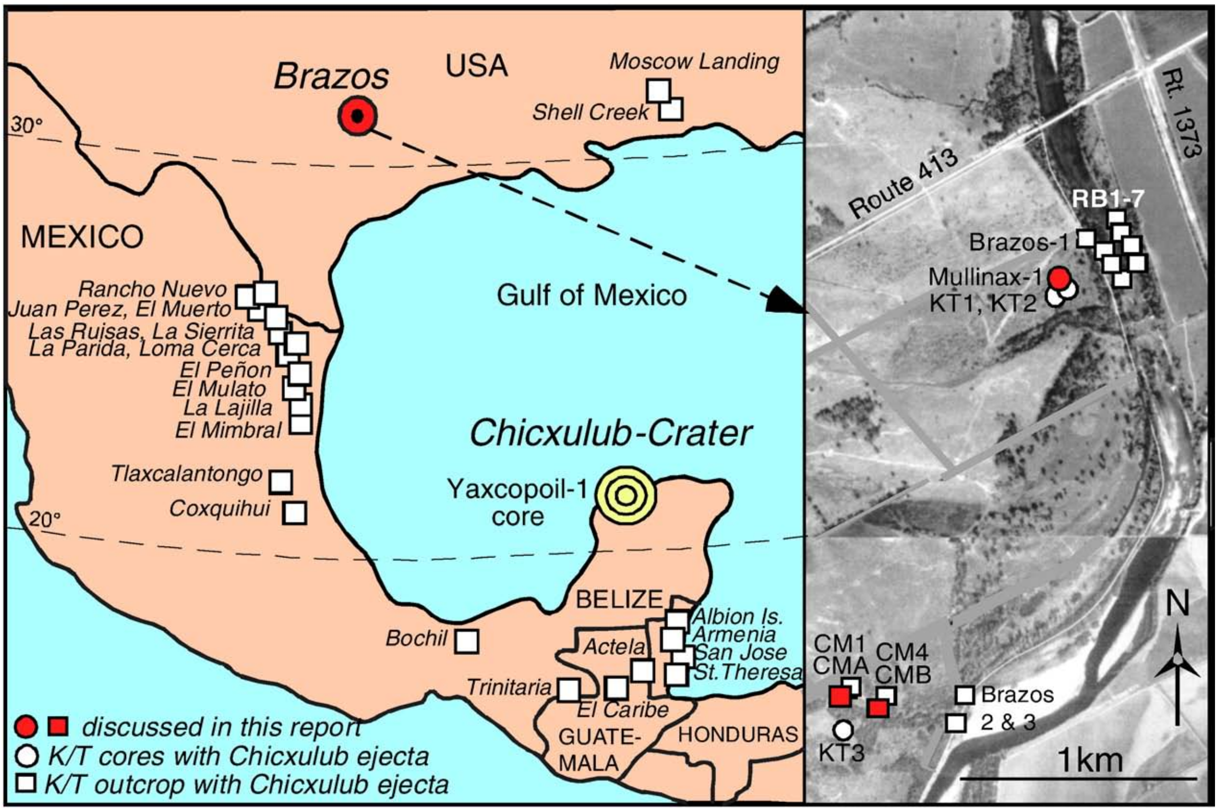

**Fig. 1.** Location map of Cretaceous–Tertiary boundary sections with Chicxulub impact spherule ejecta in Central America, Texas and Caribbean. Evidence from Texas presented in this study is from the new core Mullinax-1 (Mull-1) and a new outcrop sequence from the Cottonmouth Creek.

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**Fig. 2.** Cottonmouth Creek waterfall section showing the yellow clay layer that represents the Chicxulub impact spherule layer now altered to cheto smectite. This yellow clay layer is 45–60 cm below the sandstone complex, which has two reworked spherule layers at the base. Note that the glass spherule alteration to 100% cheto smectite is the same in all three layers. The K–T boundary is about 40 cm above the top of the sandstone complex.

data. The 38–63 µm size fraction was examined for very small species that may not be present in the larger size fractions, particularly in the early Danian.

Stable isotopes are based on well-preserved specimens of the benthic foraminifer *Lenticulina* spp. in the size fraction 150–250 µm with little or no sediment infilling chambers, as earlier illustrated in Barrera and Keller (1990). Stable isotope analysis was performed using a fully automated carbonate preparation system (MultiCarb) connected on-line to an isotope ratio mass spectrometer (Optima, Micromas Ltd., UK). Isotope ratio values are reported relative to V-PDB. Accuracy was checked in each analytical batch by measuring the isotope ratio in the NBS-19 standard with $\delta^{13}C = 1.95‰$ (V-PDB). Accuracy and precision, assessed on the basis of repeated measurements of the carbonate standard, was generally better than ±0.06‰ for each analytical batch.

## 3. Lithology and depositional environment

The lithology, mineralogy, stable isotopes and depositional environment of core Mull-1 and the Cottonmouth Creek (CMA and CMB) sections were detailed in Keller et al. (2007a) and only a brief summary is provided here. The late Maastrichtian sediments below the sandstone complex consist of undisturbed bedded and burrowed dark grey claystone with invertebrate shells, including the small ammonite, *Discoscaphites iris* (Conrad, 1858), which is indicative of the uppermost Maastrichtian ammonite zone in North America (Neil Landman, written communication 2005). At the Cottonmouth Creek, a prominent 3–4 cm thick yellow clay layer is present 45–60 cm below the base of the sandstone complex (Fig. 2). The yellow clay consists of 100% cheto smectite derived from altered Chicxulub impact glass with the same composition as in the two spherule-rich layers at the base of the sandstone complex (Keller et al., 2007a,b, 2008a). Cheto smectite has been widely observed in altered impact glass spherule layers in Mexico, Guatemala and Belize (Debrabant et al., 1999; Keller et al., 2003b). In the Brazos area, the yellow clay (Cheto smectite) marks the time of the Chicxulub impact.

The sandstone complex is about 40 cm thick in the CMAW and Mull-1 sections, but extends up to 1.8 m in the Darting Minnow Creek to the south of Cottonmouth Creek. The variable thickness reflects the size and position of the submarine channels. Sediment deposition is relatively consistent in all outcrops (Yancey, 1996). A layer of locally derived lithified clasts overlies the erosional base along with coarse green sandstone with glauconite, shells, phosphatic clasts and spherules (Fig. 3A and B). In most sections this spherule unit consists of 2–3 upward fining layers characterized by cheto smectite, similar to the yellow clay below (Keller et al., 2007a, 2008a). Some clasts contain well-preserved spherules, others contain burrows or mud cracks infilled with spherules. These clasts were lithified well prior to erosion, transport and redeposition (Fig. 3C–F). They suggest deposition in very shallow water and possibly subaerial exposure on topographic highs, as also indicated by the highly negative (−7 to −9‰) $\delta^{13}C$ values of the clasts that suggest secondary calcite precipitated from isotopically light meteoric water. These clasts thus provide strong evidence of the existence of an older spherule ejecta layer that was exposed and eroded during the sea level fall.

Above the spherule unit is a ~15–25 cm thick hummocky cross-bedded sandstone (HCS) with large *Ophiomorpha* burrows marked by erosive base and top. Gale (2006) reported up to five such upward fining sandstone units with ripples and burrows in the Brazos River bed, and interpreted these as seasonal storms. At the top, 10–15 cm thick upward fining silty mudstone with small, truncated burrows suggests fine mud settling from the water column (Smit et al., 1996; T. Adatte unpublished data).

The return to normal sedimentation is indicated by bedded dark claystone and mudstone with foraminifera, shells and burrows commonly infilled with framboidal pyrite that suggest low oxygen conditions. No lithological change occurs up to 25 cm above the K–T boundary where a 10 cm thick burrowed marly limestone concretion

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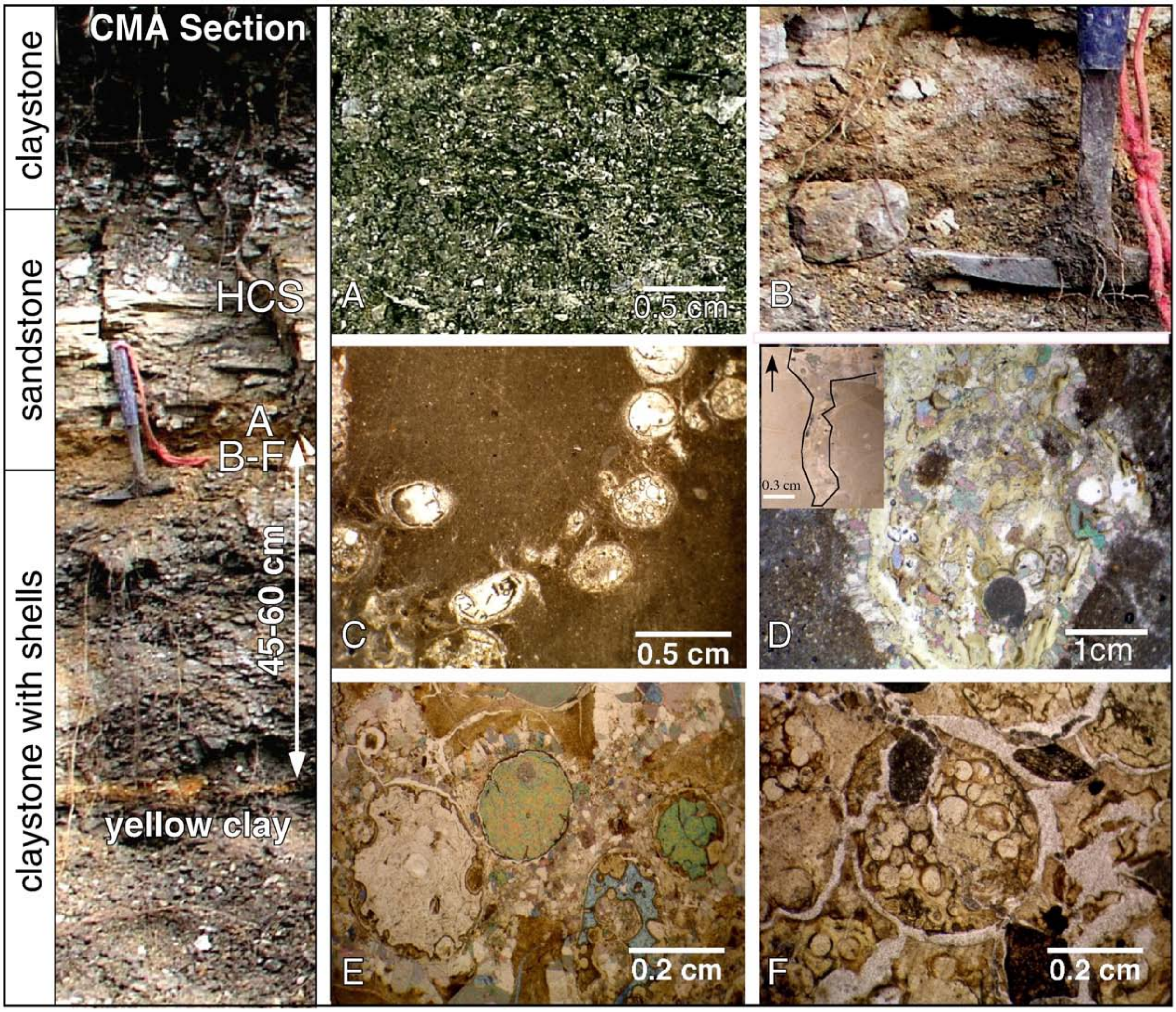

**Fig. 3.** The CMA section located 10 m from the waterfall (Fig. 2). A. Reworked spherules in shell hash and glauconite. B. Locally derived clasts at the base of the sandstone complex. C. Impact spherules within clasts infilling cracks. D. Impact spherules infill 0.3 cm long crack, which is lined with secondary gypsum. E–F. Impact spherules within clasts. The presence of clasts with impact spherules is strong evidence that the original spherule deposition predates deposition of the sandstone complex.

horizon is present. The 35 cm above consist of a strongly burrowed marly claystone truncated by a hiatus and overlain by gray silty shale with burrows and shells.

## 4. Biostratigraphy

### 4.1. K–T transition — age control

This study uses the high-resolution planktic foraminiferal zonation of the El Kef stratotype section developed by Keller et al. (1995), Pardo et al. (1996) and Li and Keller (1998a,b, Fig. 4). In the Brazos sections, the Maastrichtian was recovered in core Mull-1, but outcrop exposures along Cottonmouth Creek are limited to the uppermost Maastrichtian beginning about 1 m below the sandstone complex. In Mull-1, the uppermost Maastrichtian zone CF1 index species *Plummerita hantkeninoides* is rare though relatively continuously present in the 75 cm below the sandstone complex with additional occurrences at 9.55 and 9.7 m and a single specimen at 11.1 m (Figs. 5 and 6). We tentatively placed the base of zone CF1 at 9.7 m, excluding the isolated occurrence. At the CMAW section, *P. hantkeninoides* is also present in the exposed 1 m below the sandstone complex.

In the El Kef stratotype section of Tunisia, as well as globally, the K–T boundary is easily identified based on the mass extinction of planktic foraminifera, a negative $\delta^{13}$C shift and the first appearances of three Danian species (*Parvularugoglobigerina extensa, Woodringina hornerstownensis, Globoconusa daubjergensis*, Fig. 4). The Danian species first appear in the basal 5–10 cm of the 50 cm thick boundary clay (Arenillas et al., 2000; Keller et al., 2002; Luciani, 2002; Molina et al., 2006; Keller et al., 2008a). In the Brazos sections, these three K–T defining criteria clearly identify the K–T boundary 80 cm and 40 cm above the sandstone complex in Mull-1 and Cottonmouth Creek sections, respectively (Figs. 5–7). The 40 cm difference in the two sections is likely the result of local topography and erosion patterns. No Ir anomaly or impact spherules are present at the K–T boundary.

The first appearances of *P. eugubina* and *P. longiapertura* define the P0/P1a zone boundary (Figs. 4 and 5). These species are rare in the Brazos sections and their presence at 10–20 cm above the K–T boundary may not represent their evolutionary first appearances. A secondary marker for the P0/P1a boundary is the first post-K–T minimum in $\delta^{13}$C values, which tentatively places this boundary at 10 cm above the K–T boundary. Zone P1a is subdivided into subzones P1a(1) and P1a(2) based on the first appearances of *Parasubbotina pseudobulloides* and *Subbotina triloculinoides* (Fig. 4). At Cottonmouth Creek, subzone P1a(1) spans 45 cm and is characterized by positive $\delta^{13}$C and $\delta^{18}$O excursions. Subzone P1a(2) appears to be missing due to a hiatus, as suggested by the abrupt termination of *P. extensa*,

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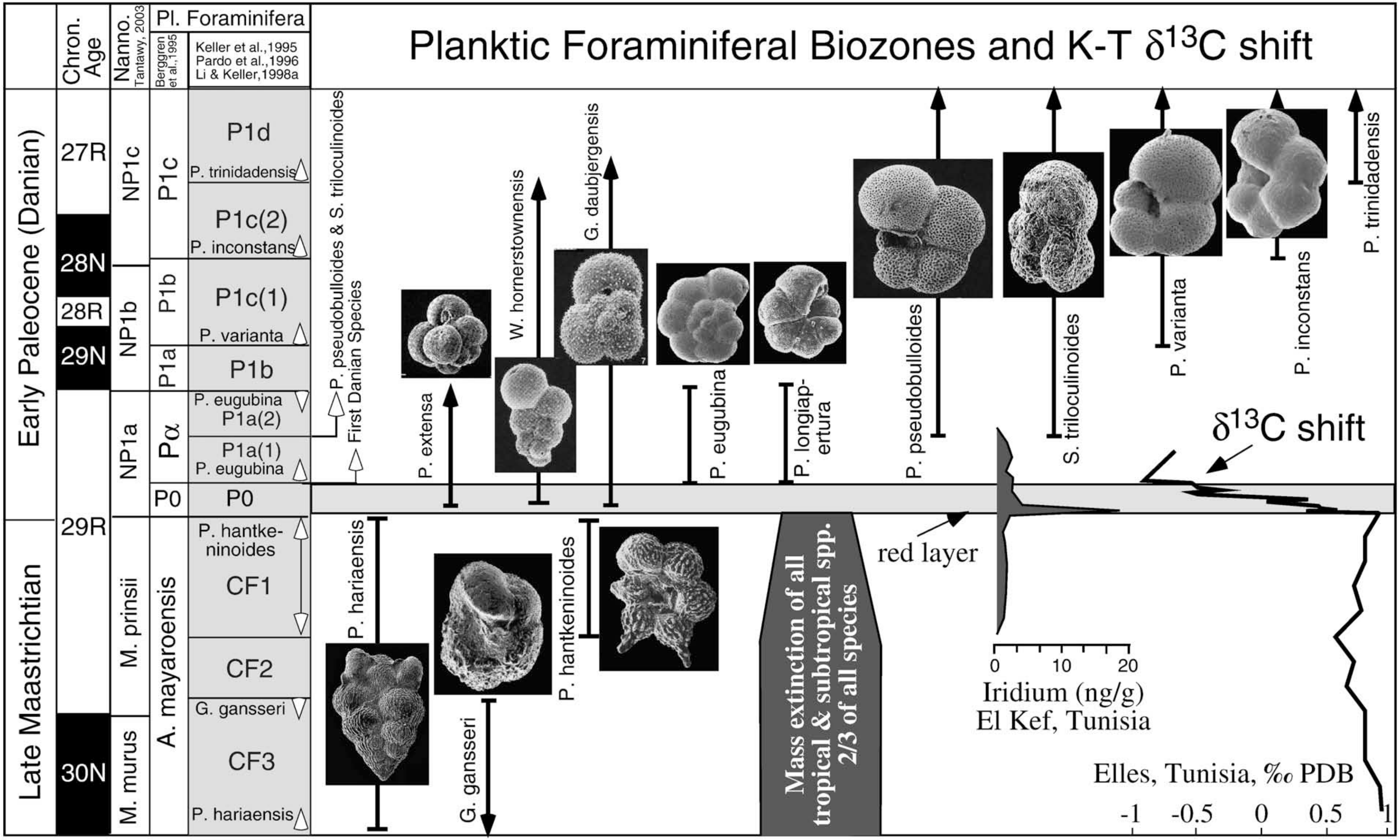

**Fig. 4.** Planktic foraminiferal biozonation across the Cretaceous–Tertiary transition at the El Kef and Elles stratotype and co-stratotype sections of Tunnisia based on Keller et al. (1995), Pardo et al. (1996) and Li and Keller (1998a) with comparison to the zonal scheme by Berggren et al. (1995) and the nannofossil zonation by Tantawy (2003). The K–T boundary is defined by the mass extinction of all tropical and subtropical species, the first appearances of Danian species in the boundary clay layer, the $\delta^{13}$C shift and the iridium anomaly.

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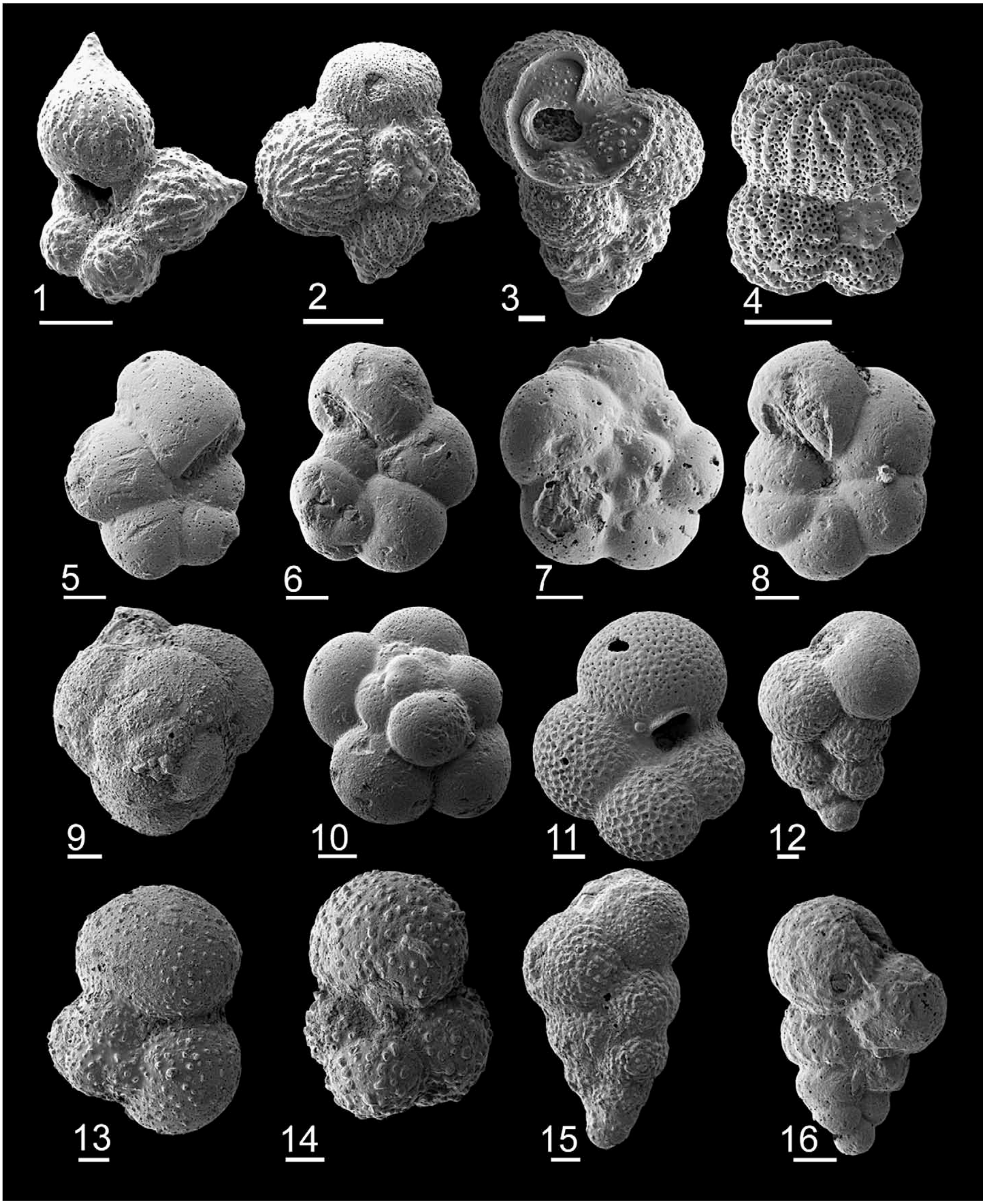

**Fig. 5.** SEM illustrations of planktic foraminifera from Brazos sections: Cretaceous species 1–4 from core Mull-1, zone CF1. 1–2. *Plummerita hantkeninoides*, scale bar 50 and 100 µm, respectively, 3. *Guembelitria cretacea*, scale bar 10 µm, 4. *Rugoblobigerina macrocephala,* scale bar 50 µm. Danian specimens (5–16) from Cottonmouth Creek sections, scale bar 10 µm. 5–6. *Parvularugoglobigerina longiapertura*, 7–8. *P. eugubina*, 9–10. *P. extensa*, 11. *Parasubbotina varianta*, 12. *Woodringina claytonensis*, 13–14. *Globoconusa daubjergensis*, 15–16. *Woodringina hornerstownensis*. Note the excellent preservation, absence of calcite overgrowth, clear pustules (3) and open pores and well-defined ridges (1–2, 4) in Cretaceous specimens. Such preservation argues against a diagenetic overprint in stable isotope data. In contrast, early Danian specimens are affected by dissolution.

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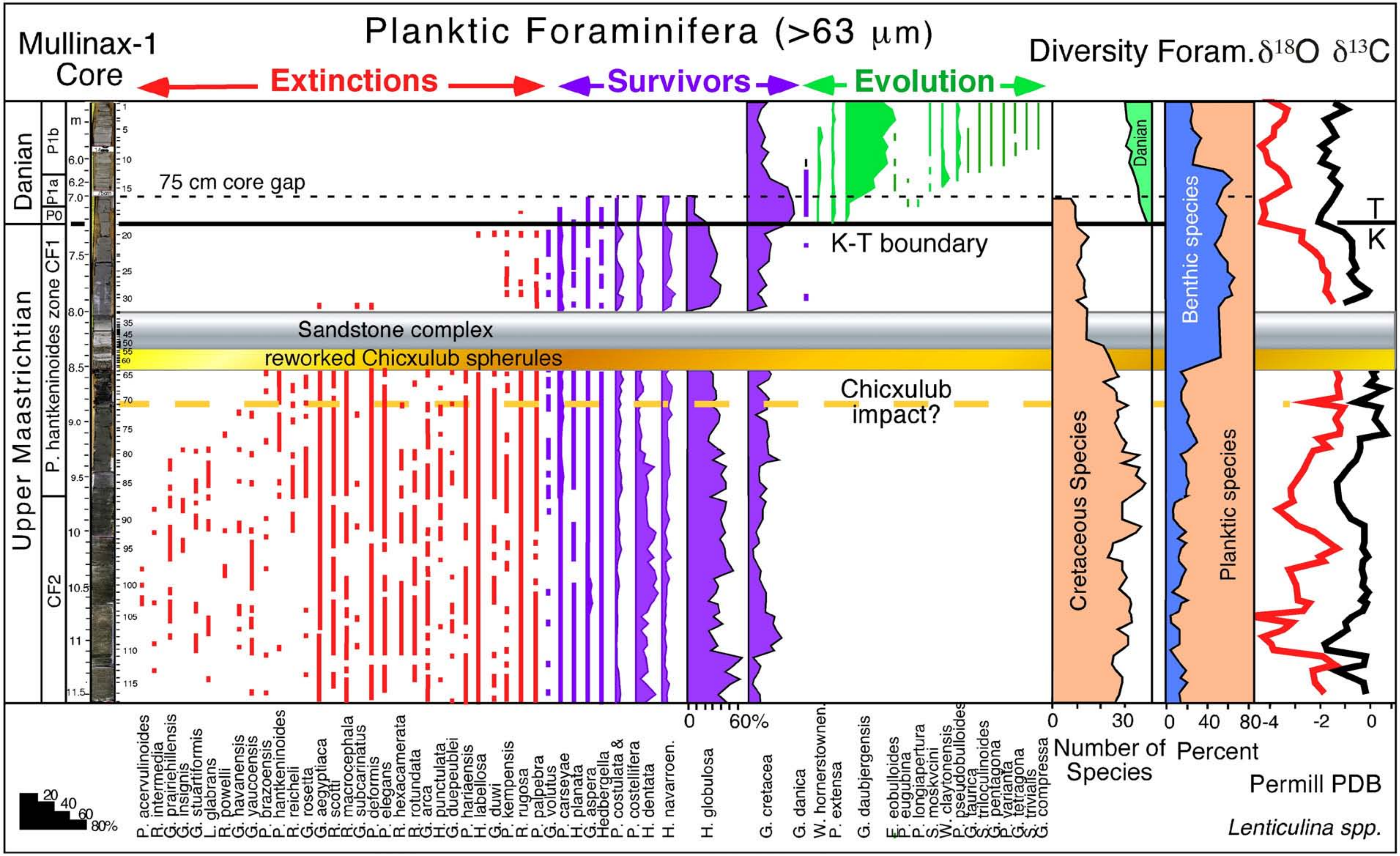

**Fig. 6.** Stable isotopes and planktic foraminiferal ranges and species abundances of smaller species (>63 µm) in the upper Maastrichtian to Danian in core Mullinax-1 (Mull-1). Note the K–T boundary is marked by the $\delta^{13}C$ shift, first Danian species and species extinctions. Cretaceous species diversity is very low above the sandstone complex because of the shallow inner neritic environment, which persisted into the early Danian. The altered Chicxulub glass spherule layer is marked by the negative $\delta^{13}C$ and $\delta^{18}O$ excursions, but no significant changes are apparent in diversity or abundance of species.

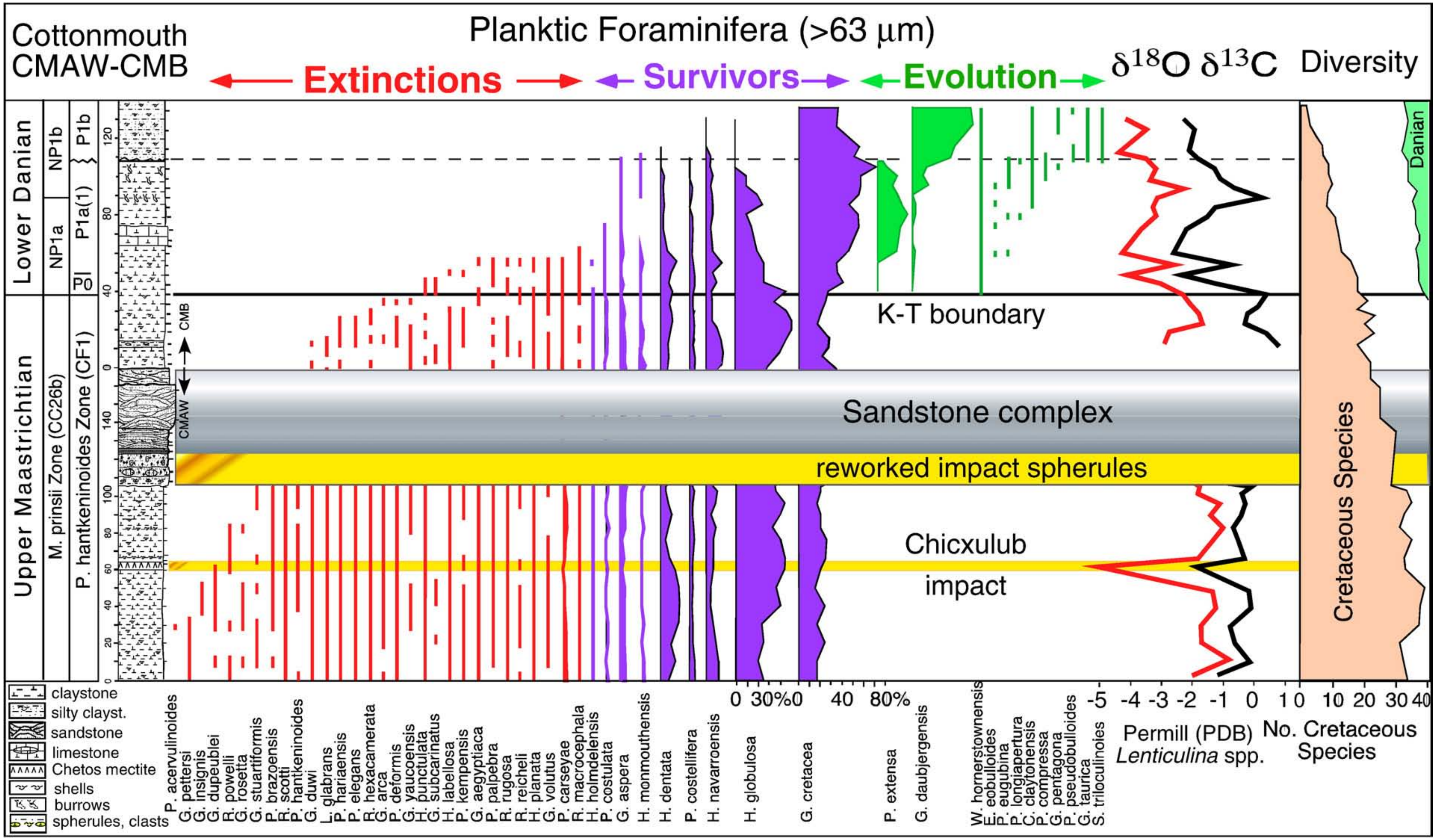

**Fig. 7.** Stable isotopes and planktic foraminiferal ranges and species abundances of smaller species (>63 µm) in the upper Maastrichtian to Danian in the Cottonmouth Creek (CMAW-CMB) sections. Most Cretaceous species persist to the K–T boundary. Species richness decreased gradually beginning with the sea-level fall and onset of sandstone deposition. The original Chicxulub glass spherule layer, now altered to cheto smectite) is marked by negative $\delta^{13}C$ and $\delta^{18}O$ excursions, but no significant changes are apparent in diversity or abundance of species.

coincident increase in abundance of *G. daubjergensis* (Fig. 5), simultaneous first appearances of *P. pseudobulloides, S. triloculinoides* and *G. taurica,* but absence of *P. eugubina.* All of these biotic markers coincide with a major lithologic change from shale to very fossiliferous silty shale (Fig. 7). The first large (>150 μm) well-developed early Danian planktic foraminiferal assemblages indicative of zone P1b appear in this silty shale and suggest that the hiatus is limited to subzone P1a(2). In Mull-1, a 75 cm core gap is present in zone P1a and as a result most of subzone P1a(1) and the positive $\delta^{13}C$ excursion are missing (Fig. 6).

### *4.2. K–T defined by impact evidence?*

Despite the easily identifiable global K–T criteria, the placement of the K–T boundary (KTB) in the Brazos sections has been contentious. This is largely because the Chixculub impact is believed to have caused the K–T mass extinction and therefore the presence of impact spherules at the base of the sandstone complex must define the K–T boundary and the sandstone complex an impact generated tsunami deposit (e.g., Hansen et al., 1987; Bourgeois et al., 1988; Hansen et al., 1993; Smit et al., 1996; Heymann et al., 1998; Schulte et al., 2006, 2008). This interpretation gains support from the recent proposal to identify the K–T boundary based on just two criteria, the evidence of an asteroid impact and the mass extinction (Molina et al., 2006). The problem with such restrictive criteria is that it leads to circular reasoning. One cannot test the hypothesis that the Chicxulub impact caused the K–T boundary mass extinction by defining the impact as the K–T boundary.

The problems associated with using impact criteria (iridium and impact spherules) to identify the K–T boundary were reviewed by Keller (2008) and specifically for Brazos by Keller et al. (2008a) in rebuttal to Schulte et al. (2008). The main problem with using iridium is that multiple Ir anomalies of cosmic and/or volcanic origins are commonly observed above or below the mass extinction (Sawlowicz, 1993; Keller et al., 2003a; Grachev et al., 2005; Stüben et al., 2005; Keller, 2008; Keller et al., 2008a). In Texas, none of the three Ir anomalies coincide with the K–T boundary or impact spherules (Asaro et al., 1982; Graup et al., 1989; Rocchia et al., 1996; Keller et al., 2008a). The problem with using Chicxulub impact spherules is that they are never associated with the K–T boundary layer in expanded sections in Mexico or Texas. Only in condensed and frequently disturbed deep-sea sections, such as at Bass River, Blake Nose and Demerara Rise, is juxtaposition of the mass extinction, Ir anomaly and Chicxulub spherules observed and claimed as proof that the Chicxulub impact caused the K–T mass extinction (e.g., Olsson et al., 1997; Norris et al., 1999, 2000; MacLeod et al., 2007). With so much variability in the stratigraphic position and regional occurrence of the impact signals, it is prudent to rely on independent global K–T criteria, such as the mass extinction, first appearances of Danian species and the $\delta^{13}C$ shift (Fig. 4).

## 5. Stable isotopes

Preservation of Maastrichtian specimens is excellent (Fig. 5), as also observed by Barrera and Keller (1990). Examination by scanning electron microscope (SEM) did not reveal signs of calcite overgrowth or recrystallization in Maastrichtian species. Benthic $\delta^{18}O$ values at Brazos vary between −0.5‰ to −4‰ and are generally lower than typical Late Maastrichtian deep-sea values that vary between +0.9‰ to −0.5‰ (Li and Keller, 1989c; Barrera and Savin, 1999; Li and Keller, 1999; Frank et al., 2005). These differences reflect the warmer bottom temperatures on continental shelves as compared with deep oceans. However the presence of abundant pyrite framboids in upper Maastrichtian sediments at Brazos also suggest that the light $\delta^{18}O$ carbonate may have been partially produced during bacterial sulfate reduction. Above the K–T boundary, thin and fragile foraminiferal tests (Fig. 5) show dissolution effects and diagenetic replacement (Barrera and Keller, 1990).

Stable isotope results for core Mull-1 and the Cottonmouth (CMAW-CMB) are based on the benthic foraminifer *Lenticulina* spp. (Figs. 6 and 7). Benthic species were analyzed because no planktic K–T survivors are abundant enough for analysis (but see Barrera and Keller, 1990). In Mull-1, three major negative $\delta^{18}O$ and $\delta^{13}C$ excursions characterize the CF2-CF1 interval. The first excursion in the upper zone CF2 shows rapid parallel decreases of 2.5‰ and 2‰ in $\delta^{18}O$ and $\delta^{13}C$, respectively. After the $\delta^{13}C$ drop, there is a steady recovery with a plateau reached at pre-excursion values, whereas $\delta^{18}O$ values remain low, but variable, increasing only just before the second negative excursion.

The second negative $\delta^{18}O$ and $\delta^{13}C$ excursions peak at the CF2/CF1 boundary. Both show parallel increases, reaching maxima simultaneously 60 cm below the sandstone complex in Mull-1. Values remain relatively steady up to the sandstone complex, except for short 1.5‰ and 1‰ excursions in $\delta^{18}O$ and $\delta^{13}C$ correlative with the peak $\delta^{18}O$ and $\delta^{13}C$ excursions of −3.5‰ and 1.6‰ at the original Chicxulub impact spherule layer at Cottonmouth Creek (Figs. 6 and 7). Above the sandstone complex, Maastrichtian $\delta^{18}O$ and $\delta^{13}C$ values continue, then decrease gradually and drop to minimum values at the K–T boundary. Positive $\delta^{18}O$ and $\delta^{13}C$ excursions in P1a(1) of Cottonmouth Creek and reduced excursion in Mull-1 due to a core gap mark a brief recovery, as previously documented by Barrera and Keller (1990).

### *5.1. Climatic trends*

The negative $\delta^{18}O$ and $\delta^{13}C$ excursions mark climate warming and decreased productivity. Previous studies have shown climatic warming of 3–4 °C during the late Maastrichtian zones CF1-CF2 in marine and terrestrial environments (e.g., Li and Keller, 1998b; Olsson et al., 2001; Nordt et al., 2003; Wilf et al., 2003; MacLeod et al., 2005). The expanded core Mull-1 record shows this warm interval as two short warm events followed by gradual cooling and steady cool conditions across the sandstone complex (Fig. 6). This cooling trend was interrupted only by the short negative $\delta^{18}O$ and $\delta^{13}C$ excursions associated with the Chicxulub impact that suggest a significant transient effect on climate and primary productivity, though a partially diagenetic overprint cannot be ruled out. The K–T boundary is preceded by gradual warming and decreasing productivity, suggesting that environmental changes began near the end of the Maastrichtian and culminated in rapid warming and a drop in productivity at the K–T boundary (Figs. 6 and 7). A temporary post-K–T recovery occurred in the early Danian zone P1a.

Late Maastrichtian climate warming has been attributed to a variety of possible causes, including greenhouse gas emissions from Deccan volcanism (Ravizza and Peucker-Ehrenbrink, 2003). Others have suggested that CO2 emissions were insufficient to account for the 3–4 °C warming and attribute the end-Maastrichtian cooling to massive Deccan eruptions and $SO_2$ emissions (see Chenet et al., 2007). Emerging new data on the rate and timing of Deccan eruptions, gas emissions and the position of the K–T boundary within the Deccan lava pile (Chenet et al., 2007, 2008, in press; Keller et al., 2008b; Self et al., 2008) is likely to substantially improve our understanding of these climatic changes.

## 6. Paleoenvironmental proxies

### *6.1. Paleodepth and planktic/benthic ratio*

In a study of benthic foraminifera in Brazos core KT3 and outcrops Keller (1992, p. 82) observed very low species richness (~10 species) as compared with 20–25 species at El Kef, Caravaca or the Negev where middle to outer shelf or upper slope paleodepths were estimated. She concluded that deposition at Brazos occurred in a

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much shallower middle to outer neritic environment. This paleodepth comparison was overly optimistic. Current data on planktic foraminiferal depth ranking, the planktic/benthic ratio, stable isotopes and lithologic characteristics suggest that the Brazos environment shallowed from middle to inner shelf depths by the time of sandstone deposition in zone CF1.

Planktic/benthic (P/B) ratios are frequently used as parameter for paleobathymetric reconstructions. In normal neritic condition, the P/B ratio is expected to increase with depth due to higher productivity of planktic foraminifera in open sea environments. In inner neritic environments benthic foraminifera are dominant as deeper dwelling planktic foraminifera are excluded from shallow environments. Deposition at Brazos during the upper Maastrichtian CF2-CF1 interval below the sandstone complex occurred in progressively decreasing middle neritic depths (<100 m), as suggested by the gradually decreasing species richness and increasingly rare and sporadically present larger deeper dwelling planktic foraminifera (Figs. 8 and 9). At the unconformity at the base of the sandstone complex, a sharp increase in benthic abundance (to >60%) and parallel decrease in planktics (all deeper dwelling species disappear) signal inner shelf depths (Fig. 8). The abrupt change is an artifact of the unconformity with an estimated 1.8 m of sediment eroded (Gale, 2006). Shallow water conditions at the unconformity are also indicated by clasts with mud cracks, sometimes infilled with spherules (Fig. 3C and D). These lithified clasts probably derived from a unit that was originally deposited in very shallow water and at least temporarily exposed to desiccation and erosion. Above the unconformity, across the K–T boundary and into the early Danian sea level gradually deepened, but remained at inner shelf depth, as indicated by continued high benthic and low planktic abundances (Fig. 6). Subsequently, increasing planktic and decreasing benthic abundances in zone P1b indicate a deeper environment.

### 6.2. Species richness and abundance

Late Maastrichtian species richness (number of species in any given sample) of planktic foraminifera (63–150 μm) in the CMAW-CMB and Mull-1 sections varies between 30–38 and 28–34 species, respectively, and gradually decreases through the K–T boundary beginning below the sandstone complex (Figs. 6 and 7). The slightly lower overall species richness at Mull-1 is likely due to the smaller sample size available from the Mull-1 core and hence lower probability of finding rare species. In contrast, species richness of the larger (>150 μm) specialized and predominantly deeper dwelling, or *K*-strategy, species remains nearly constant between 18–23 in both sections below the sandstone complex (Figs. 8 and 9). No larger species are present above this interval because deeper dwelling species are excluded in inner neritic depths, though some dwarfed species survived (Fig. 7). The very low species richness at Brazos is probably partly due to the relatively eutrophic conditions, indicated by high TOC and pyrite framboids, which were probably unfavorable for symbiont-bearing species such as racemiguembelinids.

Relative abundances of individual species populations are more sensitive indicators of environmental change than the presence or absence of species. In the 63–150 μm size fraction, late Maastrichtian assemblages are dominated by the low oxygen tolerant *Heterohelix globulosa,* less common *Heterohelix dentata* and *Heterohelix navarroensis* (10–30%) and common *Guembelitria cretacea* (20–30%, Figs. 6 and 7). This pattern remains relatively constant largely because only species tolerant of environmental fluctuations (*r*-strategists) thrived. Similar abundance patterns are generally observed in continental shelf and marginal environments with *Guembelitria* abundances varying with the degree of environmental stress (e.g., Schmitz et al., 1992; Keller et al., 1993; Apellaniz et al., 1997; Luciani, 1997; Keller et al., 1998; Luciani, 2002; Abramovich et al., 2002; Keller, 2001; Hart et al., 2005; Pardo and Keller, in press).

A similar faunal abundance pattern is observed in the >150 μm size fraction, which assesses mainly the environment for larger, complex ornamented species, or *K*-strategists. This size fraction is also dominated by *H. globulosa* and common *H. dentata* and *Globigerinella aspera* during the late Maastrichtian zones CF1-CF2 (Figs. 8 and 9). The only other notable abundances are *Pseudoguembelina costulata*, *P. costellifera*, *Rugoglobigerina rugosa*, *Rugoglobigerina macrocephala*, *R. scotti*, *Planoglobulina carseyae*, *Pseudotextularia elegans* and *P. deformis.* Globotruncanids, racemiguembelinids and planoglobulinids are rare, sporadically present and dwarfed. Similar to the smaller size fraction, there is no significant change in species abundances (Figs. 8 and 9).

## 7. Biotic effects of end-Cretaceous events

### 7.1. Chicxulub impact caused no extinctions

The oldest and original Chicxulub impact spherule ejecta layer in the Cottonmouth Creek (CMAW) section occurs in the lower part of zone CF1 between 45–60 cm below the sandstone complex and consists of a 3–4 cm thick spherule layer altered to cheto smectite (Keller et al., 2007a). Negative $\delta^{18}$O and $\delta^{13}$C excursions suggest significant short-term environmental effects (Figs. 6 and 7). The biotic effects can be evaluated from the planktic foraminiferal record in both small (>63 μm) and larger (>150 μm) species. In the CMAW and Mull-1 Sections 4 and 9 smaller species (>63 μm), and 3 and 6 larger (>150 μm) species, respectively, gradually disappeared below the impact spherule layer Figs. 6–9). The higher number of species disappearing in core Mull-1 is due to the smaller sample size and hence under-representation of rare species. However, the gradual species disappearances, rare and sporadic occurrences are a result of increasing biotic stress affecting deeper dwelling species in the shallowing shelf environment. In open marine environments, all of these species are known to range up to the K–T boundary. Thus, no species extinctions can be attributed to the Chicxulub impact and no significant changes occurred in dominant species populations.

### 7.2. Sea-level change — pseudo mass extinction

An estimate of biotic stress levels associated with the sea-level fall to inner neritic depths can be obtained from assemblages above and below the sandstone complex that marks this event. In the smaller size fraction (>63 μm) 29 of the 33 species at Cottonmouth Creek and 18 of 33 species at Mull-1 are present above the sandstone complex (Figs. 6 and 7). All but 12 of these species are very rare and sporadically present in both sections and 14 are dwarfed morphotypes of larger species (*K*-strategists). There are no significant changes in dominant species abundances. As noted above, the fewer species present in Mull-1 are due to the smaller sample size available from the core and hence under-representation of rare species.

In both sections the most dramatic change in planktic foraminifera occurred in the larger specialized species (>150 μm), which are also deeper dwellers. All of these disappeared as deeper habitats were eliminated, although some dwarfed morphotypes survived (Figs. 8 and 9) (MacLeod et al., 2000; Keller and Abramovich, in press). The sea-level fall to inner neritic depths thus caused the most dramatic change in larger (>150 μm) planktic foraminifera and marks a pseudo mass extinction. Some workers interpret this pseudo mass extinction as the K–T mass extinction caused by the Chicxulub impact at the base of the sandstone complex (Hansen et al., 1993; Smit et al., 1996; Schulte et al., 2006, 2008).

### 7.3. K–T mass extinction

The K–T mass extinction in the Brazos sections is typical of shallow marginal environments with reduced species diversity. In the

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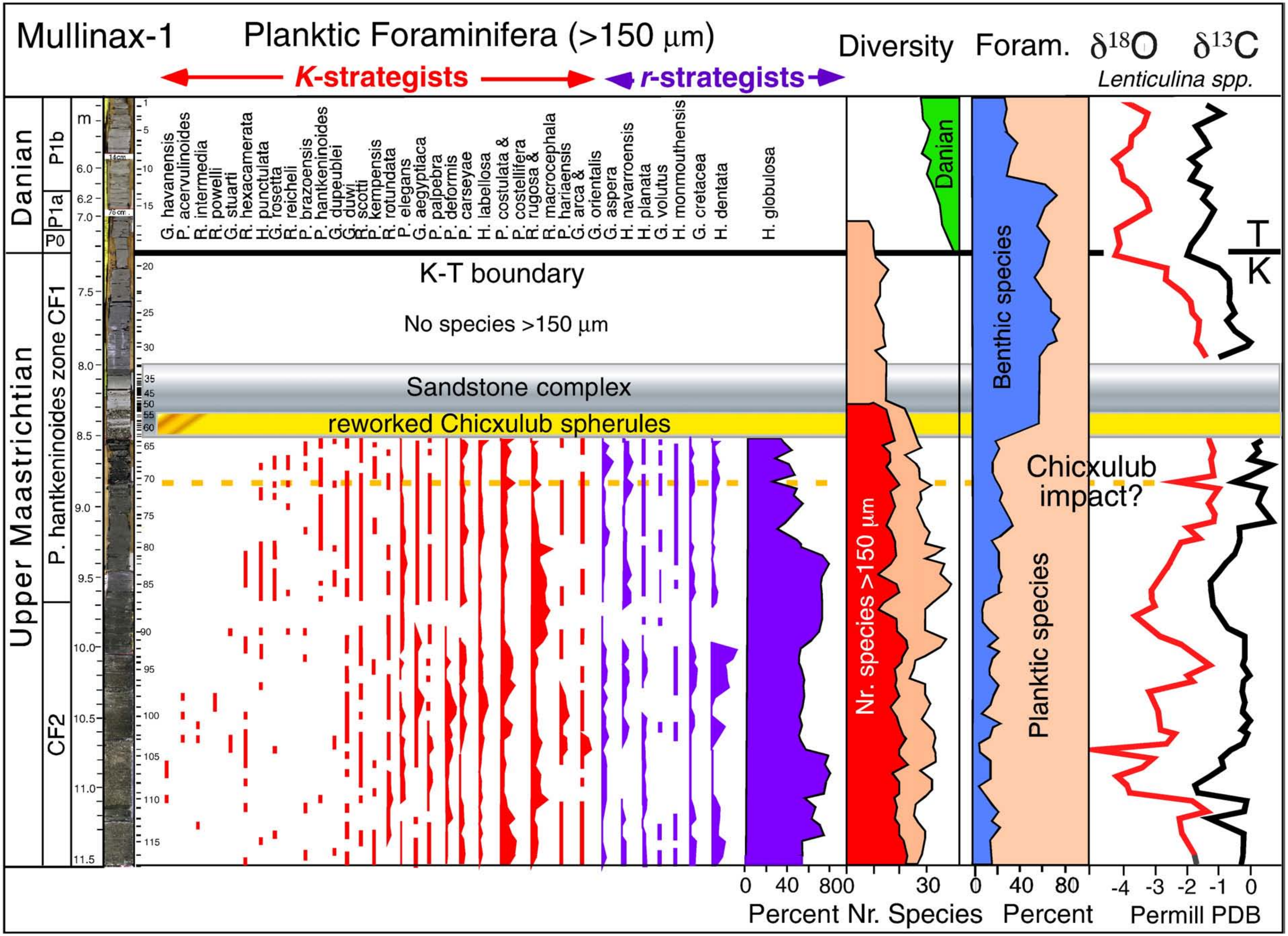

**Fig. 8.** Stable isotopes and planktic foraminiferal ranges and species abundances of larger species (>150 µm) in the upper Maastrichtian to Danian in the Mullinax-1 core. All larger species living in deeper waters disappeared forming a pseudo mass extinction at the unconformity at the base of the sandstone complex. Their disappearances are due to the shallow inner neritic depth and probably eutrophic conditions. All of these species are known to survive up to the K–T boundary.

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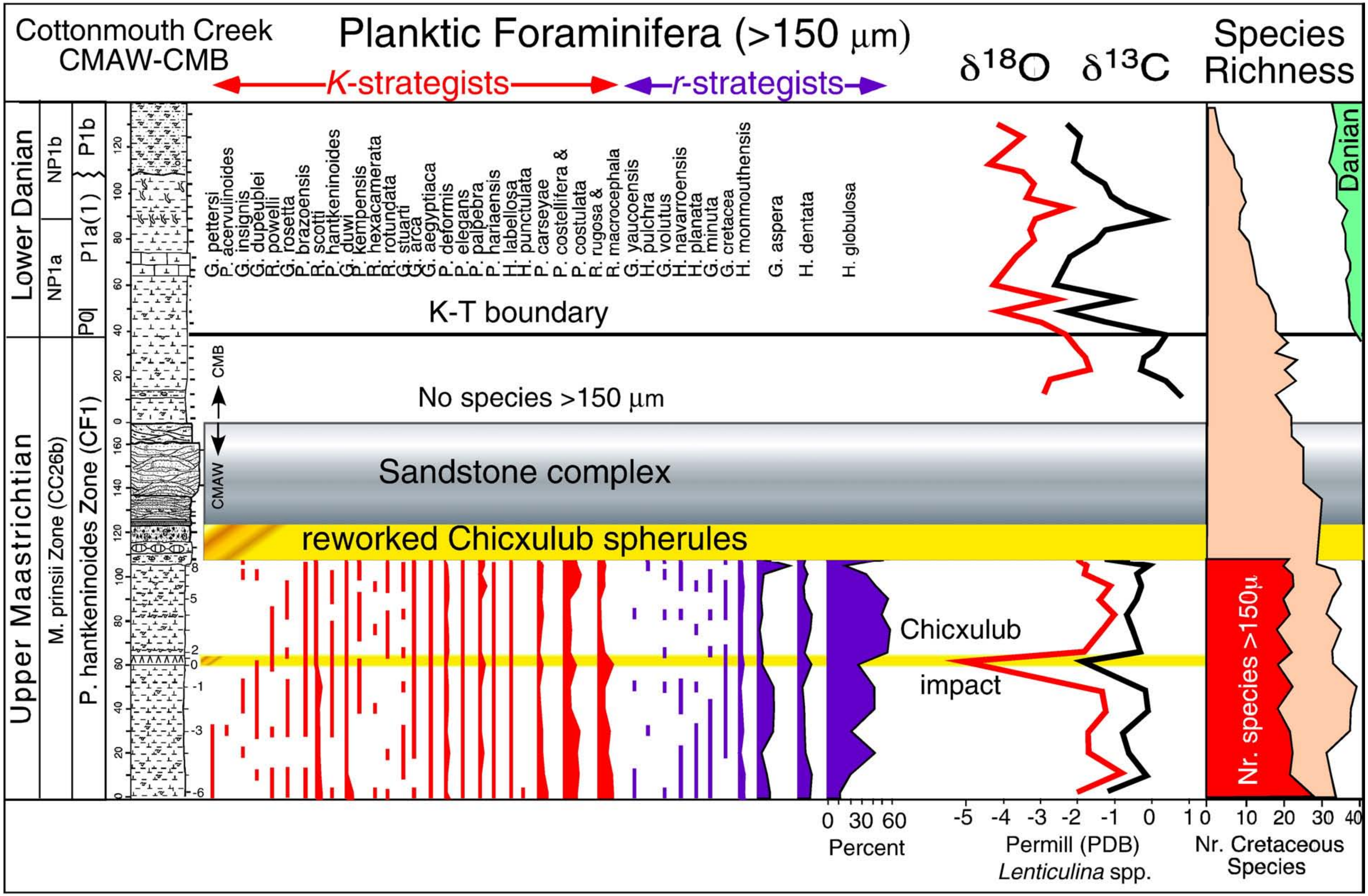

**Fig. 9.** Stable isotopes and planktic foraminiferal ranges and species abundances of larger species (>150 µm) in the upper Maastrichtian to Danian in the Cottonmouth Creek (CMAW-CMB) sections. All larger species living in deeper waters disappeared and mark a pseudo mass extinction at the unconformity at the base of the sandstone complex. Their disappearances are due to the shallow inner neritic depth and probably eutrophic conditions. All of these species are known to survive up to the K–T boundary.

Cottonmouth section, of the 29 species below the K–T boundary, 21 are present in the 20 cm above, mostly due to reworking and some survivors (Fig. 6). The same pattern is observed in Mull-1, though fewer rare species are present due to smaller sample size. The same eight Cretaceous species are common in both sections above the K–T boundary (e.g., *Guembelitria cretacea*, *Heterohelix globulosa*, *H. dentata*, *H. navarroensis*, *Hedbergella monmouthensis*, *Pseudoguembelina costulata*, *P. costellifera*, *Globigerinelloides aspera*, Figs. 6 and 7). All of these species are commonly observed in early Danian sediments and may be short-term K–T survivors (Keller, 1988, 1989a,b; Barrera and Keller, 1990; Keller et al., 1993; Luciani, 1997, 2002; Keller et al., 2002; Molina et al., 2006). Only the disaster opportunist *G. cretacea* is a long-term K–T survivor.

*Heterohelix globulosa*, a short-term survivor, as indicated by stable isotope measurements at Brazos and Nye Klov in Denmark (Barrera and Keller, 1990; Keller et al., 1993), dominated the late Maastrichtian, gradually decreased across the K–T boundary and disappeared in zone P1a. During the same time the disaster opportunist *Guembelitria* rapidly increased to ~80%, coincident with the evolution of the first Danian species and the negative $\delta^{13}$C shift. This is the observed biotic stress pattern in continuous K–T sections globally, although the change to *Guembelitria* dominance is usually more abrupt in the deep-sea due to condensed sedimentation (review in Keller and Pardo, 2004; Keller, 2008).

However, the Brazos mass extinction differs significantly from continental shelf and open marine environments by the more gradual extinction pattern and about 50% lower species richness. Both of these are the result of the shallow depositional environment, as observed from similarly shallow areas in Denmark, the south of Tunisia and Argentina (Keller et al., 1993, 1998, 2007b). Sea level changes thus have profound biotic effects in shallow continental shelf environments.

## 8. Discussion

### 8.1. Biotic response to environmental stress

Species richness and the relative abundances of individual species populations are two commonly used proxies to assess environmental changes. In recent years, isotopic depth ranking studies of planktic foraminifera have greatly advanced our understanding of the nature of environmental stress associated with faunal turnovers (Abramovich et al., 2003; Frank et al., 2005). Based on these studies diversity changes and biotic stress conditions across a spectrum of environments from open marine to continental shelf and marginal seas can now be understood as a function of watermass stratification and sea water depths (Fig. 10).

Large Cretaceous species comprise a very diverse group of generally complex, ornamented and highly specialized species, or *K*-strategists, that thrived in open marine tropical and subtropical environments (e.g., planoglobulinids, pseudoguembelinids, racemiguembelinids, globotruncanids, rugoglobigerinids, Fig. 10). But *K*-strategists were intolerant of environmental changes and hence prone to extinction (Begon et al., 1996a,b; Abramovich et al., 1998; Keller and Pardo, 2004; Keller and Abramovich, in press). Most thrived at intermediate or thermocline depths, except for pseudoguembelinids (*P. palpebra*, *P. hariaensis*, *P.*

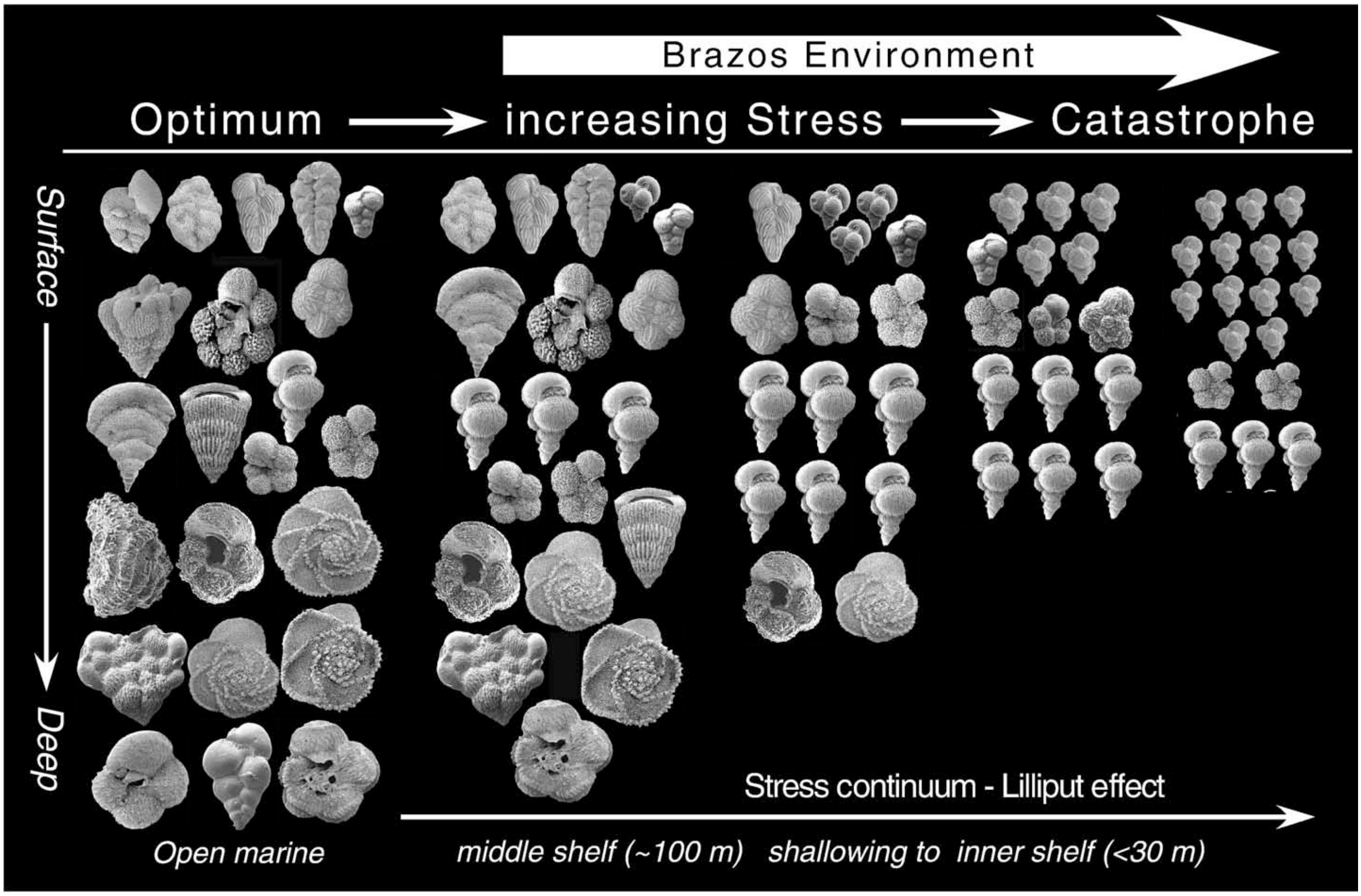

**Fig. 10.** Model showing the effects of biotic stress upon planktic foraminifera induced by a shallowing marine environment. Optimum conditions occur in open marine conditions deeper than 250 m. Shallowing to middle neritic depth results in ~50% reduction in species diversity. With further shallowing to inner neritic environments and increasing biotic stress, species diversity successively decreases. Catastrophic conditions are reflected by nearly monospecific assemblages and are generally accompanied by eutrophic conditions. In the Brazos environment, these biotic stress conditions accompany the gradual sea-level fall from middle to inner neritic depths well before the K–T boundary event.

*costulata*, *P. costellifera*) and rugoglobigerinids, which thrived in the lower part of the surface mixed layer (Abramovich et al., 2003). Because of the specialized habitats required by *K*-strategists, maximum species diversity (about 50–65 species) is observed only in optimum, well-stratified open marine tropical and subtropical environments that are generally deeper than 250 m (Fig. 10). In shallower environments (e.g., middle shelf ~100 m), species richness is reduced by about 50% as the deeper dwelling *K*-strategists are eliminated and survivors may be dwarfed as a result of environmental stress. Further shallowing to inner neritic depth results in exclusion of nearly all *K*-strategists and dwarfing of survivors as observed in the Brazos sections beginning below and continuing above the sandstone complex.

Smaller species, or *r*-strategists (e.g., heterohelicids, hedbergellids, guembelitrids, globigerinellids), are less diverse ecologic generalists that thrived in the surface mixed layer and low oxygen conditions. They are generally more tolerant of environmental perturbations, including variations in temperature, salinity, oxygen and nutrients commonly associated with shallow water environments or catastrophes (Koutsoukos, 1996; Keller and Pardo, 2004). Two species groups are particularly important environmental indicators. Heterohelicids (e.g., *Heterohelix globulosa*, *H. navarroensis*, *H. planata*, *H. dentata*) thrived in low oxygen environments, whereas guembelitrids (*G. cretacea*, *G. trifolia*, *G. danica*, *G. irregularis*, *G. dammula*) thrived in nutrient-rich surface waters where few other species survived and are therefore known as disaster opportunists. *R*-strategists therefore tend to be survivors in high stress conditions, whether in shallow shelf environments, the aftermath of the K–T mass extinction, or any other catastrophes (Fig. 10).

Thus, while increasing biotic stress results in the reduction and the eventual elimination of all *K*-strategists and some *r*-strategists as catastrophic conditions are approached, a small group of low oxygen tolerant heterohelicids and opportunistic surface dwellers survived and thrived (Fig. 10). Some of these species responded to environmental catastrophes by opportunistic blooms, such as observed for *Heterohelix* and *Guembelitria* species (Keller and Pardo, 2004), with a subset showing morphological abnormalities (Coccioni and Luciani, 2007). Reduced adult species size, or dwarfing (Lilliput effect), is another biotic response to high stress conditions that affects *K*-strategists and many *r*-strategists (e.g., Kucera and Malmgren, 1998; MacLeod et al., 2000; Olsson et al., 2001; Abramovich and Keller, 2003; Keller and Abramovich, in press). All of these biotic stress conditions were observed in the planktic foraminiferal assemblages of the Brazos sections as a result of the shallowing sea to inner shelf depth, long-term climate changes and the K–T event. But no measurable effects are associated with the Chicxulub impact.

### 8.2. Brazos depositional scenario

The K–T sections along the Brazos River in Texas reveal three stratigraphically separate events: the Chicxulub impact, sea-level fall and K–T mass extinction. These sections are thus unique in that they provide the opportunity to evaluate the biotic effects before and after each event in a shallow continental shelf environment. Upper Maastrichtian (zones CF2 and CF1) sedimentation occurred in a shallowing middle shelf environment (HST, Fig. 11) during two phases of rapid climate warming followed by gradual cooling (Fig. 11). The Chicxulub impact struck Yucatan during the early part of the cooling phase. Although this impact likely caused at least regional catastrophic destruction (e.g., earthquakes, tsunami waves), there is no evidence of any significant disturbance associated with the ejecta layer in Brazos sediments or in NE Mexico (review in Keller et al., 2003a; Keller, 2008).

The sandstone complex, which is commonly interpreted as the K–T impact-tsunami event (e.g., Bourgeois et al., 1988; Smit et al., 1992,

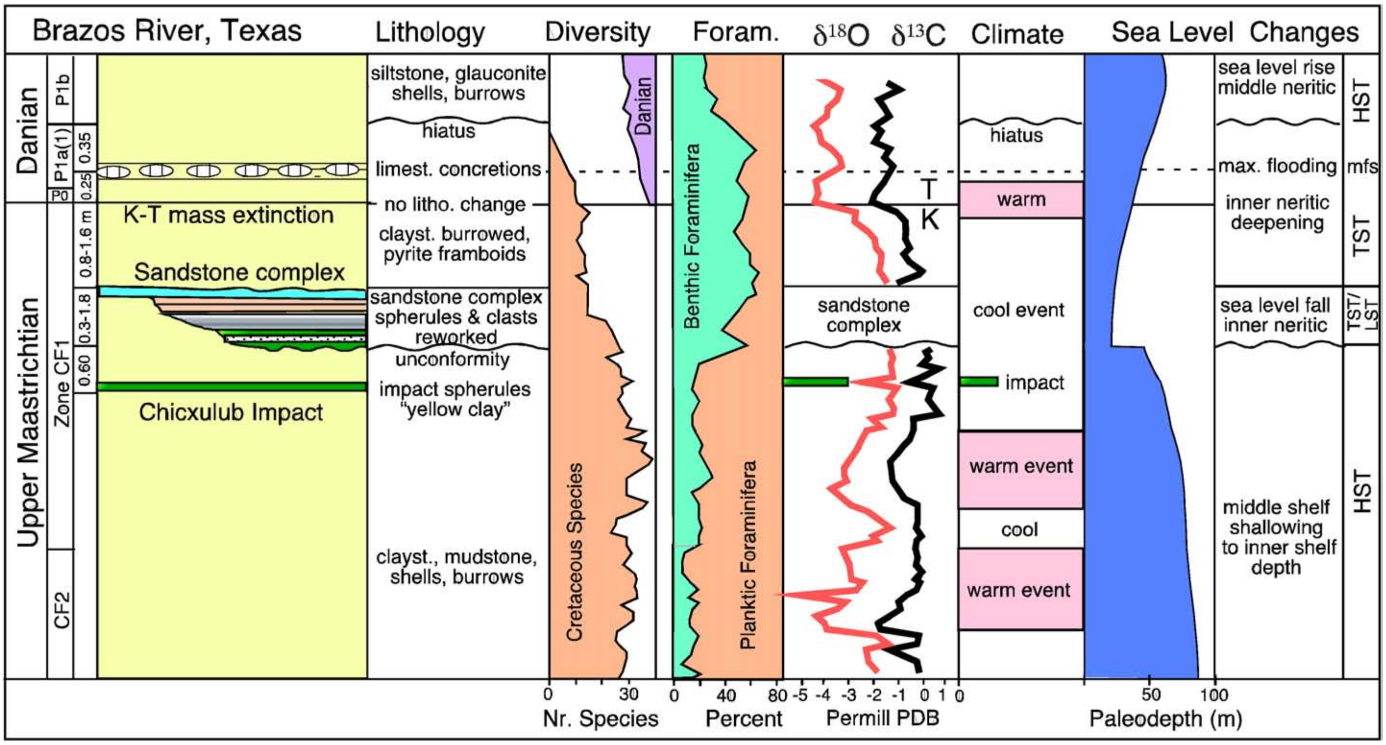

**Fig. 11.** Summary graph of the biotic and environmental effects observed during the late Maastrichtian to early Danian along the Brazos River of Texas. The sea-level fall and sandstone deposition occurred during the latest Maastrichtian cooling that followed the global greenhouse warming in CF2-CF1. The Chicxulub impact struck Yucatan during the cooling phase, but prior to sandstone deposition. No significant long-term environmental changes or biotic effects can be recognized. The sea-level fall to inner neritic depths resulted in a pseudo-extinction of all larger species due to exclusion of the deeper dwelling species. The K–T boundary is well marked by the $\delta^{13}$C shift, extinctions and first appearance of Danian species up to 80 cm above the sandstone complex.

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1996; Heymann et al., 1998; Smit, 1999; Smit et al., 2004; Schulte et al., 2006, 2008), was deposited during the middle part of the cooling phase. By this time, sea-level had reached shallow inner neritic depths (<10 m), scouring channels at least 1.8 m into sediments and infilling them during periods of rapid sediment influx (e.g., tempestites, including eroded sands, glauconite, spherules and clasts with spherules) alternating with periods of normal sedimentation (e.g., well-sorted sand, multiple episodes of suspension settling, three upward fining and truncated spherule-rich units, burrowed horizons) (Yancey, 1996; Gale, 2006; Keller et al., 2007a, 2008a). These sediment patterns are inconsistent with tsunami formation.

In these shallow inner neritic depths, planktic species diversity and relative abundance of planktic foraminifera decreased leaving impoverished dwarfed assemblages (Keller and Abramovich, in press; MacLeod et al., 2000) and creating a pseudo mass extinction (Figs. 8 and 9), which has been interpreted by some workers as the K–T mass extinction caused by the Chicxulub impact.

Sea level began to rise during sandstone deposition and continued to rise above it and across the K–T boundary. At the same time $\delta^{18}$O and $\delta^{13}$C data show gradually decreasing late Maastrichtian values culminating in the characteristic K–T shift to lower early Danian signals (Fig. 11). The same impoverished planktic assemblages that began with the sea level fall continued up to the K–T boundary and some survived for a short time (e.g., heterohelicids, Figs. 6 and 7), leaving a nearly monospecific survivor assemblage of the disaster opportunist *Guembelitria cretacea* (~80%). The same extinction and survivorship patterns are known from K–T sections across latitudes in continental shelf and open marine environments (Keller and Pardo, 2004; Pardo and Keller, in press). Brazos sections only differ in their lower species diversity of 25–30 species, as compared with 50–65 species in optimal open marine environments (Fig. 10).

### *8.3. Impacts and mass extinctions*

The absence of any recognizable biotic effects as a result of the Chicxulub impact comes as a surprise mainly because we have *assumed* that this impact caused the K–T mass extinction. A survey of impact craters and mass extinctions over the past 500 my reveals that apart from the K–T boundary, none of the five major mass extinctions can be attributed to an impact (Courtillot, 1999; Wignall, 2001; White and Saunders, 2005; Keller, 2005). The Chicxulub crater with a diameter of about 170 km is the largest known impact. Other well studied impacts that show no extinctions or significant other biotic effects include the 90–100 km in diameter late Eocene Chesapeake Bay and Popigai craters, the 100–120 km in diameter late Triassic Manicouagan and late Devonian Alamo and Woodleigh craters (Montanari and Koeberl, 2000; Wignall, 2001; Keller, 2005; Pusz et al., 2007).

If not the Chicxulub impact, what caused the K–T mass extinction? We have previously suggested another larger impact based on the prevailing view that the K–T Ir anomaly is of cosmic origin. But the absence of any significant biotic effects attributable to the Chicxulub impact suggests that even a larger impact alone may not have been sufficient to cause the K–T mass extinction. Recent studies suggest that the main phase (80%) of Deccan eruptions may have been very rapid and ended near the K–T mass extinction (Chenet et al., 2007, 2008, in press; Keller et al., 2008b). These intriguing new results suggest that the cumulative effects of Deccan volcanism and associated climate and environmental changes could have triggered the K–T mass extinction.

## 9. Conclusions

1. K–T sections along the Brazos River, Texas, reveal three stratigraphically well separated events: the Chicxulub impact spherules layer, sea-level fall (sandstone complex) and K–T mass extinction.
2. The Chicxulub impact spherule layer (altered to cheto smectite) is present in upper Maastrichtian (lower zone CF1) claystones, ~300 ky prior to the K–T boundary. No species extinctions or significant populations changes were caused by this impact.
3. A Sea-level fall from middle to inner neritic depths resulted in scoured submarine channels, which were infilled by a sandstone complex. Multiple truncated burrowing horizons and upward fining sands indicate longterm deposition and seasonal storms. Spherule-rich clasts at the base of the sandstone complex provide unequivocal evidence of an older spherule deposit.
4. The sea-level fall to inner neritic depths excluded deeper dwelling species resulting in a pseudo mass extinction that some workers mistakenly interpreted as the K–T mass extinction.
5. The K–T mass extinction occurs 40–80 cm above the sandstone complex in the studied sections coincident with the $\delta^{13}$C shift and the first appearance of Danian species. No lithological changes, Ir anomaly or impact spherules occur at the K–T boundary.
6. Oxygen isotope data indicate that the global warming during the latest Maastrichtian occurred as two distinct phases and ended in the lower zone CF1.
7. Subsequent cooling reached a maximum at the sea-level fall and deposition of the sandstone complex. Cool conditions prevailed until just below the K-T boundary, where rapid warming occurred.
8. The Chicxulub impact coincided with the early part of the latest Maastrichtian cooling phase and may have caused transient climate warming.

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