1 **Stable sea-floor conditions, sea-level and food supply**
2 **during the latest Maastrichtian at Brazos River, Texas**

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Abstract

The Cretaceous/Paleogene (K/Pg) boundary extinction event is inextricably linked to the Chicxulub impact. Environmental changes like sea-level changes and changes in food supply prior to or after the impact could however have contributed to the biotic turnover. In this study, benthic foraminifera from two cores from the Brazos River area in Texas are quantitatively analyzed in order to reconstruct environmental changes across the K/Pg boundary. Cluster analysis as well as non-metric multidimensional scaling reveals three distinct benthic foraminiferal assemblages: an upper Maastrichtian assemblage, a post-impact assemblage, and a lower Danian assemblage. The rather uniform upper Maastrichtian assemblage at Brazos River, composed of e.g. *Clavulinoides midwayensis*, *Gavelinella dumblei*, *Cibicidoides harperi*, *Gyroidinoides aequilateralis* and *Bulimina kickapooensis*, indicates a stable paleodepth of about 75-100 m up to the K/Pg boundary. Food supply indicators such as percentage Buliminaceae and foraminiferal numbers suggest a relatively low and stable food supply during this interval. Environmental disruption caused by the Chicxulub impact led to the settlement of a typical colonizer assemblage, characterized by endobenthic morphotypes such as *Ammobaculites* spp. and *Pseudouvigerina naheolensis*. During the early Danian, the typical Midway-type benthic foraminiferal shelf fauna (e.g. *Alabamina midwayensis*, *Anomalinoides acutus*, *Gyroidinoides subangulatus*, *Praebulimina carseyae* and *Cibicidoides alleni*) developed, indicating a paleodepth of 75-100 m. No clear water depth changes can be derived from the benthic foraminiferal record during this interval, although the sedimentary record suggests a shallowing followed by a transgressive pulse in Zone P1a. Food supply indicators suggest a lower food supply in the early Danian than during the upper Maastrichtian. Because of the stability of the late Maastrichtian environment we conclude that environmental disruption caused by the impact was most likely the principal cause of the benthic foraminiferal turnover across the K/Pg boundary observed at Brazos River.

Keywords: Brazos River; benthic foraminifera; Cretaceous/Paleogene boundary; sea-level; food supply; oxygenation

Highlights:

- 41 • Benthic foraminiferal assemblages of two Brazos River cores are investigated
- 42 • Sea-level, food supply and oxygenation changes across the K/Pg boundary are
- 43 studied
- 44 • Late Maastrichtian food supply was rather low and stable, also sea-level was stable
- 45 • A colonizer benthic foraminiferal assemblage emerged during Zone P0
- 46 • Early Danian sea-level was similar to the Maastrichtian, with lower food supply
- 47

48 **1. Introduction**

49 The Cretaceous/Paleogene (K/Pg) boundary marks one of the largest extinctions in the
50 Phanerozoic, and is inextricably connected to the Chicxulub impact (Alvarez et al., 1980; Smit
51 and Hertogen, 1980; Schulte et al., 2010). Total diversity of the fossilized marine genera
52 declined by ~47% from the upper Maastrichtian to the lower Danian (Sepkoski, 1996), and
53 over 90% of planktic foraminifera species went extinct (e.g. Smit, 1982; D'Hondt et al., 1996;
54 Molina et al., 1998). Extinction rates varied largely among genera, however. Where planktic
55 foraminifera almost went extinct completely, global extinction of benthic foraminifera across
56 the K/Pg boundary is quite low (Culver, 2003), where it should be noted that benthic
57 foraminifera can locally show considerable extinction patterns and assemblage changes (e.g.
58 Olsson et al., 1996, 2002; Speijer and van der Zwaan, 1996; Alegret et al., 2003; Alegret,
59 2007). .

60 Although the Chicxulub impact is commonly believed to have been the major cause of the
61 mass extinction event at the K/Pg boundary, additional causes have been suggested to have
62 contributed to the mass extinction. Perhaps the most important contributor is the CO₂ mantle
63 degassing of the Deccan Traps (e.g. Duncan and Pyle, 1988; Schoene et al., 2015) which
64 presumably caused significant temperature rises during the late Maastrichtian that would
65 have stressed ecosystems already before the impact (e.g. Keller, 2001; Keller et al., 2011).

66 In addition to the Deccan Traps degassing, sea-level changes prior to or at the K/Pg
67 boundary have been suggested to have contributed to the biotic turnover at the K/Pg
68 boundary (e.g. Brinkhuis and Zachariasse, 1988; Keller and Stinnesbeck, 1996; Hallam and
69 Wignall, 1999; O'Dea et al., 2011). For instance, marine regression reduces the amount of
70 continental shelf habitats, whereas transgression may lead to anoxia on the shelf. Both
71 effects could have contributed to extinction at the K/Pg boundary (Hallam and Wignall, 1999).

72 Furthermore, the collapse of the pelagic food web just after the K/Pg impact resulted in a
73 diminished food supply towards the sea-floor across the K/Pg boundary (e.g. D'Hondt, 2005).
74 This decrease in export productivity is believed to have been moderate, regional, and
75 insufficient to explain marine mass extinction (Alegret et al., 2012), but is often suggested to
76 have caused the temporary early Danian changes in deep-sea benthic foraminiferal

community structures at numerous locations (e.g. Speijer and van der Zwaan, 1996; Alegret et al., 2001, 2002; Culver, 2003). It is furthermore suggested that not only food quantity, but also food quality changes across the boundary influenced benthic foraminiferal communities (Thomas, 2007).

This study aims to clarify to what extent sea-level changes, changes in food supply to the sea-floor and changes in oxygenation of the sea-floor, before and after the K/Pg boundary impact could have contributed to the end-Cretaceous mass extinction. Benthic foraminifera are excellently suited to reveal changes in food supply and oxygenation as well as sea-level changes especially in neritic environments (e.g. Olsson and Nyong, 1984; Corliss and Chen, 1988; Jorissen et al., 1995; Van der Zwaan et al., 1999; Sen Gupta, 2002; Murray, 2006). In addition, unlike planktic foraminifera and calcareous nannofossils, benthic foraminifera did not go massively extinct across the boundary. Therefore, in this study, benthic foraminifera are used to reconstruct possible environmental changes across the K/Pg boundary on a virtually continuous K/Pg transition at the shallow sea Brazos River area, Texas, relatively close to the Chicxulub impact crater. Some, mostly qualitative, benthic foraminiferal research was already performed at this site (e.g. Schulte et al., 2006; Hart et al., 2011), showing a clear transition from a upper Maastrichtian benthic foraminiferal assemblage towards a new Midway-type lower Danian assemblage. This study provides a more elaborate quantitative analysis and ecological interpretation of the benthic foraminiferal assemblages across the K/Pg boundary.

2. Regional setting

Paleogeographically, the Brazos River area is located on the shallow shelf of the northern part of the Gulf of Mexico (Figure 1) (Scotese, 2012; Scotese and Dreher, 2012). This region underwent nearly continuous and predominantly siliclastic sedimentation during the late Cretaceous and early Paleogene (Davidoff and Yancey, 1993). Sedimentation rates were higher than the increase of accommodation space on the continental shelf, resulting in an outward prograding shelf margin and an overall shallowing trend from the latest Cretaceous to the early Eocene (Davidoff and Yancey, 1993). Variations in sediment supply as well as eustatic sea-level modified the progradation of the Paleogene shelf margin substantially, however (Galloway, 1989).

Figure 1. A: Approximate paleogeographic location of Brazos River, Texas on the North American shallow shelf. Also the location of the Chicxulub impact crater is indicated. Map after Scotese and Dreher (2012). B: Location of Brazos River outcrop area, where Brazos Core 1 and 2 (which were used in this study) were taken. After Schulte et al. (2006).

The late Maastrichtian Corsicana Formation of the Brazos River succession consists of gray silty claystones and mudstones with concretions. Some benthic foraminifera as well as some mollusk debris are preserved as aragonite. Shell debris is present throughout the formation. The top 0.5 m of the Corsicana Formation is a bioturbated claystone with burrow fills. In some places the soft, shell rich claystone contains >20 cm diameter clasts of intact claystone and marlstone, possibly due to reworking (Hart et al., 2011) or current drag and earthquakes (Schulte et al., 2006).

The overlying Paleogene Littig Member of the Kincaid Formation has an anomalous sandstone unit at its base. The thickness of this basal unit is variable depending on location (Gale, 2006; Hart et al., 2012). Where they are complete, the basal unit consists of a reworked, shell rich, mudstone clast bearing mudstone (Yancey and Liu, 2013) that shows no lamination (Schulte et al., 2006). On top of these mudstones, a complex of upward fining, spherule bearing, cross bedded, hummocky sandstones is present (Schulte et al., 2006; Yancey and Liu, 2013). Above this sandstone-complex, again mudstones are deposited (Hart et al., 2011).

The Brazos K/Pg outcrop area is situated between Waco and Hearne along the Brazos River in south-central Texas (Figure 1). The Brazos cores investigated in this study were drilled close to each other at the western bank of the river. Their location is about 370 m

downstream from the Texas Highway 413 Bridge, which is located near the crossing between Texas Highway 413 and 1373 (Schulte et al., 2006).

3. Material and methods

Schulte et al. (2006) describe the stratigraphy of Brazos Core 1 and Brazos Core 2 in detail. Together, Brazos Core 1 and Brazos Core 2 constitute an expanded succession of 14.5 m of the uppermost Maastrichtian and lower Danian. There is no evidence for significant hiatuses from the sedimentological and paleontological record (Schulte et al., 2006). Although the marker for the uppermost Maastrichtian biozone (CC26b, *M. prinsii*) is missing in these cores and is very rare in the area (Jiang and Gartner 1986; Schulte et al., 2006), the presence of *P. hantkeninoides* (a planktic foraminifer) in uppermost Maastrichtian material from these cores (Mai et al., 2003) and nearby Brazos River locations (Hart et al., 2012) shows that the uppermost Maastrichtian is biostratigraphically complete at the Brazos River area. The lowermost Danian record is considered to be complete and expanded in the Brazos area. Both the planktic foraminiferal as well as the nannofossil record show all biozones and subzones (Schulte et al., 2006). However, an unconformity within Subzone P1a indicates a small hiatus between lithological units I and J.

In total, 38 samples from Brazos Core 1 and Brazos Core 2 (Schulte et al., 2006) were processed for foraminiferal studies at Karlsruhe University after methods given by Pardo et al. (1996). Both cores cover the K/Pg boundary. Brazos Core 1 mainly covers the lower Danian sequence, whereas Brazos Core 2 mainly represents upper Maastrichtian sediments. The benthic foraminiferal number (BFN) represents the number of benthic foraminifera per gram dry sediment and the foraminiferal number (FN) consists of the total number of foraminifera per gram dry sediment. Both were calculated using foraminiferal counts and dry sample weight. The percentage of planktic foraminifera (%P) was determined from random square counts from the >125 µm fraction in the picking tray.

The quantitative foraminiferal study was performed on representative aliquots of the >125 µm fraction, containing 200-300 benthic foraminiferal specimens. All benthic foraminifera were picked from the residues and were mounted on reference slides. Taxonomic assignments were largely based on and adapted from Cushman (1946, 1951), Kellough (1965), Berggren

and Aubert (1975) and Olsson and Nyong (1984). The most important taxa were photographed using Scanning Electron Microscopy (SEM) and their preservation was evaluated. All original species descriptions were checked with the online version of the Ellis and Messina catalog (<http://www.micropress.org>).

For the characterization of the benthic assemblages, the parameters in Table 1 were used (after Hayek and Buzas, 2013). The percentage of endobenthic morphotypes was calculated using the assumed microhabitat preferences inferred from benthic foraminiferal morphotype analysis (e.g. Corliss, 1985; Corliss and Chen, 1988; Alegret et al., 2003) even though assuming an analogue with modern fauna can be problematic (Buzas et al., 1993). In addition, the percentage Buliminaceae (e.g. *Bulimina*, *Praebulimina*, *Pseudouvigerina*) was calculated. Buliminaceae abundance can be used as an indicator for food supply and oxygenation (Jorissen et al., 1995, 2007).

Table 1. Statistical parameters used to describe the benthic foraminiferal assemblages (after Hayek and Buzas, 2013).

Number of taxa per sample	S	(accompanied by the number of individuals examined in the split, N)
Shannon's H diversity index	H	$H = -\sum p_i \ln p_i$
Berger-Parker dominance index	BP	$BP = \max p_i$

In which p ($= n_i / \sum n$) represents the proportion of taxon i , with n being the total number of individuals.

Absolute species counts, relative abundances and the PAST software package (Hammer et al., 2001; Hammer and Harper, 2006) were used for the statistical analysis. As an aid in defining different faunal assemblages, a hierarchical cluster analysis (paired group (UPGMA), Horn similarity index) was performed on the absolute counts of taxa that occurred >2% in at least one sample. This cut-off value was used to improve reliability and relevance of the statistical analysis. In addition, both an R-mode (foraminiferal taxa) and a Q-mode (samples) non metric multidimensional scaling (NM-MDS) (Bray-Curtis similarity index, three

dimensions) was performed on relative abundances of selected taxa that occurred >2% in at least one sample. This was done in order to unravel the main benthic foraminiferal patterns. Taxa may not have a linear response to environmental gradients around the K/Pg boundary, and their habitat was very likely fragmented by the impact. Therefore, NM-MDS was chosen over PCA and CCA (Ramette, 2007). Please note that for the calculation of S, H and BP, the cut-off value of 2% was not applied.

Relative abundances, the qualitative parameters characterizing the benthic assemblages and the values of the three axes of the Q-mode NM-MDS are displayed in a composite. Doing so, Paleogene samples from Brazos Core 1 are combined with Maastrichtian samples from Brazos Core 2, resulting in one composite core covering the K/Pg boundary, conform Schulte et al. (2006). As a result, *Stainforthia* spp., which is only present >2% in Paleogene samples from Brazos Core 2, does not show a >2% abundance in the displayed composite. However, as it is present >2% in one of the samples analyzed, despite not being displayed, its value was used in this study for statistical and cluster analysis. Therefore, it was decided to display *Stainforthia* spp. in Figure 2 and show its position in the cluster analysis.

4. Results

Relative abundances of the most common taxa (Plate 1 and Plate 2) encountered in this study (>2% in at least one sample) are displayed in Figure 2. The cluster analysis as well as the NM-MDS and endobenthic morphotype percentages show that four different groups of taxa can be distinguished in the investigated record (Figure 2, Figure 3, Figure 4 and Figure 5). These four groups are:

- An upper Maastrichtian group (Cluster B2). This group is dominated by taxa that occur only or mainly in the upper Maastrichtian samples;
- A lowermost Danian post-impact 'Disaster/Recovery' group (Cluster A). This group is dominated by taxa that occur only or mainly in the lowermost Danian samples directly above the K/Pg boundary;
- A lower Danian group (Cluster C). This group is dominated by taxa that occur only or mainly in the lower Danian samples;

- A group with taxa that are present roughly equally abundant throughout the investigated record (Cluster B1).

The benthic foraminiferal turnover across the K/Pg boundary will be described here mainly based on the first three groups. Depth distributions of most dominant taxa in each group are displayed in Figure 6.

Plate 1. SEM images of the most common benthic foraminifera encountered in this study. 1a, b, c: *Anomalinoides acutus* (Plummer). 2a, b, c: *Anomalinoides midwayensis* (Plummer). 3a, b, c: *Anomalinoides umboniferus* (Schwager). 4a, b, c: *Gyroidinoides subangulatus* (Cushman). 5a, b, c: *Gyroidinoides aequilateralis* (Plummer). 6a, b, c: *Eponides elevatus* (Plummer). 7a, b, c: *Anomalinoides harperi* (Sandidge). 8a, b, c: *Cibicidoides succedens* (Brotzen). 9a, b, c: *Cibicidoides alleni* (Plummer). 10a, b, c: *Pulsiphonina prima* (Plummer).

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230 **Plate 2.** SEM images of the most common benthic foraminifera encountered in this study.

231 11a, b, c: *Alabamina midwayensis* Brotzen. 12. *Bulimina kickapooensis* Cole. 13.

232 *Praebulimina carseyae* (Plummer). 14: *Pseudouvigerina naheolensis* Cushman & Todd. 15a,

233 b, c: *Gavelinella dumblei* (Applin). 16: *Loxostomoides applinae* (Plummer). 17: *Clavulinoides*

234 *midwayensis* (Cushman). 18: *Gaudryina pyramidata* Cushman. 19: *Ammobaculites* sp.

235 (Cushman). 20: *Coryphostoma midwayensis* (Cushman). 21a, b: *Lenticulina degolyeri*

236 (Plummer). 22a, b: *Lenticulina dissona* (Plummer). 23: *Siphogenerinoides plummerae*

237 (Cushman).

Figure 2. Relative abundances of the most common benthic foraminiferal taxa encountered in this study (>2%) and the result of the cluster analysis performed on these taxa (paired group (UPGMA), Horn similarity index).

Figure 3. Non-metric multidimensional scaling (NM-MDS). A: Q-mode NM-MDS (on all samples in the dataset). B: R-mode NM-MDS (on benthic foraminiferal taxa that occur >2% in at least one sample in the complete dataset).

Figure 4. Relative cluster abundances and non-metric multidimensional scaling axes 1, 2 and 3 across the Cretaceous/Paleogene boundary.

Figure 5. Endobenthic morphotype percentages (%Endobenthic morphotypes total), Endobenthic morphotype percentages excluding endobenthic agglutinated taxa (%Endobenthic morphotypes excl. agglutinated taxa) percentages Bulminaceae (%Bulminaceae), numbers of foraminifera/g dry sediment (FN), numbers of benthic foraminifera/g dry sediment (BFN), percentage planktic foraminifera (%P), Shannon's H

diversity index, Berger-Parker dominance index (BP), number of taxa per sample split (S), number of individuals examined per sample (N).

	C/L	IN	MN	ON	BA	Ref.
Lower Danian						
<i>Anomalinoides midwayensis</i>	■ ■ ■ ■ ■ ————— ■ ■ ■ ■ ■					1,2,7
<i>Anomalinoides acutus</i>	■ ■ ■ ■ ■ ———— ■ ■ ■ ■ ■					1,2
<i>Cibicidoides alleni</i>	■ ■ ■ ■ ■ ————— ■ ■ ■ ■ ■					1,2,4,6
<i>Alabamina midwayensis</i>	————— ■ ■ ■ ■ ■					1,5,6,7
<i>Gyroidinoides subangulata</i>		—————				3
Disaster/Recovery phase						
<i>Eponides elevatus</i>	————— ■ ■ ■ ■ ■					1,4,7
<i>Ammobaculites</i> spp.	—————					1,2,6
<i>Anomalinoides umboniferus</i>	————— ■ ■ ■ ■ ■					1,4,6
<i>Anomalinoides midwayensis</i>	■ ■ ■ ■ ■ ————— ■ ■ ■ ■ ■					1,2,7
<i>Pseudouvirgerina naheolensis</i>		■ ■ ■ ■ ■ ■ ■ ■ ■ ■				1
Upper Maastrichtian						
<i>Anomalinoides umboniferus</i>	————— ■ ■ ■ ■ ■					1,4,6
<i>Anomalinoides midwayensis</i>	■ ■ ■ ■ ■ ————— ■ ■ ■ ■ ■					1,2,7
<i>Cibicidoides harperi</i>		————— ■ ■ ■ ■ ■				1
<i>Gyroidina aequilateralis</i>		—————				3
<i>Clavulinoides midwayensis</i>			—————			1,3

Figure 6. Depth distributions of most dominant taxa per interval encountered at Brazos River.

References: 1-(Kellough, 1965), 2-(Berggren and Aubert, 1975); 3-(Olsson and Nyong, 1984); 4-(Saint-Marc and Berggren, 1988); 5-(Speijer and Schmitz, 1998); 6-(Schnack, 2000); 7-(Stassen et al., 2009). C/L: Coastal/Lagoonal. IN: Inner neritic. MN: Middle neritic. ON: Outer neritic. BA: Bathyal.

4.1 Upper Maastrichtian

The quantitative records (H, BP, N, BFN, relative species abundances) and the statistical evaluation (NM-MDS) show that the composition of the upper Maastrichtian benthic foraminiferal assemblage is very stable. Only Shannon diversity (H) and dominance (BP) show a slight trend towards lower and higher values respectively, and appears largely determined by the overall slight increase in *Clavulinoides midwayensis*. No common taxa disappear below the K/Pg boundary. Except for *Chilostomella* spp., which is rarely present in upper Maastrichtian samples, no taxa enter the upper Maastrichtian record either. The five most common taxa that are largely restricted to the upper Maastrichtian (*Cl. midwayensis*, *Gavelinella dumblei*, *Cibicidoides harperi*, *Gyroidinoides aequilateralis* and *Bulimina kickapooensis*) together represent ~50-70% of the assemblage in most investigated upper Maastrichtian samples. Other taxa that are common in the upper Maastrichtian are *Anomalinoides midwavensis*, *A. umboniferus* and *Lenticulina* spp.. Schulte et al. (2006)

referred to this assemblage as the Corsicana assemblage, named after the Maastrichtian Corsicana Formation.

H ranges between 1.9 and 2.3, which reflects a rather equal distribution of taxa. BP ranges from 18-38%, indicating an assemblage with a moderately high dominance. The number of taxa found in this part of the record ranges from 14 to 17. BFN is ~40, FN is ~200. This is both very low. Within the uppermost Maastrichtian beds, BFN and FN double, however. The percentage planktic foraminifera is rather high and constant in the upper Maastrichtian, between 75 and 90%. Throughout the upper Maastrichtian, about 25-45% of the assemblage are endobenthic morphotypes. These are mostly agglutinated taxa (*C. midwayensis*, ~15-40% of the assemblage) and some are Buliminaceae (~2-5%).

Eight taxa occur both in the upper Maastrichtian as well as in the lower Danian Subzone P1a, and can therefore be regarded as survivor taxa. The reworking of specimens cannot be ruled out completely, however (see below). Although the observed interval may not be long enough for some taxa to re-appear in the record above the K/Pg boundary, out of a total of 20 most common taxa occurring in the upper Maastrichtian, 9 taxa seem to have disappeared from the record during Zone P0 and Zone P α (~45%).

4.2 Post-impact 'Disaster and Recovery'

Within the lowermost Danian Zones P0 and P α , the NM-MDS, H, BP and relative species abundances indicate an unstable foraminiferal assemblage. The assemblage is dominated by coarsely grained planspiral agglutinated taxa, belonging to the genus *Ammobaculites* (~0 to 54% of the assemblage). Other typical 'Disaster and Recovery' taxa are *Pseudouvierina naheolensis*, which shows a first occurrence in near the base of Zone P0, and *Eponides elevatus*. Together, these three taxa represent up to ~72% of the assemblage within Zone P0. *Anomalinoides umboniferus* is also relatively abundant within this zone. Other taxa that are common in the 'Disaster and Recovery' zone are *An. midwayensis* and *Lenticulina* spp. At the base of Zone P0, many taxa typical for the Maastrichtian are still present in the record, but disappear towards the top of Zone P0. Also planktic foraminiferal percentages (>125 microns) gradually decrease towards 0% towards the top of Zone P0, whereas new benthic species such as *Alabama midwayensis* and *Anomalinoides acutus*, appear.

The number of taxa in the basal part of Zone P0 is similar to the number of taxa found in the upper Maastrichtian. However, in the top of Zone P0, where the typical Maastrichtian taxa disappear from the record, the number of taxa found in the assemblage drops to 11. Simultaneously, BP increases to 54% in the basal part of Zone P0, where it recovers towards Maastrichtian values towards the top of Zone P0. Together, these observations suggest relatively large proportions of potentially reworked planktic and benthic specimens in the lowermost part of Zone P0. In addition to this, H drops to 1.4 within the lowermost Danian. This indicates a less diverse assemblage dominated by fewer taxa within this interval compared to the late Maastrichtian. H recovers towards the top of Zone P0 to Maastrichtian values. Endobenthic morphotypes are dominant during the entire interval (~10-77%), mainly because of the abundant presence of *Ammobaculites* spp.. Buliminaceae are also commonly present during Zone P0 (~2-18%), mainly because of the abundant presence of *P. naheolensis*.

4.3 Lower Danian

As can be derived from the NM-MDS and the relative species abundances, a fully new assemblage type is established in the lower Danian Subzone P1a. Most dominant taxa found in the new assemblage are typical for the Midway type fauna (Berggren and Aubert, 1975). The most common species are *Al. midwayensis*, *A. acutus*, *An. midwayensis* and *Gyroidinoides subangulatus*. Together, these species constitute of ~67-84% of the total assemblage. Other common lower Danian taxa are *Lenticulina* spp., *Praebulimina carseyae* and *Cibicidoides alleni*. Eleven new taxa appear commonly in the investigated record of the lower Danian (an increase of ~100% compared to the 11 taxa present in the basal Danian shale beds). This number is similar to the number of taxa that disappeared from the record across the K/Pg boundary.

Numbers of taxa per sample split (S) are slightly higher than below the K/Pg boundary in this interval (up to 21), and continue to increase as new species continue to appear in the record. H indicates an increasing diversity towards the top of the sequence approaching upper Maastrichtian values. Also dominance (BP) is similar to the upper Maastrichtian in Subzone P1a with values between 25-38% for the most common taxon in the assemblage. BFN and FN increase upwards and reach values over 10 times higher than upper Maastrichtian values.

The percentage endobenthics is rather constant in this interval. They are however lower than in the upper Maastrichtian (10-15% of the assemblage), mainly because the agglutinated taxa that were present in the upper Maastrichtian almost disappeared from the assemblage. Buliminaceae percentages are low and similar to the upper Maastrichtian, although they peak slightly in the lower part of Subzone P1a (5-8%). The percentage planktic foraminifera (>125 micron) increases towards the top of the investigated interval to ~50%.

5. Discussion

5.1 Reworking

It has been argued that the sandstone bed at the base of P0 (lithological unit B through G) is a single tsunami deposit consisting of reworked Maastrichtian material (e.g. Bourgeois et al. (1988); Olsson and Liu (1993); Smit et al. (1996); Lawton et al. (2005)). However, *P. naeolensis* shows a first occurrence near the base of the calcareous clay-rich unit F and *Ammobaculites* spp. (which occurred only sporadically before the K/Pg boundary) dominates at this level. In addition, planktic foraminiferal percentages and percentages of several Maastrichtian taxa gradually decline towards the top of Zone P0.

These observations together suggest a mixture of reworked and *in situ* foraminifera throughout Zone P0, with fewer reworked specimens towards the top of the zone. Schulte et al. (2006), Gale (2006), Hart et al. (2011, 2012) and Yancey and Liu (2013) suggested a series of depositional events to have resulted in lithological units A-F at the base of Zone P0, rather than a single tsunami event. The gradual disappearance of Maastrichtian taxa, together with the first occurrence of *P. naeolensis* and the spike occurrence of *Ammobaculites* spp. during Zone P0 and P α supports this conclusion. The sporadic occurrence of Maastrichtian species in the lower Danian Subzone P1a suggests only minor reworking in this interval.

5.2 Taphonomic effects

The preservation of calcareous foraminifera, both benthic as well as planktic, is good to very good in the entire record (see Plate 1 and Plate 2). The surface of the foraminiferal shells is only slightly etched, indicating limited dissolution only. Some foraminifera are slightly overgrown with calcite, which occurs more often within Danian Subzone P1a.

The relatively high abundance of agglutinated foraminifera (mostly *Ammobaculites* spp.) within Zone P0 could indicate more severe dissolution. However, other factors leading to the relatively large agglutinated foraminiferal abundance should be considered as well, taking into consideration the good quality of the calcareous benthic as well as planktic foraminifera. The relatively high abundance of *Ammobaculites* spp. in combination with the increased Buliminaceae resembles the signal found in studies concerning benthic foraminiferal colonization patterns of new habitats, for instance after volcanic ash fall (e.g. Hess et al., 2001), turbidites (Hess et al., 2005), or in colonization experiments (Kaminski et al., 1988). In an overview study on colonization of new habitats by benthic foraminifera, Alve (1999) generally concludes that small endobenthic species, both agglutinated as well as calcareous, are among the first and most successful colonizers of soft bottom habitats from shallow waters to deep sea. In addition, in the deep sea, trochospiral agglutinated taxa are the most abundant colonizers (Alve, 1999). This all suggests that the planispiral agglutinated *Ammobaculites* spp. and the endobenthic *P. naeolensis* in Zone P0 in this study are also part of a typical colonization assemblage rather than the result of taphonomic effects.

5.3 Food supply and sea-floor oxygenation

The fairly stable late Maastrichtian assemblage composition and species abundances indicate that food supply during this interval was quite stable. Buliminaceae percentages are low, which suggests low food supply and high oxygenation levels. Also dominance in this interval is relatively low, while diversity is relatively high, which suggests a relatively low food supply as well. In addition, BFN in the Maastrichtian is rather low compared to for instance El Kef (Speijer and van der Zwaan, 1996) which could also be an indication of low productivity levels and thus low food supply. It should be noted however that it is also possible that the low BFN reflects a higher sedimentation rate at Brazos River, rather than lower productivity levels. For instance, carbonate content at El Kef in the upper Maastrichtian sediments is ~30% (Keller and Lindinger, 1989), where at Brazos River, it is ~5% (Schulte et al., 2006). This suggests stronger dilution with siliciclastics at Brazos River, leading to an overall lower BFN. Unfortunately, actual benthic accumulation rates cannot be calculated, because of the problematic age control in the late Maastrichtian in this core. A conclusive comparison with other sites regarding BFN is therefore not possible.

394 Interestingly, the relatively high endobenthic morphotype percentages in the late
395 Maastrichtian, mainly caused by the high abundance of agglutinated taxon *Cl. midwayensis*,
396 suggest that food supply was relatively high (Jorissen et al., 1995; Peryt, 2004). If *Cl.*
397 *midwayensis* is not taken into consideration, however, endobenthic morphotype percentages
398 would be quite low (Figure 5). It is possible that *Cl. midwayensis* did not have the assumed
399 endobenthic lifestyle, and the assumed analogue with modern fauna is not correct. If this is
400 the case, the endobenthic signal matches the other signals for this interval and would suggest
401 a low food supply..

402 As was discussed in Section 5.2, the slightly increased Buliminaceae (mainly *P. naheolensis*)
403 percentages and high relative abundances of the agglutinated planispiral taxon
404 *Ammobaculites* spp. in Zone P0 most likely reflect the benthic foraminiferal colonization of a
405 new habitat, regardless of oxygenation or food supply levels. However, as was suggested by
406 Hess et al. (2005), turbidites (comparable to the series of event deposits of Zone P0 in Brazos
407 River) can provide a source of enhanced organic matter input to the sea floor. In addition,
408 Hess et al. (2005) found in their study that pore water oxygenation of the turbidites was
409 initially low. Similar conditions could have favored the 'colonizer taxa' at Brazos River.

410 Unfortunately, the suggested possible influence of food supply and particularly anoxia on the
411 benthic community during the earliest phase of Zone P0 at Brazos River cannot be confirmed
412 by this study. Buliminaceae percentages are only slightly elevated in Zone P0, suggesting no
413 significant relationship between anoxia, food supply and the occurrence of colonizer taxa like
414 Buliminaceae. However, it should be noted that in other post-impact sites, the peak in
415 colonization taxa tends to be very short-lived (e.g. Speijer and van der Zwaan, 1996; Alegret
416 and Thomas, 2004, 2005, 2009). It is therefore possible that the initial colonization phase at
417 Brazos River occurred already earlier than could be detected by the lowermost Danian
418 sample available in this study. The slightly elevated Buliminaceae in the earliest Danian could
419 then possibly reflect the aftermath of an actual crisis.

420 In the early Danian, low Buliminaceae percentages and low endobenthic morphotype
421 percentages (mainly caused by the disappearance of *Clavulinoides midwayensis*) indicate a
422 food supply comparable to the late Maastrichtian. Dominance continues to decrease and
423 diversity continues to increase during Subzone P1a, suggesting a gradually decreasing food

supply during this interval (cf. Gooday et al., 2000). BFN increases significantly however, especially towards the top of Unit I, while grain size seems to increase simultaneously (the sediment becomes more sandy (Schulte et al., 2006)). This could indicate a winnowing effect, where clay is removed from the sediments, which in turn could have increased concentrations of foraminifera in the sediment. Unfortunately, as only the >125 µm size fraction is considered in this study, this possible winnowing effect cannot be verified.

5.4 Sea-level change across the K/Pg boundary

The dominant taxa in the upper Maastrichtian assemblage suggest a middle neritic water depth of ~75-100 m during this interval (Figure 6), like was also suggested by e.g. Hart et al. (2011) despite high planktic foraminifera percentages that would indicate a much larger water depth (Van der Zwaan et al., 1990). In fact, during the same interval, similar planktic percentages are found in the New Jersey shallow shelf environment (Olsson et al., 2002) and in the Tethyan outer neritic realm (Speijer and van der Zwaan, 1996; Speijer and Schmitz, 1998; Speijer, 2003). This implies that at least in late Cretaceous and Paleogene low latitudinal marginal basins the production of planktic foraminifera relative to benthic foraminifera was higher compared to today's situation, leading to rather high planktic percentages in Maastrichtian to Paleocene shelf environments.

The rather stable benthic foraminifer assemblage suggests neither shallowing nor deepening of the basin during the late Maastrichtian at Brazos River. Sedimentological data (Schulte et al., 2006; Hart et al., 2013), as well as planktic foraminiferal percentages support this view. Sea-level changes before the K/Pg boundary are therefore considered to be unlikely to have influenced the benthic foraminiferal turnover across the K/Pg boundary observed at Brazos River. The sequence boundary observed between the Corsicana and Kincaid Formations, that has been interpreted as the result of a sea level fall (e.g. Gale, 2006), is most likely an erosional surface caused by tsunami waves or tempestites and is observed at other locations near the impact crater as well (Olsson et al., 1996; Hart et al., 2013).

During the earliest Paleocene, the benthic assemblage at Brazos River most likely reflects a colonizer assemblage, primarily the result of a disrupted environment (see Section 5.2 and Section 5.3). However, most abundant taxa in Zone P0, directly above the K/Pg boundary,

are recognized as coastal taxa (*E. elevatus*, *A. umboniferus*, *Ammobaculites* spp.) and therefore could be indicative of shallowing. Hart et al. (2011) furthermore relate the disappearance of larger agglutinated taxa to shallowing during this interval. Although water depth as a controlling factor on this post-impact assemblage cannot be ruled out, it should be questioned if a disturbed, still unstable assemblage can be used to derive paleodepths from.

Planktic percentages could be a useful additional tool to derive paleodepth. The use of planktic percentages as a depth indicator in a post extinction setting is, however, inappropriate (cf. Hart et al., 2012). As over 90% of planktic foraminiferal species went extinct across the K/Pg boundary (D'Hondt et al., 1996), while in general, benthic foraminiferal extinction was quite low (Culver, 2003), the planktic percentage directly after the K/Pg boundary would reflect an apparent shallowing that would not necessarily have actually occurred. This effect would be enhanced by the fact that in this study, planktic percentages were calculated based on the >125 µm fraction, while the planktic survivor taxa were very small and are therefore most likely underrepresented in this study. Therefore, in this post-impact interval, no estimates of possible water depths based on foraminiferal data were made.

A typical Midway-type fauna develops during the early Danian (Subzone P1a). This fauna generally indicates a middle neritic water depth (Berggren and Aubert, 1975; Saint-Marc and Berggren, 1988) which corresponds to depths of ~75-100 m, similar to the late Maastrichtian water depth (Figure 6). Based on the decreased coarse detritus input towards the top of Subzone P1a, an early Danian transgression was suggested (e.g. Schulte et al., 2006; Hart et al., 2011). This transgression can however not be confirmed based on the benthic foraminiferal assemblages.

6. Conclusions

- Benthic foraminiferal assemblages suggest that sea-level and food supply at Brazos River were stable during the late Maastrichtian (75-100 m paleodepth). Late Maastrichtian sea-level changes or food supply changes are therefore not likely to have contributed to the benthic foraminiferal turnover rates across the K/Pg boundary at Brazos River.

- The benthic foraminiferal assemblage directly above the K/Pg boundary most likely reflects a colonizer assemblage resulting from a disrupted environment related to the impact.
- The Midway-type fauna in the early Danian suggests a paleodepth similar to the late Maastrichtian (~75-100 m) during this interval. Although sedimentological data (Schulte et al., 2006) suggest shallowing and deepening during this interval, the available micropaleontological data do not provide support for this. Food supply indicators and assemblage diversity suggest a relatively low food supply during this interval, which decreases during Subzone P1a.

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