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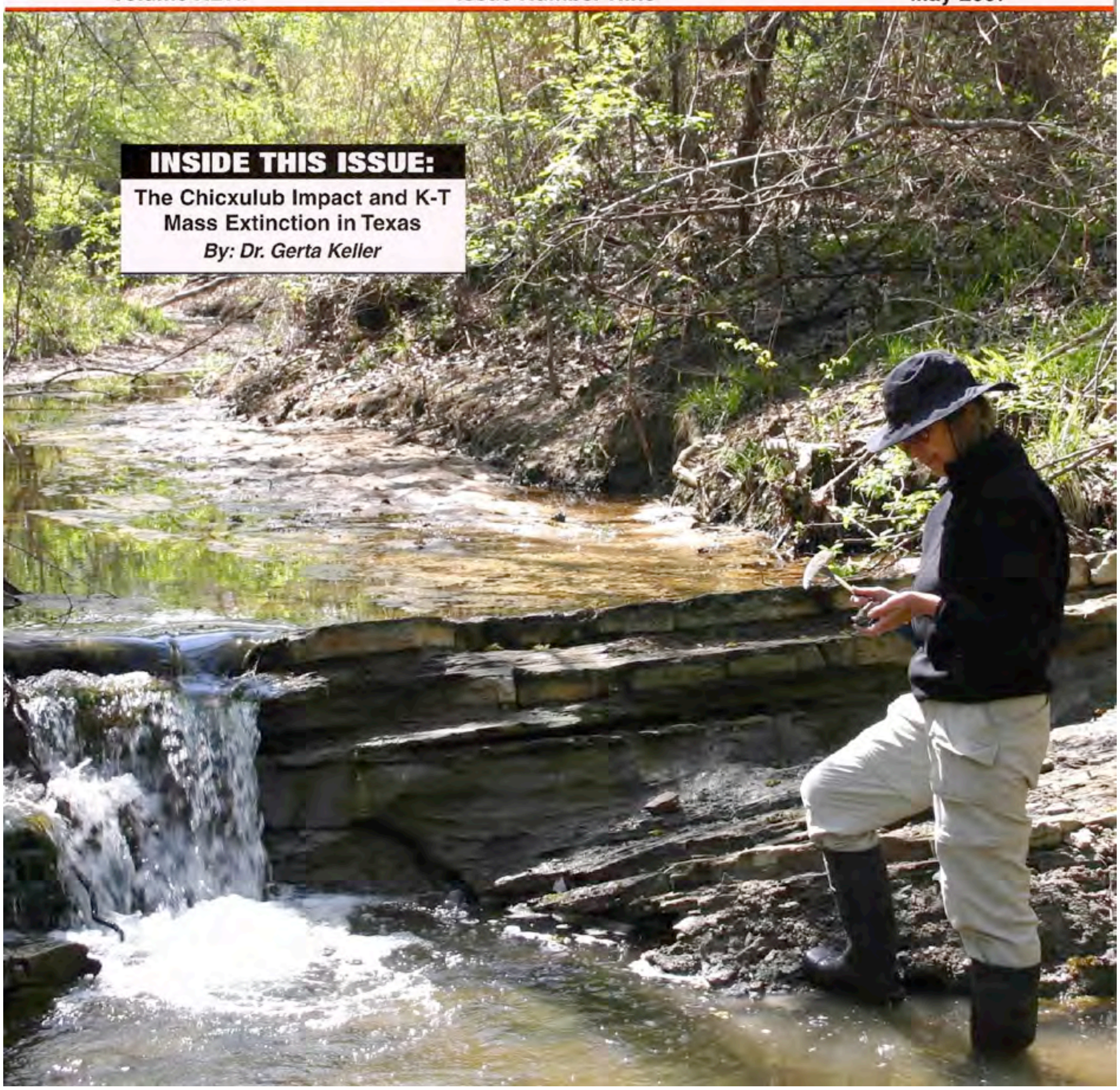

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The Chicxulub Impact and K-T Mass Extinction in Texas

By: Dr. Gerta Keller

The Chicxulub Impact and K-T Mass Extinction in Texas

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Abstract

The K-T sequences along the Brazos River of Falls County, Texas, provide the most important and critical information regarding the age and biotic effects of the Chicxulub impact outside of Mexico. New investigations based on outcrops and new cores drilled by DOSECC and funded by the National Science Foundation reveal a complex history of three tectonically undisturbed and stratigraphically well-separated events: the Chicxulub impact spherule ejecta layer, a sea-level lowstand sandstone complex, and the K-T mass extinction. The newly discovered Chicxulub impact spherule layer is the oldest of the three events and marks the time of the impact about 300,000 years before the K-T boundary (base of zone CF1), consistent with similar observations from NE Mexico and the Chicxulub crater core Yaxcopoil-l. The sea level lowstand sandstone complex predates the K-T boundary by about 100,000 years and contains clasts with Chicxulub impact spherules eroded from the original impact spherule layer. The third event is the K-T boundary mass extinction, which is not linked to the Chicxulub impact. These results indicate that a combination of impacts (Chicxulub and K-T), volcanism and climate changes caused increasingly stressful environmental conditions that culminated in the end-Cretaceous mass extinction.

*Research on the Brazos sections was done in collaboration with Thierry Adatte, University of Neuchatel, Switzerland, Gerald Baum, Lewis Energy Group, San Antonio, TX, Thomas Yancey, Texas A&M, Zsolt Berner and Doris Stueben, Karlsruhe University, Germany, Sigal Abramovich, Ben Gurion University, Israel, Michael Prauss, University of Berlin, Germany, Abdel, Aziz Tantawy, South Valley University, Aswan, Egypt, Silvia Gardin, Nicolas Thibault and Bruno Galbrun, Université Pierre et Marie Curie Paris 6, France, and Markus Harting, University of Utrecht, Netherlands.

1. Introduction

The theory that a large meteorite impact on Yucatan caused the mass extinction of dinosaurs and many other organisms at the Cretaceous-Tertiary (K-T) boundary is widely believed as proven with the discoveries of the Chicxulub crater on Yucatan in 1990 (Hildebrand et al., 1990) and impact melt-rock spherules at the base of a sandstone complex throughout Mexico and Central America in close stratigraphic proximity to the K-T boundary (Smit et al., 1992; Stinnesbeck et al., 1993; Adatte et al., 1996). Recently, this 25-year old theory has been challenged by discoveries of Chicxulub impact spherules and breccia in crater core Yaxcopoil-1 and spherule ejecta layers in NE Mexico within upper Maastrichtian sediments that indicate that this impact predates the K-T boundary mass extinction and Ir anomaly by about 300,000 years (Keller et al., 2003a, 2004). Therefore, the Chicxculub impact could not have caused the end-Cretaceous mass extinction. The Ir anomaly at the K-T boundary most likely represents a second large impact, assuming that the Ir is extraterrestrial rather than volcanic in origin.

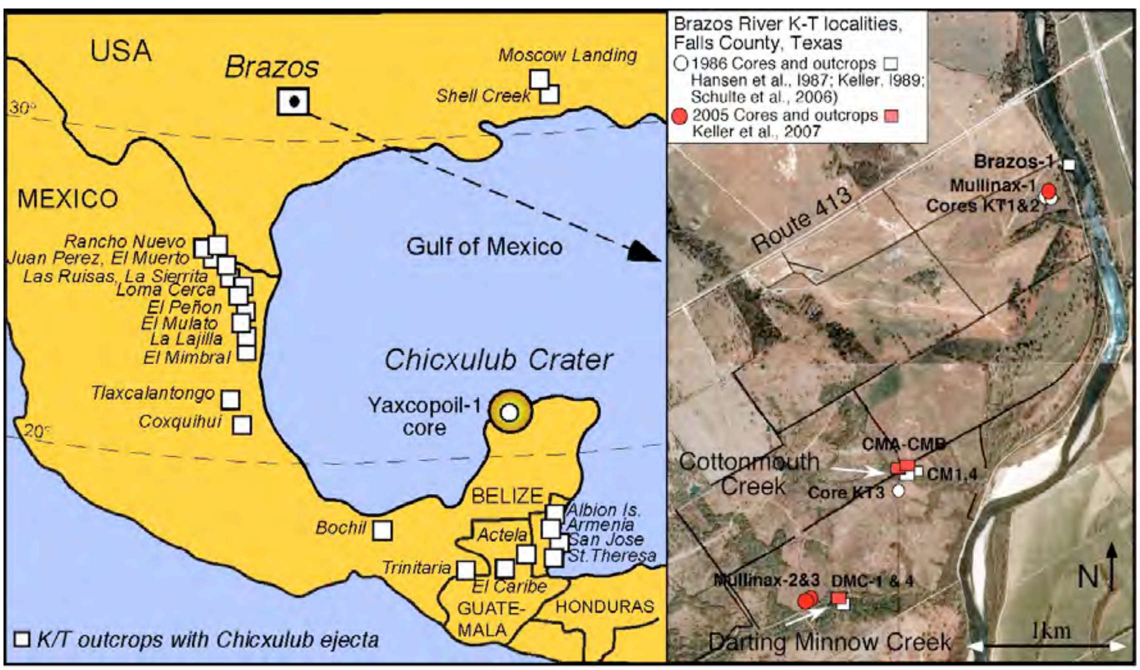

Figure 1. Locations of K-T boundary sequences analyzed with Chicxulub ejecta in the US, Mexico, Guatemala, Belize and the Chicxulub crater. Insert shows locations of the new and published Brazos River cores and outcrop sequences in Falls County, Texas.

To test these challenging results from NE Mexico and the impact crater core, the National Science Foundation (NSF-EAR) supported new drilling by DOSECC along the Brazos River, Falls County, Texas (Fig. 1). This area was chosen for: (a) its greater distance (~1700 km) from the impact crater, which provides an undisturbed sedimentary record across the K-T transition, (b) a complete stratigraphic sequences comparable to the K-T boundary stratotype section at El Kef, Tunisia. (c) the absence of significant tectonic activity, (d) excellent preservation of microfossils, and (e) the presence of a sandstone complex, commonly interpreted as impact generated 'tsunami deposits' (Hansen et al., l987; Bourgeois et al., l988; Smit et al., l996; Heymann et al., l998; Schulte et al., 2006), or sea-level lowstand 'event deposit' (Yancey, 1996; Gale, 2006; Keller et al., 2007). In addition, the Brazos River area affords a relatively simple and inexpensive coring of only 50-100 feet to recover the K-T transition. These attributes mark the Brazos River, Falls County, area as the most important K-T locality outside Mexico and critical to resolving the current controversy regarding the age of the Chicxulub impact and its potential kill-effect. The Brazos study was specifically designed to address three main objectives:

(l) Determine the Age of the Chicxulub impact in order to test the current controversy over whether this impact was the K-T killer as commonly believed, or predated the K-T boundary by 300 k.y., as suggested by the new Chicxulub crater core Yaxcopoil-1 and outcrops in NE Mexico (Keller et al., 2003a, 2004).

(2) Search for the original Chicxulub spherule ejecta layer. In northeastern Mexico, the original Chicxulub spherule ejecta layer was discovered interbedded in upper Maastrichtian marls 4 m to 5 m below a sandstone complex that marks a sea level lowstand (Keller et al., 2003a). This sandstone complex is commonly interpreted as impact-generated tsunami deposits because of the presence of reworked impact spherules at the base. Finding the original spherule ejecta layer in the Brazos sections would provide further strong proof of the late Maastrichtian age of the Chicxulub impact.

(3) Evaluate the Biotic effects of the Chicxulub impact. It is commonly believed that the Chicxulub impact caused the K-T mass extinction. The Brazos sections provide an excellent test of the biotic effects of this impact in a shallow shelf environment at 1700 km from the impact crater. The critical issue is whether an impact the size of Chicxulub, which left a crater of 175 km in diameter, can cause mass extinctions.

This report is a summary of the results first reported in Keller et al. (2007) and focuses on the age, stratigraphy, geochemistry and depositional environment of the Chicxulub ejecta in the Brazos River area of Texas.

1.1 Core and outcrop locations and recovery

Three 75-100 feet deep holes were cored with a CS-500 rig by DOSECC (Drilling, Observation and Sampling of the Earths Continental Crust), the same scientific drilling company that drilled the Chicxulub impact crater hole Yaxcopoil-1 (Fig. 2). The new core Mullinax-1 is located on a meadow about 370 m downstream from the Highway 413 Bridge over the Brazos River, another two cores were drilled near the Darting Minnow Creek (DM) about 3 km to the south (Fig. 1). The onsite scientific team consisted of Gerta Keller (Princeton University), Jerry Baum (Lewis Energy Group) and Tom Yancey (Texas A&M).

In addition to drilling, fieldwork recovered new outcrops along the Brazos River tributaries of the Cottonmouth Creek (CM) and Darting Minnow Creek (DM) about 2 and 3 km to the south of core Mullinax-1 (Fig. 1).

Fig. 2. New drilling of the Brzos K-T sections was done by DOSECC and supported by grants from the National Science Foundation (NSF-EAR).

Fig. 3. The onsite scientific team: Jerry Baum, Gerta Keller and Tom Yancey.

1.2 Methods

The cores and outcrops were sampled at an average of 5-10 cm intervals with 1-2 cm spacing across critical intervals. The samples were distributed for study to an international team of paleontololgists, sedimentologists, mineralogists and geochemists to determine the biostratigraphy and quantify species abundance changes, determine stable isotopes of bulk rock, organic carbon and individual foraminiferal species, and perform palemagnetic analysis. Sediments were analyzed for bulk rock and clay mineralogy (XRD), total organic carbon contents (Rock-Eval) and grain size based on granulometry (Laser Particle Sizer). Geochemistry of impact glass spherules was determined based on raster electron microscopy (REM), back-scatter electron imaging (BSE), wavelength-dispersive (WDS) and energy-dispersive (EDS) electron microprobe of polished and carbon coated thin sections. Data are presented in Keller et al. (2007).

2. Brazos K-T transition

The upper Maastrichtian sediments of the Brazos River area are commonly assigned to the Corsicana/Kemp Formation with earliest Tertiary sediments (Danian zones P0 to P1b) assigned to the Littig Member of the Kincaid Formation. In practice, the Corsicana/Kemp Formation is assigned to the sediments below the sandstone complex and the Kincaid Formation to the sediments above it. Throughout the area the most prominent and correlatable feature of the Brazos outcrops and cores is thus a sandstone complex with dark grey mudstones and claystones above and below it (Fig. 4). There is no recognizable lithological change at the K-T boundary. Primarily for this reason, the sandstone complex was originally described as the K-T boundary and interpreted as deposited by impact generated tsunami waves (Hansen et al., 1987; Bourgeois et al., 1988; Smit et al., 1996). This interpretation was popular, but controversial because nannofossil and planktic foraminiferal analyses revealed that the K-T boundary occurred well above this sandstone complex (Jiang and Gartner, 1986; Keller, 1989) along with an Ir anomaly (Rocchia et al., 1996). In subsequent studies, this sandstone complex has been variously called 'event deposit', 'Chicxulub impact tsunami deposit' (Schulte et al., 2006), or 'storm deposits' associated with a sea level lowstand (Keller, 1989; Yancey, 1996; Gale, 2006). Any study of the Brazos K-T transition thus necessarily focuses on this sandstone complex and then evaluates the sediments above and below. This is also the approach used in this report.

2.1 Sandstone Complex: sea level lowstand or tsunami deposit?

The sandstone complex infills submarine canyons or incised valleys, and is therefore highly variable laterally, thinning out and eventually disappears. Sedimentological features may vary from deposit to deposit as a result of variable erosion and/or depositional environments. The thickest sandstone complex exposure is found in the Darting Minnow Creek where it spans about 1.8 m (Fig. 4). At this locality, the K-T boundary is located above the waterfall, but difficult to reach in the creek bed. The new cores Mullinax-2 and 3 are located on a meadow about 150 m from this outcrop. At this locality the sandstone complex is absent and an erosion surface with mudcracks and rootlets suggests subaereal exposure during a sea level lowstand. This confirms the very shallow inner neritic depositional environment indicated by foraminifera and suggests variable topography with some temporary islands in the Brazos area at the time of the latest Maastrichtian sea level lowstand.

Figure 4. Darting Minnow Creek sandstone complex with Chicxulub impact spherules near the base (at water level). Thin-bedded sandstones overlie the glauconite, phosphate and spherule-rich deposits. The K-T boundary is above the event deposit, but difficult to access in the Creek bed.

The base of the sandstone complex is characteristically marked by an undulating erosion surface. Above it, the first deposition consists of calcareous concretions and mudstone or shale clasts from the underlying upper Maastrichtian sediments that range in size from a few cm to tens of centimeters (Fig. 5A,B). Some clasts contain Chicxulub impact spherules (C, D), other clasts contain desiccation cracks infilled with impact spherules and rimmed by gypsum (C). The desiccation cracks indicate subaereal exposure at some time prior to clast formation. The spherules in these clasts indicate that the Chicxulub impact spherules were deposited well prior to erosion and clast formation, transport and redeposition at the base of the sandstone complex. They thus provide strong evidence that the impact occurred at some time before the sea level drop and deposition of the sandstone complex.

A coarse dark grey-green sandstone rich in altered impact spherules, glauconite, phosphatic clasts, broken shells, reworked foraminifera and small (<2 cm) clasts from the underlying sediments overlies the large clast layer and may range from 10 cm to 40 cm in thickness. This unit consists of three or more upward fining spherule-rich sandstone layers followed by thin layers of rippled sandstone, as shown for the Mullinax-1 core

(Fig. 6). These units are diagnostic of storms with high-energy debris flows followed by upward waning energy depositing the rippled sandstone. In the Brazos River bed, two or more such sequences can be seen exposed during low water levels.

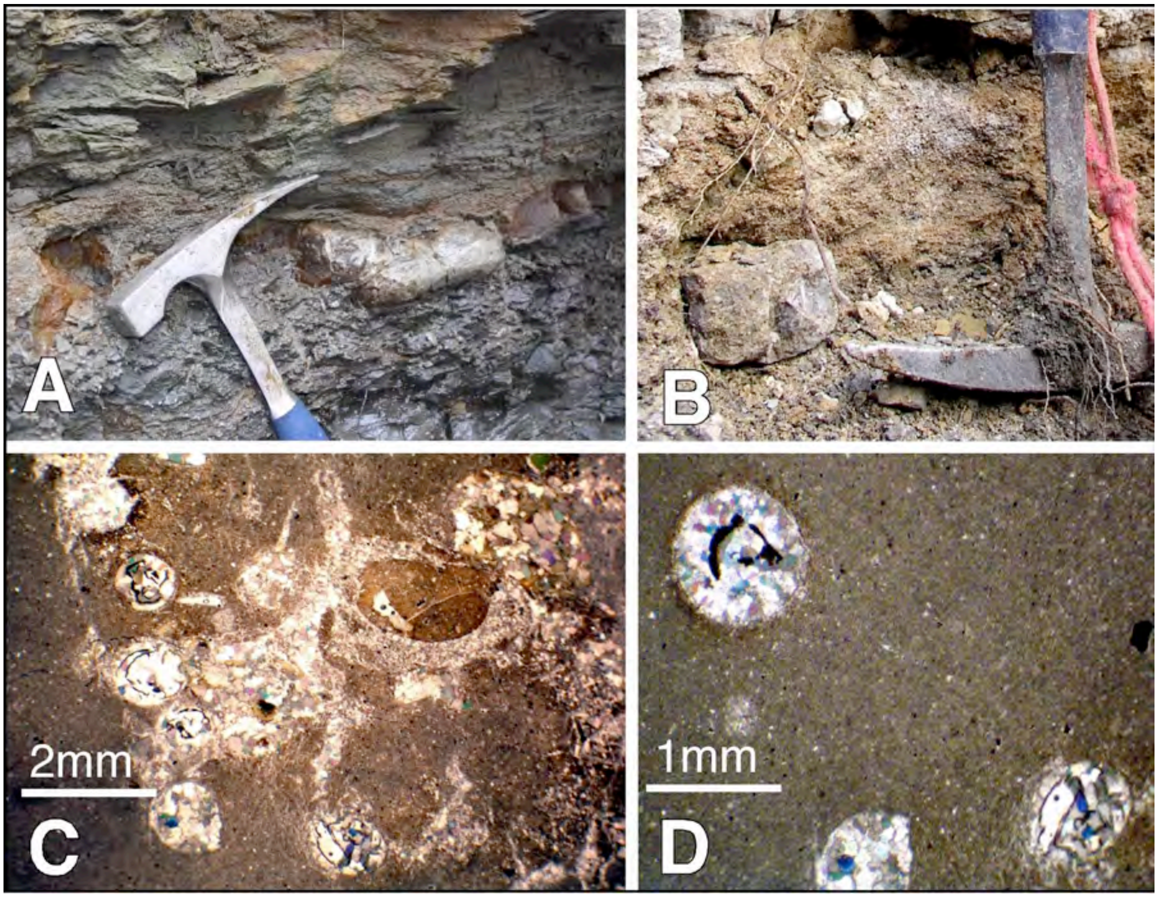

Figure 5. A-B: mudstone clasts and calcareous concretions overlie the erosion surface at the base of the sandstone complex, as shown from Cottonmouth and Darting Minnow Creeks. C-D: thin section micrographs of clasts and concretions that contain impact spherules, some of which infill desiccation cracks (C) that indicate subaereal erosion at sometime after spherule deposition, but prior to clast formation, erosion and redeposition at the base of the sandstone complex.

Geochemical and mineralogical analyses of the spherule-rich sandstones show very low TOC (< 0.1%), a drop to <10% phyllosilicates and variable calcite (due to variable abundances of shells, Fig. 7). Fine fraction $\delta^{13}C$ values are highly negative overall (up to –7‰) due to diagenetic alteration. Smectites, which average 70% in upper Maastrichtian sediments, abruptly reach 100% in the spherule-rich sandstone, where they consist of almost 100% Mg-smectite (cheto smectite) derived from altered Chicxulub impact glass.

Above this spherule-rich unit is a hummocky cross-bedded sandstone (HCS), which is strongly burrowed in vertical and horizontal directions and infilled with dark grey mudstone, which must have originated from overlying sediments that were subsequently eroded. Burrows (*Ophiomorpha*, *Thalassinoides, Planolites*) are truncated

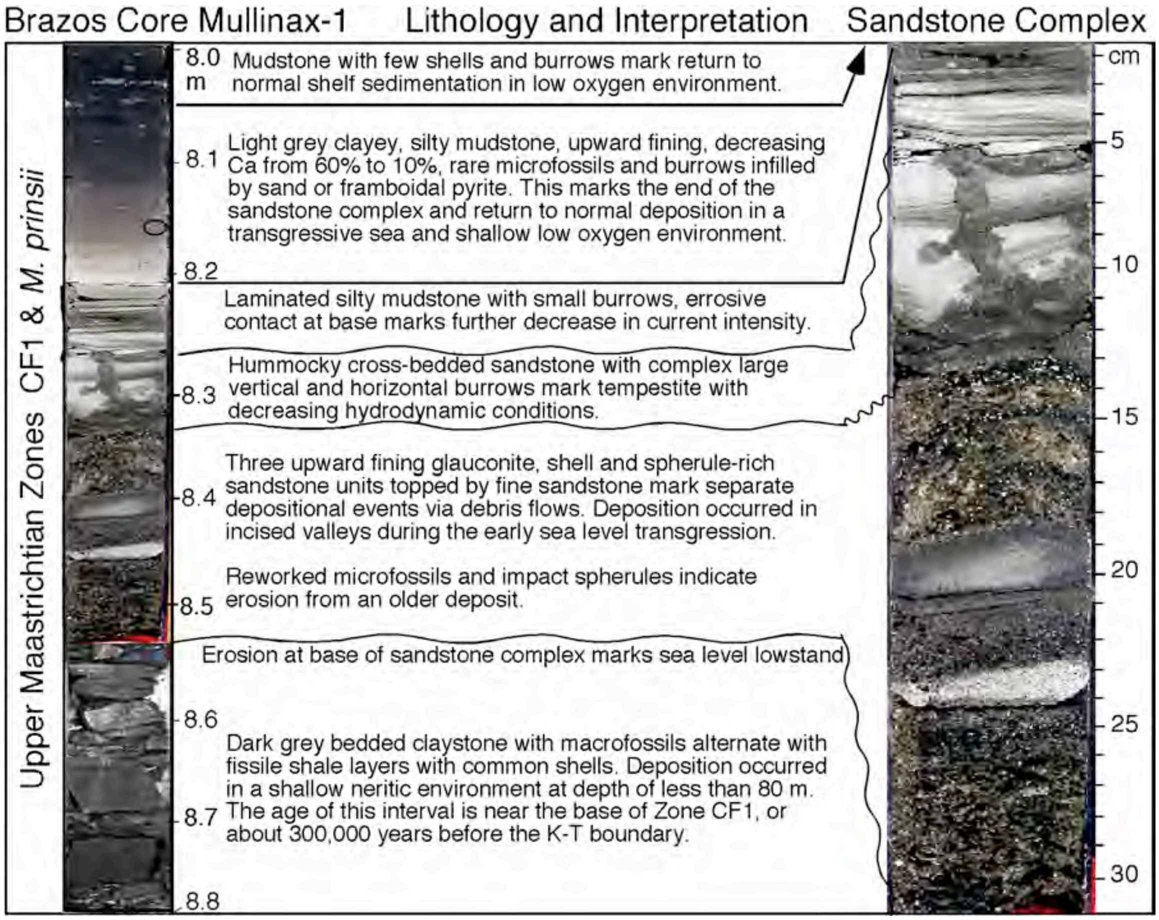

Fig. 6. Lithology, description and interpretation of the sandstone complex in core Mullinax-1. Note the three upward fining, glauconitic, spherule-rich, coarse sandstone units suggest deposition by tempestites. The overlying bioturbated hummocky cross-bedded sandstone, finely bedded sandstone and upward fining indicate decreasing hydrodynamic conditions and a return to normal shallow shelf sedimentation. Modified from Keller et al., 2007.

by erosion at the top, as also observed in the Brazos River bed outcrops (Gale, 2006). Overlying this erosion surface are laminated clayey siltstone and mudstone layers. Above these, fine, calcareous silty mudstones show high, but decreasing calcite contents and upward fining grain size (granulometric data, Fig. 7). This unit marks the end of the sandstone complex with a gradual transition to normal sedimentation by 8.1 m (Fig. 6). The same geochemical and mineralogical patterns can be observed in the Cottonmouth Creek outcrop.

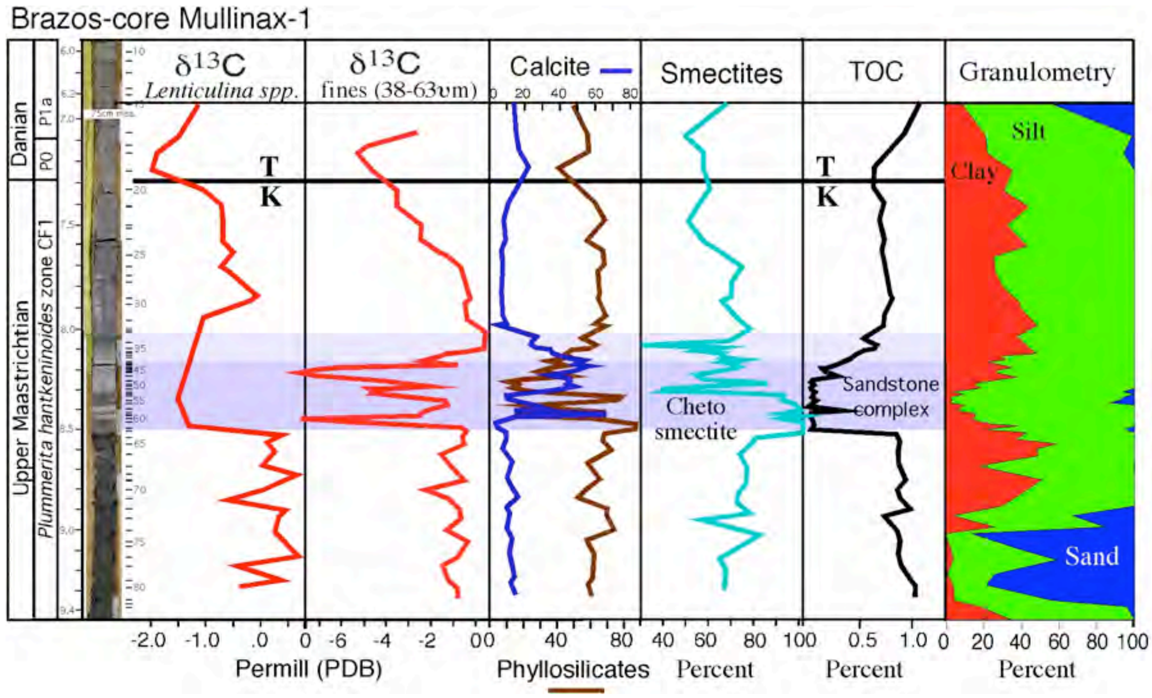

Figure 7. Mineralogical, geochemical and granulometric data above and below the sandstone complex in the core Mullinax-1 reveal normal late Maastrichtian marine sedimentation patterns. Cheto smectite derived from altered impact glass spherules mark the reworked spherulitic sandstone layers. The K-T boundary is characterized by the negative $\delta^{13}C$ shift and faunal and floral turnovers. Modified from Keller et al., 2007.

2.2. The K-T boundary

No significant lithologic change is present at the K-T boundary in the Brazos sequences. Above the sandstone complex, the dark grey to black dysoxic zone with pyrite framboids spans 10 cm in core Mullinax-1 (Fig. 8, 8.1-8.2 m) and is recognizable in outcrops by pyrite nodules distributed over a 20 cm thick interval. Above it, an 80 cm thick interval of dark to medium grey, irregularly bedded silty mudstones prevails with the same clay/silt ratios as below the sandstone complex (Fig. 7). Scattered and commonly flattened macrofossil shells are sometimes concentrated in thin layers and burrows are few and commonly replaced by framboidal pyrite. This suggests that low oxygen conditions continued, as also indicated by the low oxygen tolerant assemblages of planktic and benthic foraminifera. The presence of late Maastrichtian planktic foraminiferal assemblages, palynomorphs and nannofossils in this interval indicate that deposition occurred during the late Maastrichtian planktic foraminiferal zone CF1. All mineralogical and geochemical indicators, including phyllosilicates, carbonate, TOC and $\delta^{13}C$, return to pre-sandstone complex values up to the K-T boundary, though bulk rock $\delta^{13}C$ values and smectite begins to gradually decrease at 7.65 m. (Fig. 7). This clearly marks deposition of this 80 cm interval during the latest Maastrichtian in a gradually deepening, but still shallow neritic low oxygen environment with high terrestrial influx.

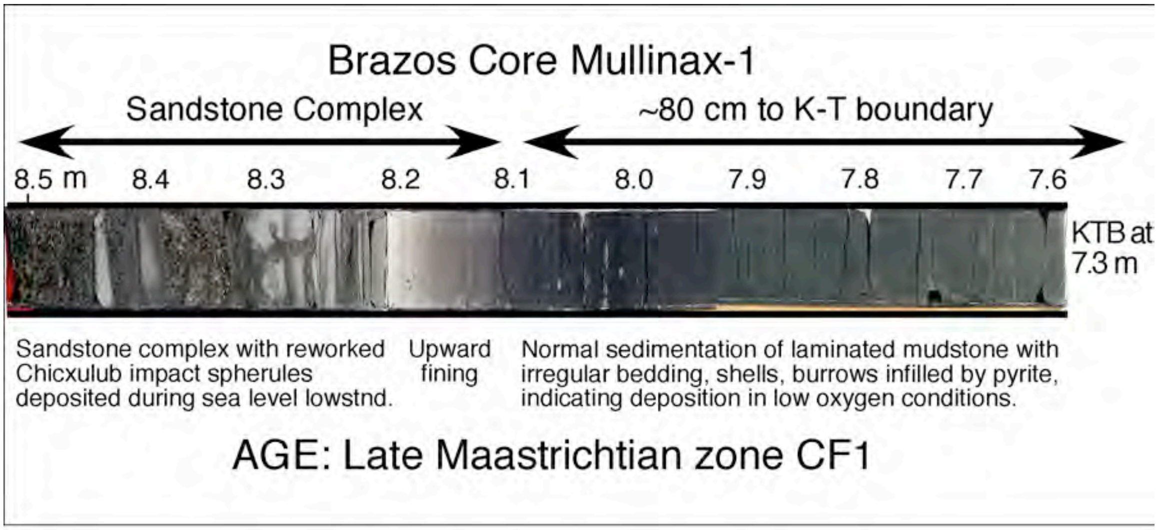

Figure 8. The interval from the sandstone complex to the K-T boundary at Mullinax-1 consists of 80 cm of normal shallow neritic sedimentation with all the characteristics of the late Maastrichtian prior to the sea level lowstnd and sandstone complex (Fig. 7), including late Maasrichtian microfossil assemblages. This indicates that the sandstone complex is unrelated to the K-T boundary event and predates it about 100,000 years.

In core Mullinax-1, the K-T boundary occurs at 7.3 m, or 80 cm above the top of the upward fining sandstone complex (Fig. 8). However, in the Cottonmouth Creek this interval is only 30-40 cm thick and shows erosion. In both localities, the K-T boundary is marked by the negative $\delta^{13}C$ shift (Fig. 7), which characterizes this boundary worldwide, the first appearances of Danian planktic foraminiferal species *Woodringina hornerstownensis, Parvularugoglobigerina extensa and Globigerina daubjergensis*, and the extinction of tropical and subtropical species. There is no lithological change at the K-T boundary, which may be attributed to the shallow depositional environment and relatively high terrestrial influx. Most important for the K-T boundary scenario is the fact that the sandstone complex and the K-T boundary mass extinction are temporally well separated in time and show no causal relationship. Thus the Chicxulub impact (marked by the spherules at the base of the sandstone complex) cannot be considered as coeval with the K-T mass extinction. The same stratigraphic relationship between the K-T and sandstone complex was observed in sections from NE Mexico indicating that the Chicxulub impact predates the K-T boundary (Keller et al., 2003a).

2.3. The original Chicxulub impact ejecta layer

Although the Chicxulub impact is commonly interpreted as the cause of the K-T mass extinction, the Brazos K-T sections do not support this hypothesis. As noted above, this is indicated by the fact that (a) the sandstone complex predates the K-T boundary, (b) the impact spherules are reworked in the glauconite and spherule-rich sandstone layers of the sandstone complex, and (c) the presence of impact spherules in the concretions and mudstone clasts at the base of the sandstone complex, which indicate erosion from an older Chicxulub impact ejecta layer. Thus, the original Chicxulub spherule ejecta layer should be found in the underlying late Maastrichtian sediments below the sandstone complex.

We discovered the undisturbed original impact spherule ejecta layer, now altered to a 3 cm thick yellow clay, 45-60 cm below the sandstone complex in the Cottonmouth Creek outcrop (Fig. 9). The yellow clay layer is interbedded in dark grey to black thinly bedded claystone with common macrofossil shells and burrows. It can be traced laterally over 20-30 m depending on outcrop exposures. No disturbance can be observed in the sedimentary layers above or below the yellow clay.

Microfossils indicate a Latest Maastrichtian age based on the *Micula prinsii* nannofossil zone and planktic foraminiferal zone CF1, which spans the last 300,000 years of the Maastrichtian (Pardo et al., l996). The first appearance of the zone CF1 index species, *Plummerita hantkeninoides,* occurs 20 cm below the yellow clay. This indicates that deposition of the yellow clay (e.g., Chicxulub impact) predates the K-T boundary by about 300,000 years, correlative with the age earlier determined for the original Chicxulub impact spherule layer from sections in NE Mexico and the impact breccia in the Chicxulub impact crater core Yaxcopoil-1 (Keller et al., 2003a, 2004).

Figure 9. Cottonmouth Creek waterfall drapes over the resistant sandstone complex with reworked impact spherules at the base. The original Chicxulub impact spherule layer is present in a 3 cm thick yellow layer 60 cm below the sandstone complex and interbedded within undisturbed claystone layers. Microfossils date the Chicxulub impact layer as base of zone CF1, or 300,000 before the K-T boundary mass extinction.

The yellow clay, as well as the clay in the spherule-rich sandstone of this outcrop, core Mullinax-1 and elsewhere, consist of nearly 100% Mg-smectite (Figs. 10, 11). Mg-smectite is derived from weathering of glass (001 reflection, low cristallinity index, 0.5 to 0.8°2 θ) with the 060 reflection around 61° indicating a composition corresponding to nontronite, or cheto Mg-smectite (Debrabant et al., l999; Keller et al., 2003b). In contrast, smectite in Maastrichtian and Danian claystones is a common montmorillonite derived from weathering of soils, as indicated by the 060 reflection between 61.7° and 62.3° (Moore and Reynolds, l997). This coincidence in mineral compositions strongly suggests a common origin for the yellow clay and the spherule-rich layers of the sandstone complex, which are identified as Chicxulub impact spherules.

Figure 10. Cheto smectite derived from altered impact glass marks the Chixculub spherule layer and the reworked spherules at the base of the sandstone complex in the Cottonmouth Creek.

Geochemical analyses of the smectite phases from the yellow clay layer and from the spherule-rich sandstone layers support this conclusion. All three layers are similar and reveal typical Mg enriched cheto type-smectite high in SiO_2 (66-71%), Al_2O_3 (19-20%), FeO (4.4. 4.8%), MgO (2.8-3.3%) with minor K_2O (1-1.1%) and NaO (<0.5%). This composition is very similar to the altered smectite rims from Haiti glass spherules and to NE Mexico altered glass spherules (Izett, l991; Schulte et al., 2003; Stueben et al., 2005).

The glass geochemistry of spherules within the concretions and clasts at the base of the sandstone complex and the relic spherules in the yellow clay (Fig. 12) show very similar compositions with two types of spherules. Spherules #1 are characterized by 48-50% SiO_2, 15-18% FeO, 10-12% Al_2O_3, 3-4% MgO and 1.3-1.7 % CaO. Spherules #2 show lower FeO (2-3%), higher CaO (3-4%) and lower total oxides (81%), which reflects more intense weathering through hydration or oxidation. These Brazos spherule compositions closely correlate with Fe-rich and weathered Chicxulub impact spherules from NE Mexico and Haiti (Izett, 1991; Schulte et al., 2003; Stueben et al., 2005).

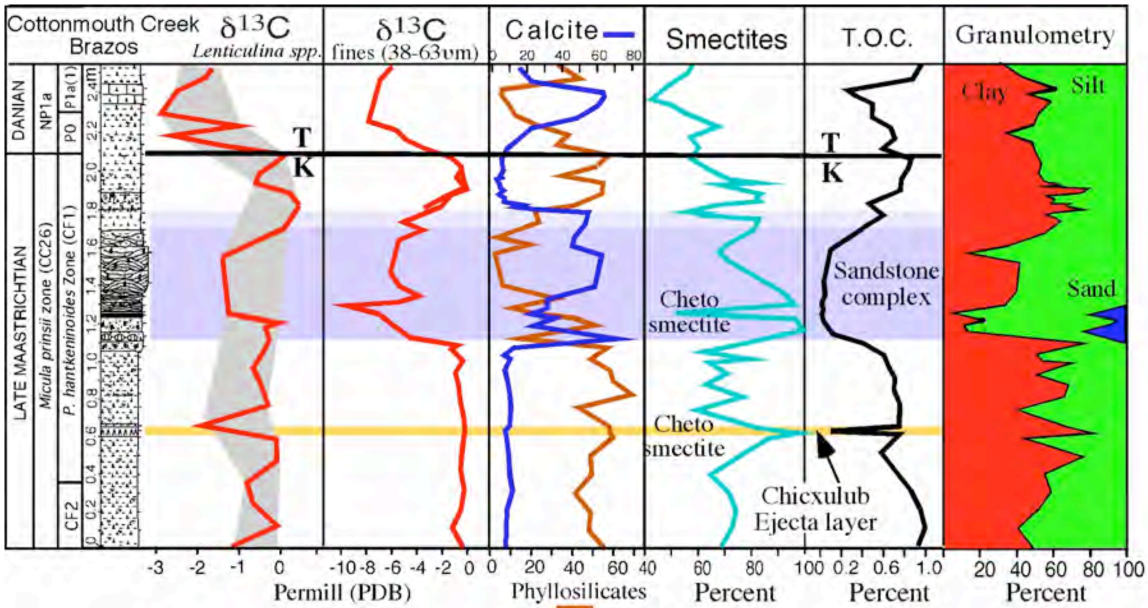

Figure 11. Mineralogical, geochemical and granulometric data above and below the sandstone complex and Chicxulub spherule ejecta layer at Cottonmouth Creek reveal normal late Maastrichtian marine sedimentation patterns. Cheto smectite derived from altered impact glass spherules mark the reworked spherules at the base of the sandstone complex. Cheto smectite also characterizes the original spherule ejecta layer in Maastrichtian claystones below. The K-T boundary is characterized by the negative $\delta^{13}C$ shift and faunal and floral turnovers. Modified from Keller et al., 2007.

Thus, despite the clay alteration of the glass spherules with only relic glass preserved in the yellow clay, the Chicxulub impact origin of this layer can be determined based on: a) the presence of cheto smectite, b) geochemistry of preserved glass, c) the identical cheto smectite and glass geochemistry of the spherule-rich layer and clasts at the base of the sandstone complex, and d) correlation with cheto smectite and geochemistry of Chicxulub impact spherules in NE Mexico, Haiti and the crater core Yaxcopoil-1.

Above and below the yellow clay layer, the late Maastrichtian claystones are equivalent to those of core Mullinax-1. They are relatively high in TOC (0.6-1%), phyllosilicates (50-60%), smectites (60-70%, relative to phyllosilicates, except for one peak of 100%), though calcite is a steady low ~10% (Fig. 11). $\delta^{13}C$ values are relatively constant for fine fraction (–0.5 to 0‰) and *Lenticulina* sp. (–1 and 0‰). The decrease in $\delta^{13}C$ in the sandstone complex and the yellow clay (*Lenticulina* sp.) is due to diagenetic alteration, as also observed in Mullinax-1. The apparent absence of the yellow clay layer in Mullinax-1 appears to be due to sand deposition and/or erosion below the sandstone complex.

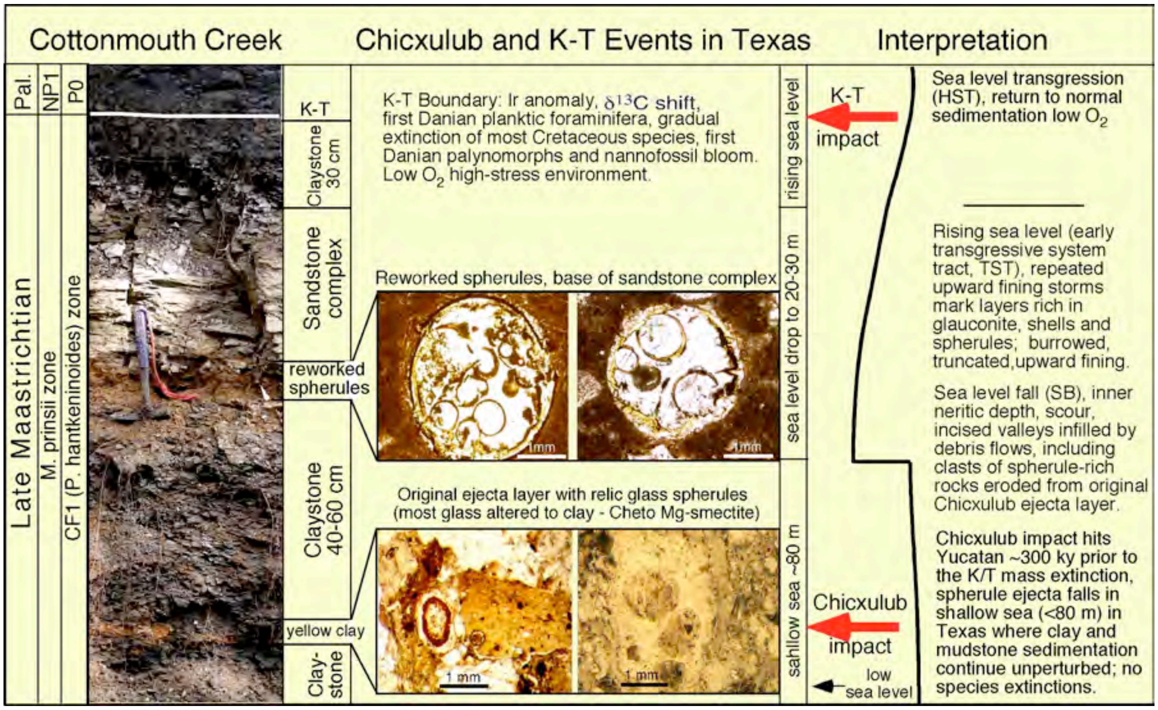

Figure 12. Sequence of three events identified at the Cottonmouth Creek outcrops: 1. Yellow clay marks the Chicxulub spherule ejecta layer now altered to cheto smectite with relic glass; this impact occurred near the base of zone CF1, about 300 ky before the K-T boundary. 2. The sandstone complex marks the latest Maastrichtian sea level fall, channel scour and subsequently infilling by storms during the early transgression. 3. The K-T boundary occurs during the subsequent sea level high and is marked by the global $\delta^{13}C$ shift and first appearance of Danian species. Modified from Keller et al., 2007.

3. Age of Chicxulub impact and Sandstone Complex

Planktic foraminifera indicate the latest Maastrichtian nannofossil *Micula prinsii* and planktic foraminifer CF1 zones for the critical interval containing the yellow clay and sandstone complex. The CF1 index species (*Plummerita hantkeninoides*), which spans the last 300 ky of the Maastrichtian first occurs a short interval below the yellow clay layer and dates the Chicxulub impact as preceding the K-T boundary by about 300,000 years. The sandstone complex is younger than the Chicxulub impact, but significantly older than the K-T boundary (Figs. 12, 13).

An absolute age for the sandstone complex is difficult to estimate because the interval eroded at the base is unknown. From field observations, Gale (1996) estimated that channels cut down to a maximum 1-1.5 m. If we assume the maximum undisturbed sedimentation from the sandstone complex to the K-T at 80 cm (Mull-1) and from the base of CF1 to the base of the sandstone complex at 80-100 cm, plus the maximum down cutting of the channel at 1.5 m, then zone CF1 spans about 3.3 m, or about 1.1 cm/1000 years. This sedimentation rate is comparable to shallow water sequences in Egypt, Israel and Tunisia and comparable to the 1.25 cm/1000 years estimated by Schulte et al. (2006) for the combined zone CF1 and CF2 interval in the old core KT2 near Mullinax-1. By this estimate, the sandstone complex predates the K-T boundary by at least 80,000 years and postdates the Chicxulub impact (yellow clay) by at least 227,000 years.

3.1. Depositional Environment during K-T transition

The most controversial aspects of the Brazos K-T transition have been the origin of the sandstone complex and the position of the K-T boundary and mass extinction event. Even before the discovery of the Chicxulub impact crater and its spherule ejecta layer, the sandstone complex was interpreted as impact-generated tsunami deposit largely due to its proximity to the K-T boundary (Bourgeois et al., l988). This interpretation necessitated placement of the K-T boundary at the base of the sandstone "tsunami" complex and the stratigraphic separation attributed to upward fining after the tsunami passed (Bourgeois et al., l988; Smit et al., l996; Heymann et al., l998; Schulte et al., 2006).

However, upward fining in core Mullinax-1 and Cottonmouth Creek localities is restricted to only 10-15 cm at the top of the sandstone complex and is followed by normal deposition in a low oxygen organic-rich shallow environment (Figs. 7, 11). Moreover, nannofossils, planktic foraminifera and palynomorphs, as well as the K-T characteristic negative $\delta^{13}C$ excursion all indicate that the K-T boundary is 80 cm above the top of the sandstone complex and its upward fining portion in Mullinax-1 and about 40 cm above in Cottonmouth Creek (Jiang and Gartner, l986; Keller, l989; Barrera and Keller, l990; Keller et al., 2007). Schulte et al. (2006) identified the K-T boundary 1.6 m above the sandstone complex in the old KT-1 core, which was drilled at the same location as Mullinax-1. However, the KT-1 core is suspect because it was terminated in this critical interval due to drilling disturbance.

3.2. Sea level regression

Lithologic characteristics of the sandstone complex, including the undulating erosion surface at the base, the clasts and concretions with impact spherules, and the shell hash, indicate that this sandstone complex was deposited during a sea level lowstand. The relative sea level change can be evaluated based on the relative abundance of planktic vs benthic species (Fig. 13). Plankic foraminifera are more diverse and abundant in deeper waters and open marine environments, whereas benthic species thrive in shallow shelf environments. The ratio of benthic and planktic groups therefore is an indicator of water depths. In the Mullinax-1 core, as at Cottonmouth creek (core KT3), species diversity decreased in the sandstone complex, and remained low up the K-T boundary mass extinction (Fig. 13). The relative abundances of planktic species shows a dramatic decease in planktic species ppopulations and concurrent increase in benthics beginning with the sandstone complex and continuing through the early Danian zone P1a (*Parvularugoglobigerina eugubina* zone). Planktics recover in zone P1b and benthics decrease. This pattern is consistent with the sea level changes inferred based on lithology and macrofossils and also observed in macrofossils (Gale, 2006).

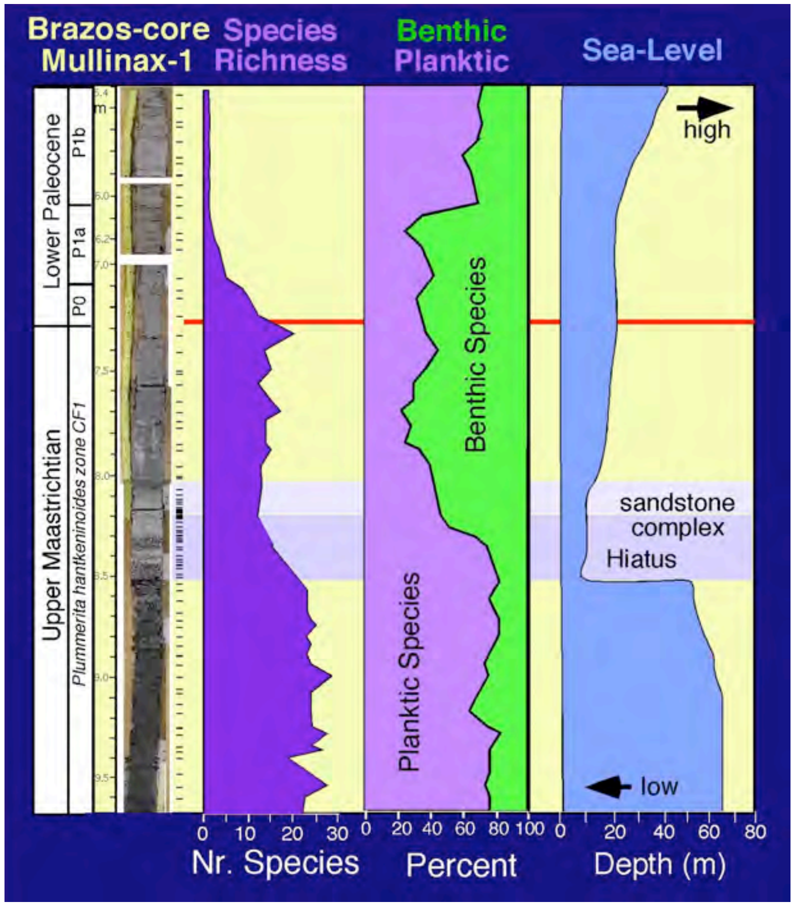

Figure 13. Species diversity changes and the relative abundances of planktic and benthic species are indicators of sea level changes. At Mullinax-1, these environmental proxies support the sea level changes observed from litology and macrofossils.

3.3. Chicxulub Impact - Erosion and Redeposition of Spherules

With new evidence from sedimentology, paleontology, and geochemistry (Yancey, l996; Gale, 2006; Keller et al., 2007), the following depositional scenario evolves (Fig. 14). During the late Maastrichtian, sediment deposition along the Brazos occurred in a shallow continental shelf environment with water depths of about 80-100 m and gradually decreasing as sea level dropped and climate cooled. Abundant macrofossils and microfossils inhabited the sea and burrowed in the mudstones and claystones. At about 300,000 years before the K-T boundary mass extinction, a large meteorite hit the shallow sea near the present village of Chicxulub on Yucatan, creating a large dust cloud of vaporized melt rock and leaving behind a 175 km diameter crater. Within hours to days of the impact, a layer of impact melt-rock spherules, ranging in size from 0.5 to 4 mm, rained down all over an area spanning at least from northern New Jersey through

Central America and the Caribbean and possibly as far south as Brazil. This impact spherule deposit has been discovered in the sedimentary sequences in NE Mexico and Brazos. Tsunami waves were likely generated by the impact-triggered earthquakes, but any tsunami deposits were likely redistributed by subsequent current activity, as indicated by the absence of any significant sedimentary disturbance above or below the original spherule deposits at Brazos or in NE Mexico (Keller et al., 2003a, 2007).

After the Chicxulub impact, sediment deposition continued much as it had before, but for the next 200,000 years, sea level dropped by about 60 m, reaching a low of only 20-30 m in western Texas and exposing nearshore areas and topographic highs to erosion. In this shallow water environment, currents incised canyons or valleys, eroded sediments from nearshore areas and transported them into deeper waters infilling the canyons (Fig. 14). The initial transport consisted of clasts ripped up from underlying lithified sediments under high-energy hydrodynamic conditions. Some of these clasts contain impact spherules, some have desiccation cracks infilled with spherules (Fig. 5). These clasts

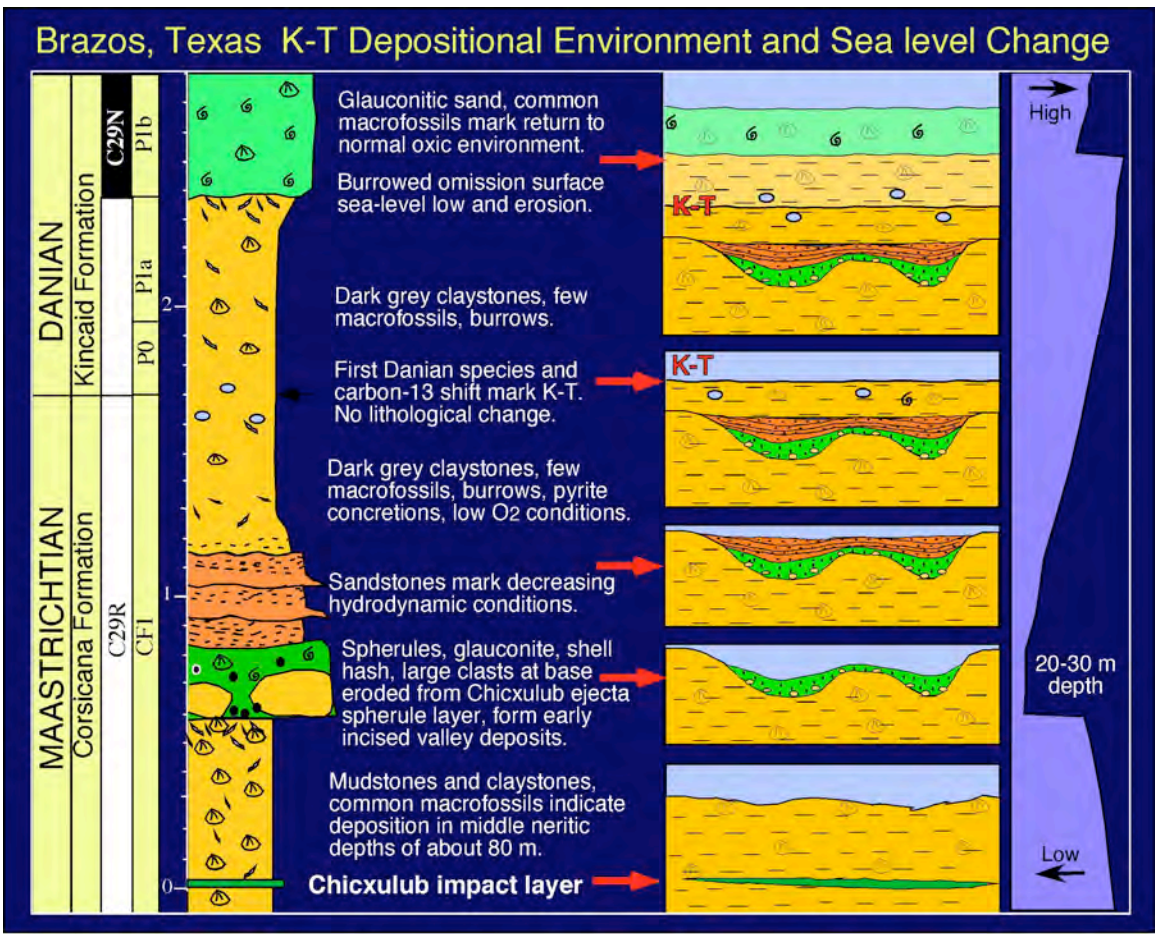

Figure 14. Depsotional environment across the K-T transition along the Brazos River in Texas. The Chicxulub impact, sea level lowstand sandstone complex and the K-T boundary are temporally separate and unrelated events. The spherules and spherule-bearing clasts at the base of the sandstone complex mark the onset of deposition in the incised valley during the sea level lowstand.

indicate that the impact spherule layer was exposed to erosion near the shore, with clasts and debris ripped up, transported and re-deposited in the incised valleys. Large clast deposition was followed by up to three units of upward fining coarse sandstone consisting of smaller clasts, glauconite, impact spherules and shell hash (Fig. 6). These units mark debris flows possibly during seasonal tempestites.

When sea level began to rise (early sea level transgression), hydrodynamic conditions decreased depositing the hummocky cross-bedded sandstone, followed by fine sand layers and upward fining calcareous sands (Fig. 14). The presence of multiple layers of truncated large and small burrows indicate repeated colonization of the sea floor by burrowing macrofossils, which were then wiped out by the sudden influx of sands during tempestites (Gale, 2006). At the top of the sandstone complex, the return to normal marine deposition is marked by an upward fining calcareous silty mudstone, with gradually decreasing carbonate and increasing clay and organic contents (Fig. 8).

With the deepening sea, claystone deposition returned in a low oxygen inner neritic or coastal environment with high terrestrial organic matter influx, as indicated by the small macrofossil shells, burrows infilled with pyrite framboids and dwarfed low diversity planktic foraminiferal assemblages. The K-T boundary mass extinction occurred in this high stress environment at Brazos. Above the K-T boundary dark grey claystone sedimentation continued much as it had before and abruptly terminates at an erosional unconformity that marks a drop in the sea level (Fig. 14). Above it, light grey-green glauconitic siltstones with abundant macrofossils indicate the return to a normal oxic marine environment.

4. Biotic effects of the Chicxulub impact

It is widely believed that the Chicxulub impact caused the end-Cretaceous mass extinction. Indeed, conventional wisdom holds that any such large impact, leaving a 175 km diameter crater, would cause major mass extinctions. But this hypothesis is based solely on the assumption that the Chicxulub impact is the K-T killer. None of the other major mass extinctions in Earth’s history are associated with major impacts (review in Keller, 2005). If the Chicxulub impact predates the K-T boundary, as shown by new evidence from Brazos, Texas, and previous evidence from NE Mexico and the Chicxulub impact crater core Yaxcopoil-1, then this hypothesis has no empirical support and must be considered false at least with respect to the Chicxulub impact. However, this does not rule out a potential second, perhaps larger impact at the K-T boundary, as suggested by the global distribution of the Ir anomaly, although massive Deccan volcanism as the source of the Ir anomaly cannot be excluded at this time.

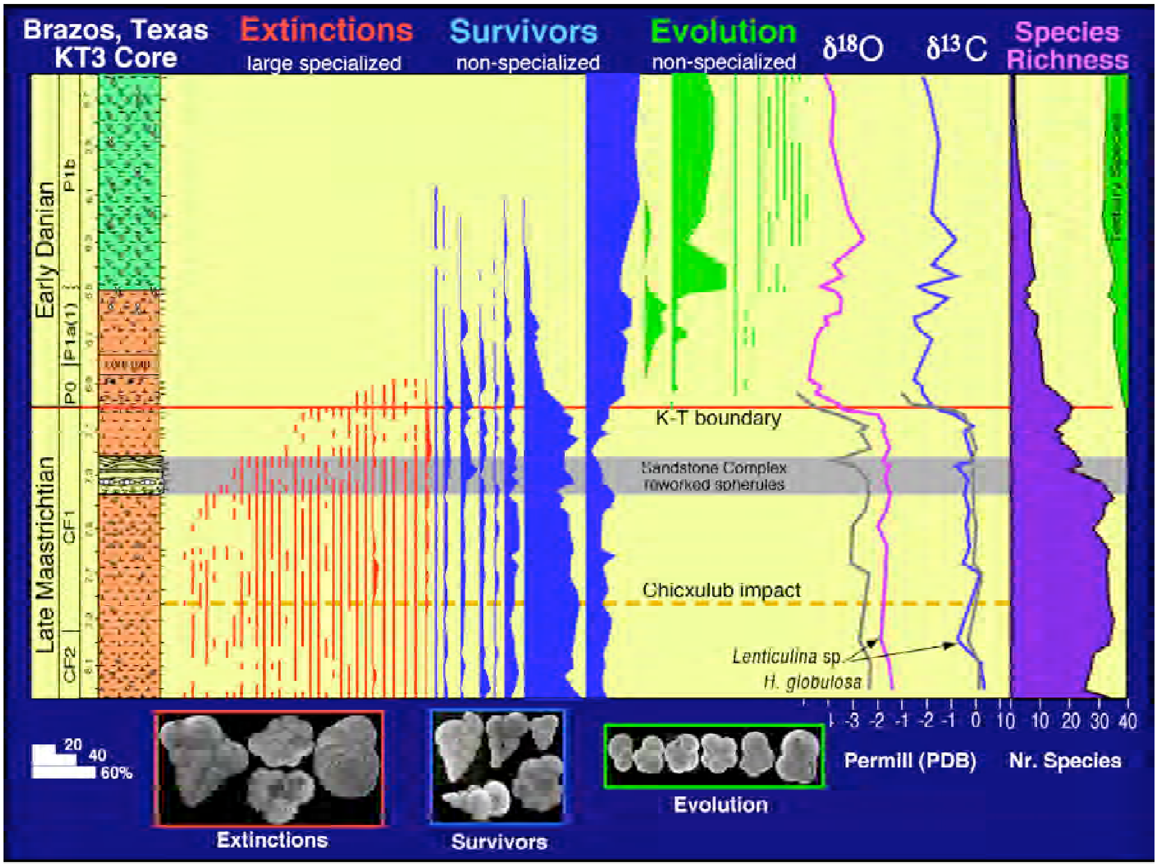

Figure 15. Planktic foraminiferal abundances across the Chicxulub impact, sandstone complex and K-T boundary at Cottonmouth Creek (Core KT3) show that the Chicxulub impact caused no mass extinction. All large tropical and subtropical species began to disappear gradually beginning below the Chicxulub ejecta layer due to the shallowing environment. All became extinct at or near the K-T boundary. Only smaller and ecologically tolerant species thrived and survived into the early Danian. In comparison, evolving new Danian species were much smaller and more stress resistant and eventually outcompeted all but one of the Cretaceous survivors.

The biotic effects of the Chicxulub impact at 1700 km from the impact crater on Yucatan can be determined based on species and abundance changes in the planktic foraminiferal assemblages before and after the impact ejecta layer (yellow clay, Fig. 15). *These data show not only that the Chicxulub impact caused no mass extinction, but also that not a single species extinction can be attributed to this impact*. The large specialized species that gradually disappeared before the K-T boundary were deeper dwellers that could not survive in the shallowing shelf environment of Brazos. This is also seen by the increasingly rare and sporadic occurrences of all tropical and subtropical species (red lines) leading up to the K-T boundary mass extinction (Fig. 15).

5. Multiple Impacts

No mass extinction scenario based on the diverse empirical records of impacts, volcanism, climate and sea level changes can match the impact-kill hypothesis advocated by Alvarez et al. (l980) in its simplicity and appeal to the imagination of young and old. In the 27 years since its publication, a massive database has been accumulated, which confirms the reality of impacts, not just one as originally proposed, but multiple impacts both large and small, over a period of several hundred thousand years. The most famous of these is the Chicxulub impact crater, but there are smaller ones, such as Boltysh. Others are known only from Ir anomalies, including one in the early Danian and the K-T impact originally proposed by Alvarez et al. (1980) based on the global Ir anomaly.

The Chicxulub impact teaches a humbling lesson. Ultimately, it was the existence of this impact crater and its stratigraphic proximity to the K-T boundary that led so many scientists to believe that this is the sole cause for the mass extinction. Over the past 20 years, high resolution stratigraphic, paleontologic, mineralogical and geochemical studies of over 200 K-T sections across the world and concentrating on Mexico, Central America and now Texas, have led to a vast accumulation of data that cannot be reconciled with the popular impact scenario. The more data we accumulated, the more complex and multi-faceted the history of this mass extinction revealed itself. Above all, it has become evident that the existence of a large impact crater alone neither proves nor explains the demise of the dinosaurs or the mass extinction of planktic foraminifera or any other groups.

Mexico, including the Chicxulub impact crater itself, has yielded a comprehensive database of independent proxies (paleontology, stratigraphy, mineralogy, geochemistry, paleomagnetism) that revealed that this impact predates the K-T boundary by about 300,000 years (Keller et al., 2003a, 2004). This work has been challenged by some workers (e.g., Soria et al., 2001; Smit et al., 2004; Lawton et al., 2005) largely on the grounds that the stratigraphic record must be disturbed by impact-induced earthquakes and tsunami waves depositing the sandstone complex, causing slumps and gravity flows and even injecting the Chicxulub spherule ejecta layer into older Maastrichtian sediments. However, all of the claimed ‘tsunami’ deposits were deposited over time during the sea level lowstand. No major disturbances have been documented in dozens of sections analyzed in NE Mexico, and no mechanism is known for injecting impact spherule layers into marine marls over large distances, leaving the marls undisturbed (Keller and Adatte, 2005; Keller and Stinnesbeck, 2002).

Now the Brazos, Texas, K-T sequences have confirmed the earlier observations in NE Mexico. They show unequivocally that the K-T boundary is younger than the sea level lowstand sandstone complex with its reworked impact spherules in clasts and concretions at the base, and the newly discovered original impact ejecta layer is much older than either. We confirmed the observations of previous workers (e., Yancey, l996; Gale, 2006) that the sandstone complex was deposited over a long time period during a low sea level, rather than a tsunami generated by the Chicxulub impact.

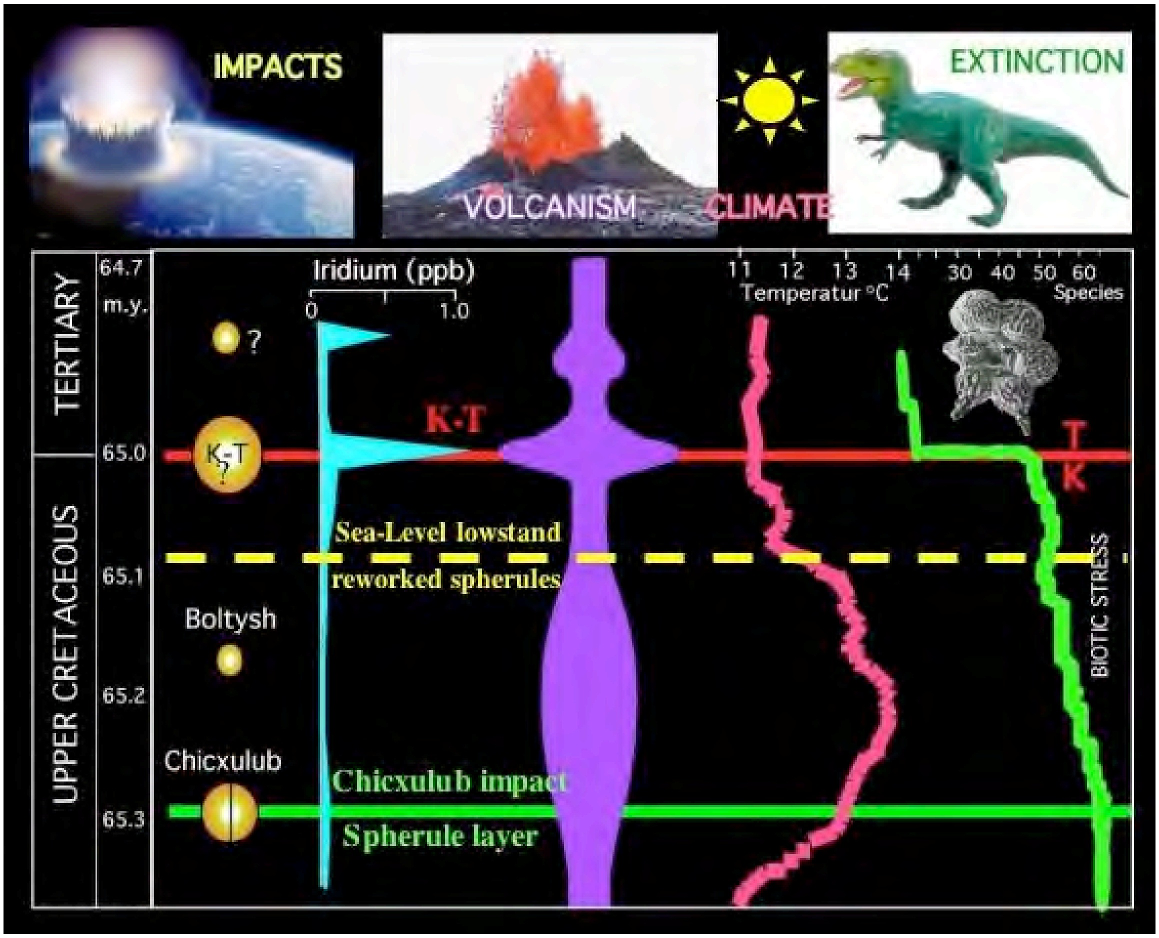

Figure 16. The current database suggests that the K-T boundary mass extinction was the result of multiple interacting events, including multiple impacts, massive volcanism, and greenhouse warming and cooling accompanied by sea level changes. Each of these events by itself would not have caused the mass extinction of the Cretaceous fauna and flora, but the coincidence of these events exceeded threshold conditions for many organisms leading to extinction.

5.1. Mass Extinction Scenario

The current database suggests that the K-T boundary mass extinction was the result of multiple interacting events, including multiple impacts, massive Deccan Traps volcanism, greenhouse warming and cooling accompanied by sea level changes (Fig. 16). Each of these events by itself would not have caused the mass extinction of the Cretaceous fauna and flora, but the coincidence of these events exceeded threshold conditions for many organisms leading to extinction. Among marine life, planktic foraminifera were most severely affected by the K-T mass extinction and therefore are an excellent measure of the timing and severity of the extinction event.

Major biotic stress began 400 thousand years before the mass extinction with the rapid climate warming as a result of massive volcanic eruptions in India. Climate warmed by at least 4°C in the oceans and 8°C on land (Fig. 16). Because climate warming is more deadly to life than cooling, most tropical and subtropical species suffered major declines, bringing them to the brink of extinction. Few tropical species exceeded 1% in abundance through this time and they never recovered. Some species adapted to the new realities of the warmer climate by changing their modes of living and finding new ecological niches. But their efforts were doomed when climate cooled again and the sea level dropped about 80,000-100,000 years before the K-T mass extinction. At this time submarine canyons formed and were subsequently infilled with eroding sediments from nearshore areas that also exposed and eroded the impact spherule layer and redeposited them in clasts, concretions and mixed with glauconite and shell hash. Indeed, proponents of the impact-tsunami hypothesis cite these reworked spherule deposits as key evidence.

The very low sea level brought a renewed challenge for tropical and subtropical species to adapt to shallow waters and cooler conditions. But the already weakened species populations failed and began to die out. In the end, renewed volcanism at K-T boundary time and possibly another large impact (suggested by the Ir anomaly) wiped out all of the tropical and subtropical species. The more ecologically tolerant survivors continued for a couple of hundred thousand years into the early Paleocene and eventually succumbed to competition of the newly evolving fauna.

6. Conclusions

The K-T sequences along the Brazos River of Falls County, Texas, have provided the most important and critical information regarding the age and biotic effects of the Chicxulub impact outside of Mexico. Excellent preservation of fossils, a relatively continuous sedimentary record, shallow shelf environment and absence of any significant tectonic disturbance make this area an excellent test case for the K-T mass extinction and the Chicxulub impact. Most important are the following findings and discoveries:

1) The sandstone complex was deposited during a sea level lowstand and infills submarine canyons. The source of the sediments includes rip-up clasts from underlying lithified strata, and erosion of sediments exposed in shallow nearshore areas.
2) The presence of clasts and concretions with Chicxulub impact spherules at the base of the sandstone complex reveals that the Chicxulub impact predates not only the K-T boundary, but also the sandstone complex.
3) The discovery of the original Chicxulub impact spherule layer inter-bedded in late Maastrichtian shale well below the sandstone complex with its reworked clasts. The original Chicxulub impact layer predates the K-T boundary by about 300,000 years, consistent with the age determined from NE Mexico and the impact crater core Yaxcopoil-1.
4) No species extinctions or significant environmental changes can be attributed to the Chicxulub impact in Texas, only 1000 km from the impact crater.

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REFERENCES

Abramovich S., and Keller, G., 2003. Planktic foraminiferal response to latest Maastrichtian abrupt warm event a case study from midlatitude DSDP Site 525: Marine Micropaleontology, v. 48, p. 225-249.

Adatte, T., Stinnesbeck, W., and Keller, G., l996, Lithostratigraphic and mineralogical correlations of near-K/T boundary clastic sediments in northeastern Mexico: Implications for mega-tsunami or sea level changes? Geol. Soc. Am. Special Paper 307, p. 197-210.

Alvarez, L.W., Alvarez, W., Asaro, F., and Michel, H.V., l980, Extraterrestrial cause for the Cretaceous-Tertiary extinction: experimental results and theoretical interpretation: *Science*, v. 208, p. 1095-1108.

Barrera, E. and G. Keller, 1990. Stable isotope evidence for gradual environmental change and species survivorship across the K/T boundary, Paleoceanography, 5(6): 867-890.

Bourgeois, J., Hansen, T.A., Wiberg, P., Kauffman, E.G., l988, A tsunami deposit at the Cretaceous-Tertiary boundary in Texas: Science, v. 141, p. 567-570.

Debrabant P., Fourcade E E., Chamley H., Rocchia R., Robin E., Bellier J.P., Gardin S., Thiebolt F., 1999, Les argiles de la transition Cretace-Tertiaire au Guatemala, temoins d'un impact d'asteroide: Bulletin de la Societe Geologique de France, v. 170, p. 643-660.

Gale, A., 2006, The Cretaceous-Tertiary boundary on the Brazos River, Falls County, Texas; evidence for impact-induced tsunami sedimentation? Proceedings of the Geologists' Association, v. 117, p. 1-13.

Hansen, T.A., Farrand, R.B., Montgomery, H.A., Billman, H.G., Blechschmidt, G.L., 1987, Sedimentology and extinction patterns across the Cretaceous-Tertiary boundary interval in east Texas: Cretaceous Research, v. 8(3), p. 229-252.

Heymann, D., Yancey, T.E., Wolbach, W.S., Thiemens, M.H., Johnson, E.A., Roach, D., Moecker, S., 1998, Geochemical markers of the Cretaceous-Tertiary boundary event at Brazos River, Texas, USA: Geochimica et Cosmochimica Acta, v. 62(1), p. 173-181.

Hildebrand, A.R., Penfield, G.T., Kring, D.A., Pilkington, M., Camargo, Z.Z., Jacobsen, S.B., Boynton, W.V., Chicxulub crater: a possible Cretaceous/Tertiary boundary impact crater on the Yucatan peninsula, Mexico, Geology 19 (1991) 867-871.

Izett, G., Dalrymple, G.B., and Snee, L.W., l99l, 40Ar/39Ar age of K-T boundary tektites from Haiti: Science, v. 252, p. l59-1543.

Jiang, M.J., Gartner, S., l986. Calcareous nannofossil succession across the Cretaceous-Tertiary boundary in east-central Texas. Micropaleontology 32, 232-255.

Keller, G., 1989. Extended K/T boundary extinctions and delayed populational change in planktic Foraminiferal faunas from Brazos River Texas, Paleoceanography, 4(3): 287-332.

Keller, G., 2005. Impacts, volcanism and mass extinctions: random coincidence or cause & effect? Australian Journal of Earth Sciences, 52, 725-757.

Keller, G. and Adatte, T., 2005, Basinward transport of Chicxulub ejecta by tsunami-induced backflow, La Popa basin, NE Mexico: Comment. Geology Online p. e88. September 2005, DOI 10.1130/0091-7613(2005)31<e88:BTOCEB>2.0.CO;2

Keller, G. and Stinnesbeck, W., 2002. Slumping and a sandbar deposit at the Cretaceous-Tertiary boundary in the El Tecolote section (northeastern Mexico): An impact-induced sediment gravity flow – Comment. Geology, v. 30, p. 382-383.

Keller, G., Stinnesbeck, W., Adatte, T., Stüben, D., 2003a. Multiple impacts across the Cretaceous-Tertiary boundary: Earth-Science Reviews, v. 62(3-4), p. 327-363.

Keller, G., Stinnesbeck, W., Adatte, T., Holland, B., Stueben, D., Harting, M., de Leon, C., de la Cruz, J. 2003b. Spherule deposits in Cretaceous/Tertiary boundary sediments in Belize and Guatemala. Geol. Soc. London 160, 783-795.

Keller, G., G., Adatte, T., Stinnesbeck, W., Rebolledo-Vieyra, M., Urrutia Fucugauchi, J., Kramar, U., and Stueben, D., 2004. Chicxulub crater predates K-T mass extinction. Proceedings of the National Academy of Sciences of the United States of America, v. 101 (ll), p. 3753-3758.

Keller, G., Adatte, T., Harting, M., Berner, Z., Baum, G., Prauss, M., Tantawy, A.A. and Stueben, D., 2007. Chicxulub impact predates the K-T boundary: new evidence from Texas, Earth Planet. Sci. Lett., doi 10.1016/j.epsl.2006.12.026

Lawton, T.F., Shipley, K.W., Aschoff, J.L., Giles, K.A., Vega, F.J., 2005, Basinward transport of Chicxulub ejecta by tsunami-induced backflow, La Popa basin, northeastern Mexico, and its implication for distribution of impact-related deposits flanking the Gulf of Mexico: Geology, v. 33, p. 81-84.

Moore, D.M., Reynolds, R.C., l997. X-Ray diffraction and the identification and Analyses of Clay Minerals. Oxford University Press, Oxford, 1997, 378pp.

Pardo, A., Ortiz, N. and Keller, G., 1996. Latest Maastrichtian and K/T boundary foraminiferal turnover and environmental changes at Agost, Spain. In, MacLeod, N. and Keller, G., (eds.), The Cretaceous-Tertiary Mass Extinction: Biotic and Environmental Effects, Norton Press, New York, p. 157-191.

Rocchia, R., Robin, E., Froget, L., Gayraud, J., 1996, Stratigraphic distribution of extraterrestrial markers at the Cretaceous-Tertiary boundary in the Gulf of Mexico area: Implications for the temporal complexity of the event: *in* Ryder, G., Fastovsky, D., Gartner, S. eds, The Cretaceous-Tertiary boundary event and other catastrophes in Earth history: Geological Society of America, Boulder, Colorado, Special Paper 307, p. 279-286.

Schulte P. Stinnesbeck, W., Steuben, d., Kramar, U., Berner, Z., Keller, G., Adatte, T., 2003, Multiple slumped? Chicxulub ejecta deposits with iron-rich spherules and quenched carbonates from the K/T transition, La Sierrita, NE Mexico: Journal of International Earth Sciences, v. 92, p. 114-142.

Schulte, P., Speijer, R.P., Mai, H., Kontny, A., 2006, The Cretaceous-Paleogene (K-P) boundary at Brazos, Texas: Sequence stratigraphy, depositional events and the Chicxulub impact: Sedimentary Geology, v. 184(1-2), p. 77-109.

Soria, A.R., Llesa, C.L., Mata, M. P., Arz, J. A., Alegret, L., Arenillas, I., and Melendez, A., 2001, Slumping and a sandbar deposit at the Cretaceous-Tertiary boundary in the El Tecolote section (northeastern Mexico): an impact-induced sediment gravity flow: Geology, v. 29, p. 231-234.

Smit J., Montanari, A., Swinburne, N.H.M., Alvarez, W., Hildebrand, A., Margolis, S.V., Claeys, P., Lowerie, W., Asaro, F., l992, Tektite-bearing deep-water clastic unit at the Cretaceous-Tertiary boundary in northeastern Mexico: Geology, v. 20, p. 99-104.

Smit, J., Roep, T.B., Alvarez, W., Montanari, A., Claeys, P., Grajales-Nishimura, J.M. and Bermudez, J., l996, Coarse-grained clastic sandstone complex at the K/T boundary around the Gulf of Mexico: Deposition by tsunami waves induced by the Chicxulub impact: Geological Society of America, Special Paper 307, p. 151-182.

Smit, J., van der Gaast, S., and Lustenhouwer, W., 2004, Is the transition to post-impact rock complete? Some remarks based on XRF scanning electron microprobe and thin section analyses of the Yaxcopoil-1 core: Meteoritics & Planetary Science, v. 39, p. 1113-1126.

Stinnesbeck, W., Barbarin, J.M., Keller, G., Lopez-Oliva, J.G., Pivnik, D., Lyons, J., Officer, C., Adatte, T., Graup, G., Rocchia, R., and Robin, E., l993, Deposition of channel deposits near the Cretaceous-Tertiary boundary in northeastern Mexico: Catastrophic or “normal” sedimentary deposits? Geology, v. 21, p. 797-800.

Stüben, D., Kramar, U., Harting, M., Stinnesbeck, W., Keller, G., 2005, High-resolution geochemical record of Cretaceous-Tertiary boundary sections in Mexico: New constraints on the K/T and Chicxulub events: Geochemica et Cosmochimica Acta. v. 69(10), p. 2559-2579.

Yancey, T.E., 1996, Stratigraphy and depositional environments of the Cretaceous-Tertiary boundary complex and basal section, Brazos River, Texas: Gulf Coast Association of Geological Societies Transactions, v. 46, p. 433-442.