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THE CRETACEOUS-PALEOGENE BOUNDARY ON THE BRAZOS RIVER, TEXAS: NEW STRATIGRAPHIC SECTIONS AND REVISED INTERPRETATIONS

Malcolm B. Hart[1], Thomas E. Yancey[2], Andrew D. Leighton[1], Brent Miller[2], Chengjie Liu[3], Christopher W. Smart[1], and Richard J. Twitchett[1]

[1]*School of Geography, Earth & Environmental Sciences, Plymouth University, Drake Circus, Plymouth PL4 8AA, U.K.*

[2]*Department of Geology & Geophysics, Texas A&M University, MS 3115, College Station, Texas 77843–3115, U.S.A.*

[3]*ExxonMobil Exploration Company, 233 Benmar Dr., Houston, Texas 77060, U.S.A.*

ABSTRACT

The investigation of new sections of the Cretaceous-Paleogene (K/Pg) transition and basal Paleocene in the Brazos River area of Texas provides evidence that the Corsicana Formation sea floor mudstones were significantly eroded by the end-Cretaceous impact disturbances. Erosional relief on the 75–100 m deep sea floor is visible in Cottonmouth Creek and the new River Bank South section as a series of ridges and erosional troughs. Trough lows are filled, in places, with mud-matrix mass flow deposits containing large blocks of Maastrichtian mudstones and transported concretions. These are overlain with granular shelly layers containing spherules and hummocky cross-stratified storm sandstones. Some of the more positive areas of the sea floor remained exposed to shelf waters and were colonized with a thin oyster pavement before burial with mudstones, siltstones, and sandstones of the Kincaid Formation. A return to quiet water conditions during the basal Paleocene is recorded in a 3–6 m section of foraminifera-rich sandstones bounded above and below with zones of carbonate and pyrite concretions, best seen on the newly described River Bank South section. The distinctive yellow-weathering claystone exposed in Cottonmouth Creek and a new locality (River Bank North), north of the Route 413 bridge, are confirmed as volcanic ashes and dated as latest Maastrichtian, thereby removing the necessity for a pre-K/Pg boundary, and pre-extinction, impact event.

INTRODUCTION

The Brazos River and its tributaries in the Falls County area of Texas (Fig. 1) contain an important series of exposures of the Cretaceous-Paleogene (K/Pg) boundary interval that has been studied intensively for documentation of events associated with the Chicxulub impact disturbance. Following the recognition of the Chicxulub impact crater (Hildebrand et al., 1991) on the Yucatan Peninsula (Mexico), the Brazos area developed an international profile as an accessible area in which to study the K/Pg boundary event. An extensive literature of nearly 50 publications devoted entirely to the Brazos exposures, or including them as an important component of a larger study, has appeared since then. Features of great interest include the occurrence of an iridium anomaly (Ganapathy et al., 1981; Asaro et al., 1982; Rocchia et al., 1996; Gertsch et al., 2011), impact ejecta (Smit and Romein, 1985; Yancey, 1996; Smit et al., 1996; Schulte et al., 2006; Yancey and Guillemette, 2008), possible impact-generated tsunami deposits (Bourgeois et al., 1988; Yancey, 1996; Smit et al., 1996) and biotic recovery from impact disturbance (Gartner and Jiang, 1985; Jiang and Gartner, 1986; Hansen et al., 1987, 1993a, 1993b; Keller, 1989; Harries, 1999). Reports focused on, or presenting, significant stratigraphic data include Hansen et al. (1984, 1987), Jiang and Gartner (1986), MacLeod and Keller (1991),

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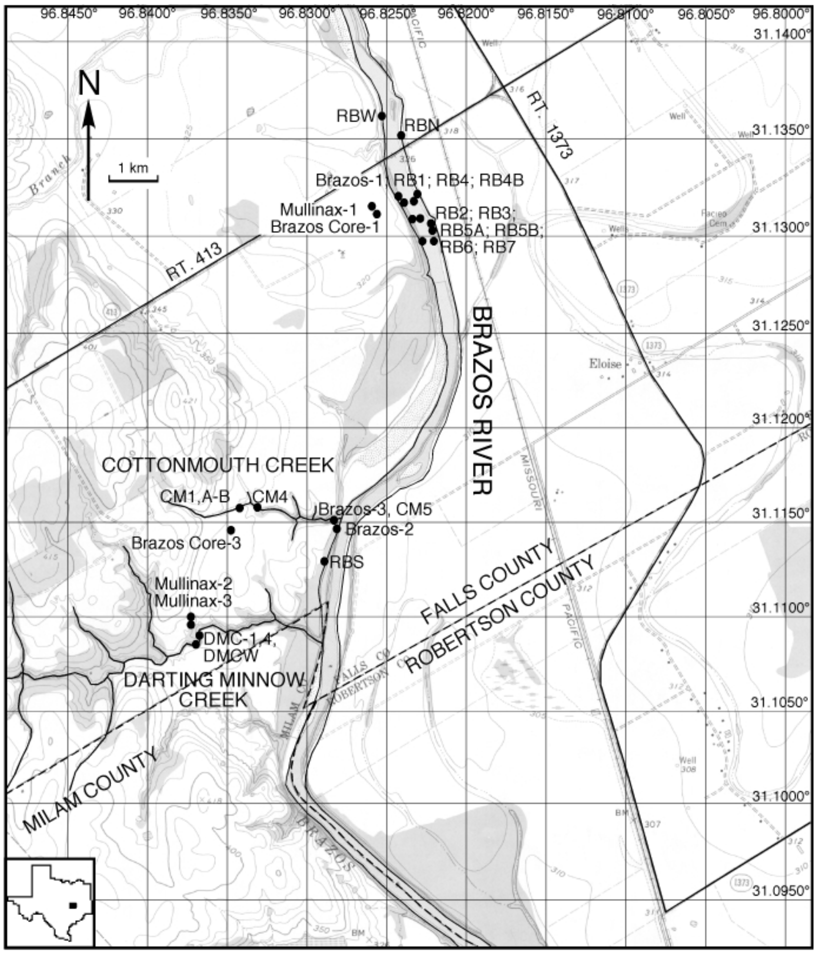

Figure 1. Location map of Brazos River area showing all outcrop locations and borehole sites used by the authors, including the Darting Minnow Creek (DMC), Cottonmouth Creek (CMC), River Bank North (RBN), River Bank West (RBW) and River Bank South (RBS) sections.

Yancey and Davidoff (1991), Yancey (1996), Gale (2006), Keller et al. (2004a, 2004b), Schulte et al. (2006), Adatte et al. (2011), and Keller and Adatte (2011). A larger group of publications on the record of biotic change and the geochemistry of the deposits exists, but it is too large to list here. However, major controversy has arisen over the criteria for the identification of the K/Pg boundary, whether it is reasonable to interpret the sedimentary deposits at the boundary as the results of tsunami wave disturbance and whether the light-colored claystone layers below the boundary represent impact ejecta deposits or volcanic ash layers. The result of this has been the development of polarized views on the interpretation of the K/Pg events in the Brazos succession. We present new data that clarify these controversies and bring some of the arguments to a well-documented resolution.

Despite the recent publication of 12 papers (see Keller and Adatte, 2011) on the Brazos outcrops and on cores drilled in 2005 to gather new data, the controversies have been perpetuated by publication of data insufficient to test the proposed evidence. For example, the dispute over the impact versus volcanic origin for the latest Cretaceous claystone layer is easily resolved with study of the fabric and mineralogy of contained phenocrysts that retain their original composition. Furthermore, interpretations of depositional environments and presence versus absence of exposure are resolvable with careful determination of depositional processes controlling sediment deposition through the section. This is accomplished with detailed foraminifera-based water depth determination available from four sections that have detailed tabulation of lithology and sedimentary structures on an outcrop scale. Concerning the controversy of the K/Pg boundary placement, deliberations by the International Commission on Stratigraphy have adopted a definitive set of criteria for placing the Era boundary (Molina et al., 2006). According to their definition, they recognize the near-coincidence of features present in the Global Stratigraphic Section and Point (GSSP) in Tunisia and other areas distal to the Chicxulub crater, but recognize that the abrupt facies changes, concentration of Ni-rich spinels, an iridium anomaly, stable isotope ($\delta^{18}O$ and $\delta^{13}C$) excursions and extinction horizons are stratigraphically separated in areas closer to the Chicxulub impact site. As all these features are related to the impact event, the best determination of the boundary is that "all the sediments generated by the meteorite impact belong to the Danian" Stage of the Paleocene Epoch (Molina et al., 2006, p. 270). In the Brazos River area, therefore, the eroded uppermost surface of the Corsicana Formation mudstones (top *Pummerita hantkeninoides* Zone should be used as the K/Pg boundary.

NEW SECTIONS IN THE BRAZOS AREA

Early studies on the Brazos succession focused on three riverbank sections (Brazos–1, Brazos–2, and Brazos–3) detailed by Hansen et al. (1984) and Jiang and Gartner (1986) and subsequent investigations included data from adjacent riverbed exposures and sections at the small waterfalls on Cottonmouth and Darting Minnow creeks (Hansen et al., 1987; Bourgeois et al., 1988; Yancey, 1996; Smit et al., 1996) (Fig. 1). The Brazos–1, Brazos–2 and Brazos–3 sections are now covered by modern flood deposits, which necessitated shifting the focus to studies of the riverbed and stream sections and to cores drilled adjacent to these sites (Fig. 1). Recently, areas of Brazos riverbank between Cottonmouth and Darting Minnow creeks that were previously obscured have been cleared of soil and now reveal laterally continuous exposures of the K/Pg boundary deposits and basal Paleocene strata over a >100 m-long cliff. These exposures reveal great lateral variability in the K/Pg boundary deposits, whereas basal Paleocene sediments contain a well-defined succession of layers that are traceable over a large area. The lithostratigraphic markers of the basal Paleocene succession described by Yancey (1996) are prominent and traceable along the Brazos River and along Cottonmouth and Darting Minnow creeks (Figs. 2 and 3). The newly described River Bank South (RBS) section was logged and sampled in October 2010 and October 2011 when river levels were low, exposing strata down to the uppermost Maastrichtian mudstones of the Corsicana Formation.

Concurrent work extended our study to areas north of the Rt. 413 bridge over the Brazos River, where nearly 15 m of Cretaceous strata are exposed in the riverbed and on the banks, extending upstream to the bend in the river above the bridge. The River Bank West (RBW) and River Bank North (RBN) sections are included in our investigations to establish a baseline for depositional trends before, and during, the time of the proposed K/Pg impact disturbance. The uppermost Maastrichtian strata are mostly forminifera-rich dark mudstones with a few sandy layers composed of quartzose sand, and two ash-fall layers.

New research on the K/Pg boundary includes investigation of both creek successions from the waterfalls to the confluence with the Brazos River and the discovery of a major new exposure south of the now covered Brazos–2 section. This ca.100 m-long river-bank section exposes the most complete succession of the boundary interval known in the area, and it has remained undescribed since it was exposed by a major flood event ~15 years ago. The lithostratigraphic markers (Lower Calcareous Concretion Horizon [LCH], Middle Sandstone Bed [MSB], Dirty Sandstone Bed [DSB], Upper Calcareous Concretion Horizon [UCH], Rusty Pyrite Concretion Horizon [RPH]) of the Paleocene succession, described by Yancey (1996), are present and traceable between the creeks and are prominent along the RBS riverbank exposure (Figs. 2 and 3). The RBS section also provides a reference for the interpretation of the lower reaches of Darting Minnow Creek, downstream of the waterfall, where the Cretaceous and Paleocene successions are variably exposed in the stream bed and adjacent banks.

Uppermost Cretaceous Mudstones

The mudstones and siltstones of the uppermost Maastrichtian (Corsicana Formation) exposed in the Brazos River, Darting Minnow Creek and Cottonmouth Creek are part of an open marine succession that was deposited in a mid-outer shelf environment below storm wave base (75–100 m water depth). There is a diverse assemblage of benthic foraminifera (Cushman, 1946; Hart et al., 2011) with a range of infaunal (mostly elongate, uniserial and biserial forms) and epifaunal (mostly biconvex and coiled forms) morphotypes: see Sliter and Baker (1972), Jones and Charnock (1985), Koutsoukos and Hart (1990), Jorissen et al. (1995), Reolid et al. (2008), and Hart et al. (2011, p. 185) for a

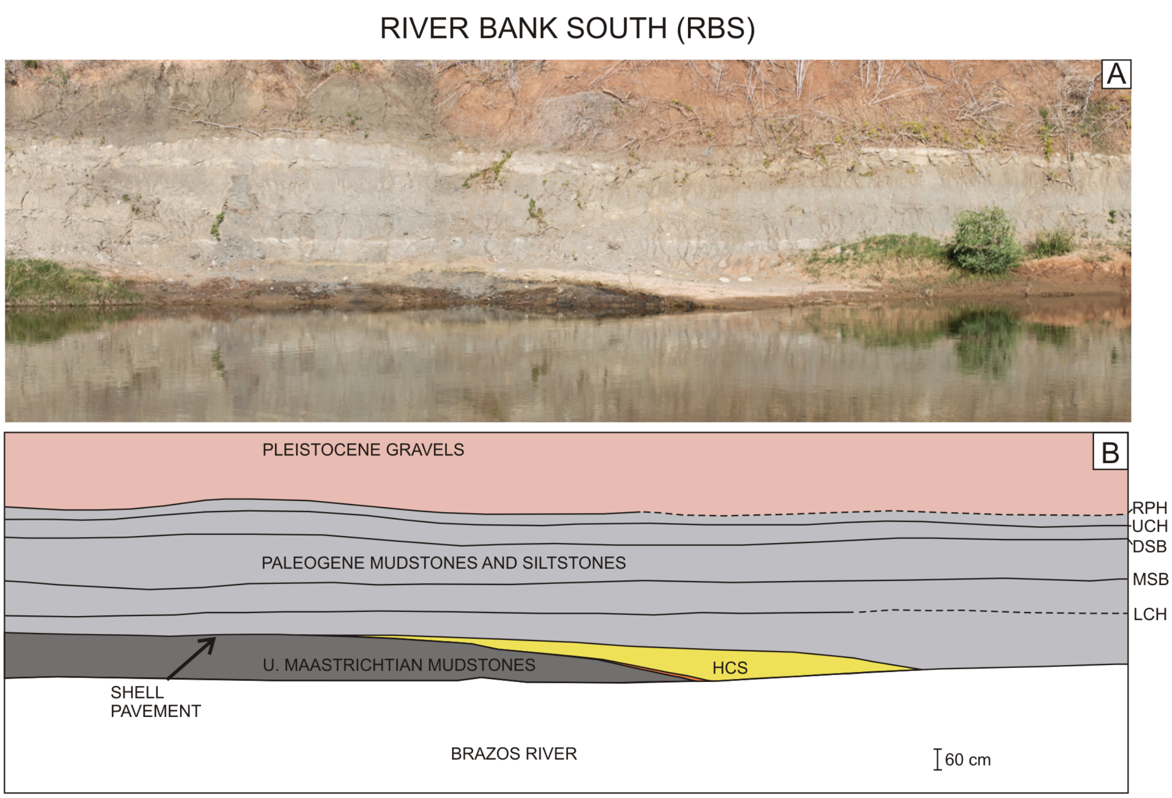

Figure 2. (A) Photograph of the RBS section taken from the east bank of the Brazos River. (B) Interpretive sketch of the RBS section identifying key stratigraphic horizons.

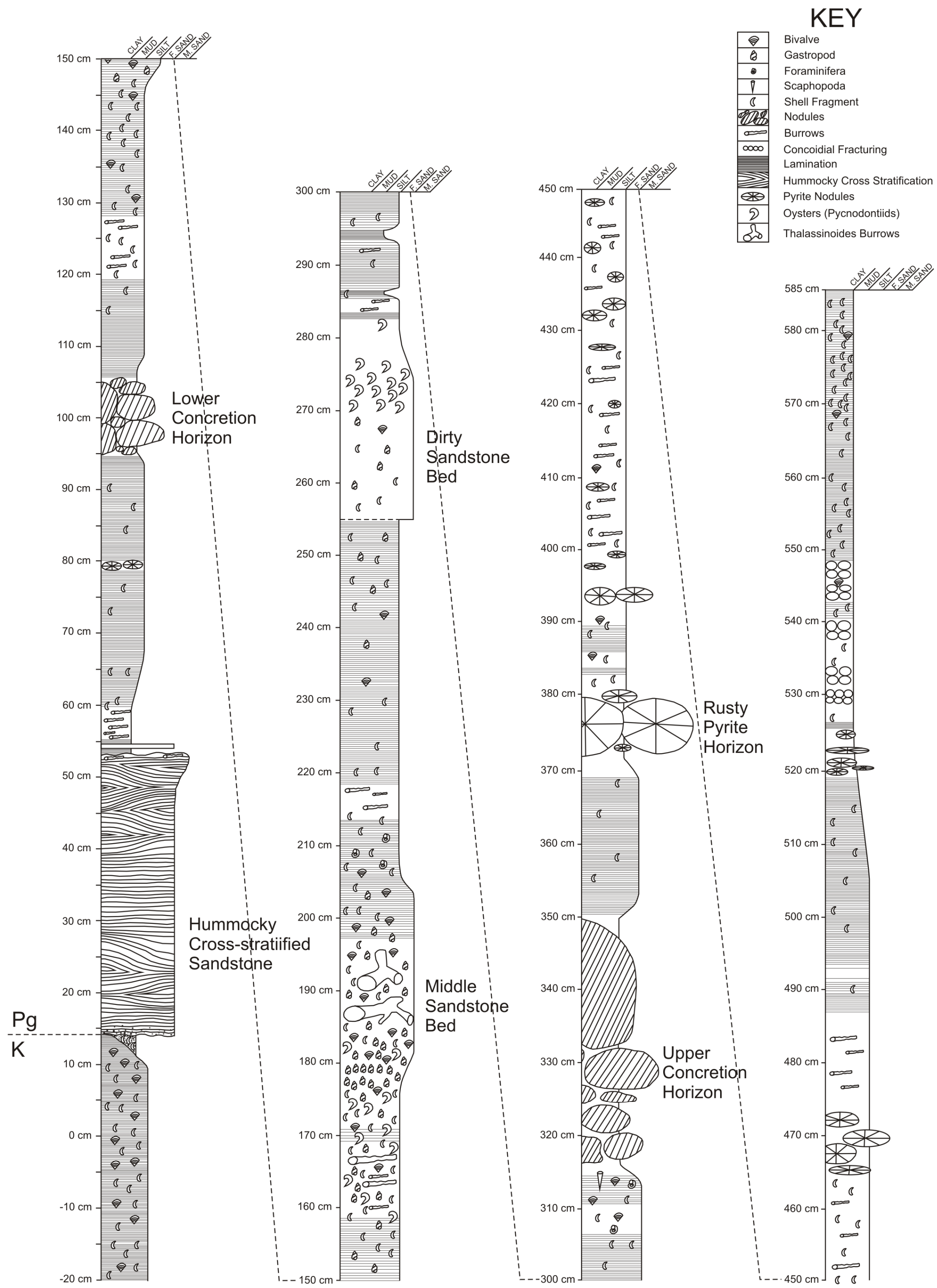

Figure 3. Sedimentary log of the RBS succession described in 2011.

fuller discussion. Planktic taxa include some deeper water morphotypes (e.g., *Globotruncana arca* (Plummer), *Globotruncana esnehensis* Nakkady, *Globotruncanella havanensis* (Voorwijk), and *Rugoglobigerina rugosa* (Plummer)) but not the deepest-living species (e.g., *Abathomphalus mayaroensis* (Bolli), and *Contusotruncana contusa* (Cushman)): see publications of Cushman (1946), Plummer (1931), Pessagno (1967), Smith and Pessagno (1973), Keller et al. (2009) and Abramovich et al. (2003, 2011). Preservation of all the foraminifera is generally good to very good and there is no evidence of sea floor dissolution or significant post-burial diagenesis. Ostracodes are also well-preserved, though rarely abundant (Maddocks, 1985), except for a low diversity flood of ostracode taxa near the top of the Middle Sandstone Bed (MSB). This level of abundance is associated with the increased presence of large lenticulinids and elongate nodosariid foraminifera. The calcareous nannofossils (Jiang and Gartner, 1986; Tantawy, 2011; Matt Hampton, 2012, pers. comm.) and dinoflagellate cysts (Prauss, 2009) present in these mudstones also record normal salinities in an open shelf environment. Within the dark mudstones, layers with abundant shell material (rarely broken) are present, with most bivalves being rather thin-shelled although still displaying aragonite preservation. Throughout the uppermost Maastrichtian, aragonitic foraminifera (e.g., *Epistomina* spp.) are also present (Hart et al., 2011) but rare.

In all sections, the uppermost Maastrichtian mudstones are characterised by the presence of small, rare *Pummerita hantkeninoides* Brönnimann, which is the zonal indicator for the uppermost Cretaceous. These forms are, however, much smaller, have reduced spines, and are less well-ornamented than those from deeper-water environments (Robaszynski et al., 1989; MacLeod et al., 2007).

Basal Paleocene Deposits

Strata above the event deposits contain several lithostratigraphic and chemostratigraphic markers that record the return to normal open marine conditions with a typical assemblage of foraminifera, ostracods, bivalves and gastropods. These mudstones, siltstones and sandstones are best developed in the southern area of outcrop spanning Cottonmouth and Darting Minnow creeks and the banks of the Brazos River (RBS section; see Figures 2 and 3) where they occur within a 5–6 m section overlain by a thin interval of claystones.

In the southern outcrop area, the event deposit sands are locally absent, as previously reported for sections Brazos–2 (absent) and Brazos–3 (very thin) by Hansen et al. (1984). This relationship is exceptionally well illustrated in the RBS section (Fig. 3). Hummocky cross-stratified sands of the event horizon, underlain by a thin lag of spherule-bearing sand, rests on the dark grey mudstones of the Maastrichtian that form the base of the section near river level. The outstanding aspect of this exposure is that the event deposit sand layers are inclined and pinch out in a downriver direction by thinning from the base of the event deposit (Fig. 4E). Whereas the Paleocene units are essentially flat-lying and continuous, the event deposit is inclined as a result of being draped over a 'positive' feature at the top of the Maastrichtian mudstones. This thickness variation in the lowermost Paleocene sediments is confined to the mudstones below the LCH horizon (Fig. 4E–4G). At the top of the positive feature, the Maastrichtian/Paleocene interface is marked by a thin bivalve shell pavement of juvenile oysters (Fig. 4B). At this point in the section, mid-outer shelf Maastrichtian mudstones are directly overlain by mid-outer shelf Paleocene mudstones with only a shell pavement at the boundary. This feature has never been reported previously in the Brazos River area.

The Paleocene mudstones, siltstones and sandstones in the RBS, RB4, RB5, and Cottonmouth Creek sections contain abundant well-preserved foraminifera. The planktic assemblage is dominated by re-worked Cretaceous taxa that provide no environmental information other than the need for a source. Upsection Paleocene taxa gradually appear though the majority are small in size (<125μm) and limited to globular (e.g., *Eoglobigerina eobulloides* [Morozova], and *Globoconusa daubjergensis* [Brönnimann]) or biserial (e.g., *Woodringina claytonensis* Loeblich and Tappan) morphotypes. These provide little environmental information as they are simply re-colonizing the niches vacated by end-Cretaceous extinctions. Use of the planktic:benthic ratio for determination of water depth is also inappropriate in a post-extinction setting where the numbers of planktic foraminifera are a response to recovery rather than bathymetry. The benthic foraminifera are, however, exceptionally diverse and well-preserved. There is a range of morphotypes present, including both epifaunal and infaunal taxa. Of particular significance are some very large forms (first noted by Plummer, 1926) that include epifaunal lenticulinids (<1 cm diameter) and infaunal, uniserial nodosariids (<1 cm long). The composition of the assemblage, and the presence of the delicate, long nodosariids (e.g., *Nodosaria affinis* Reuss, and *Vaginulina cretacea* Plummer) are all indicative of deposition below normal storm wave base in a mid–outer shelf environment (75–100 m water depth). All the micropaleontological data are being prepared for publication in a subject-specific journal.

The lithostratigraphic beds identified by Yancey (1996) along Cottonmouth Creek are increasingly well developed to the south of the area shown in Figure 1. The most prominent unit is a coarse-grained, condensed sandstone containing calcitic shells (mostly small pycnodonteinid bivalves) as well as molds of aragonitic shells and phosphatic steinkerns set in a matrix of abundant foraminifera and clay mud and a small amount of quartzose sand (<1%). The presence of a concentration of steinkerns and small phosphatic concretions in sediments with common *Thalassinoides* burrows indicates accumulation as a condensed deposit in a transgressive systems tract, as suggested by Hansen et al. (1993b). This unit is semi-lithified at the top and bottom and less lithified in the middle, resulting in locally occurring erosional profiles of upper and lower ledges. Calcareous horizons containing common carbonate concretions embedded in claystones occur a short distance above and below the sands of the condensed section. Along the Brazos River bank and Darting Minnow Creek these horizons locally produce ledges of large concretions, commonly showing abundant *Thalassinoides* burrows. The finer grained sediments encasing the carbonate concretions also contain many small pyrite concretions, a relationship best seen in strata beside section CM4 and along the lower reaches of Darting Minnow Creek. Overlying the interval with the lower calcareous horizon (LCH) and condensed sands (MSB) and upper calcareous horizon (UCH) is a horizon with large pyrite concretions (RPH). These are mostly weathered to iron oxides and the horizon is best seen in the lower reaches of Cottonmouth Creek, near the river.

Above the event bed and shell pavement in the RBS section, the Paleocene succession is beautifully exposed in a 5–6 m section (Fig. 4D). The lower calcareous concretion horizon (LCH) forms a distinct marker that is unaffected by the undulating topography of the uppermost Maastrichtian mudstones and boundary complex and serves as an ideal datum within the section. The base of the condensed sand unit (MSB of Yancey, 1996) is the most prominent unit, separated from LCH by 0.4 m of grey mudstones. The condensed interval consists of a 30 cm-thick lower zone containing calcitic shells, and phosphatic steinkerns, and *Thalassinoides* burrows. This is overlain by 45 cm of finer-grained sediment with commonly abundant shell material, small burrows and large-sized benthic foraminifera that are visible in the field: a feature also noted by Plummer (1926). The top of the condensed section consists of 25 cm of massive, well-consolidated fine grained foraminifera-rich sands with phosphatic steinkerns and small pycnodonteinid bivalves.

Approximately 30 cm of laminated, silty sediment containing sporadic shell material occurs above the condensed section and is overlain by a thick calcareous concretion horizon with large, cemented *Thalassinoides* burrows. This is a prominent marker that is part of the 'Upper Calcareous Horizon' (UCH) of Yancey (1996). A horizon of oxidised pyrite nodules (RPH) occurs 20 cm above the UCH horizon.

Above the concretion level is ~1 m of dark gray, massive siltstones with rare shell fragments and small burrows. Also within this bed are numerous weathered pyrite concretions,

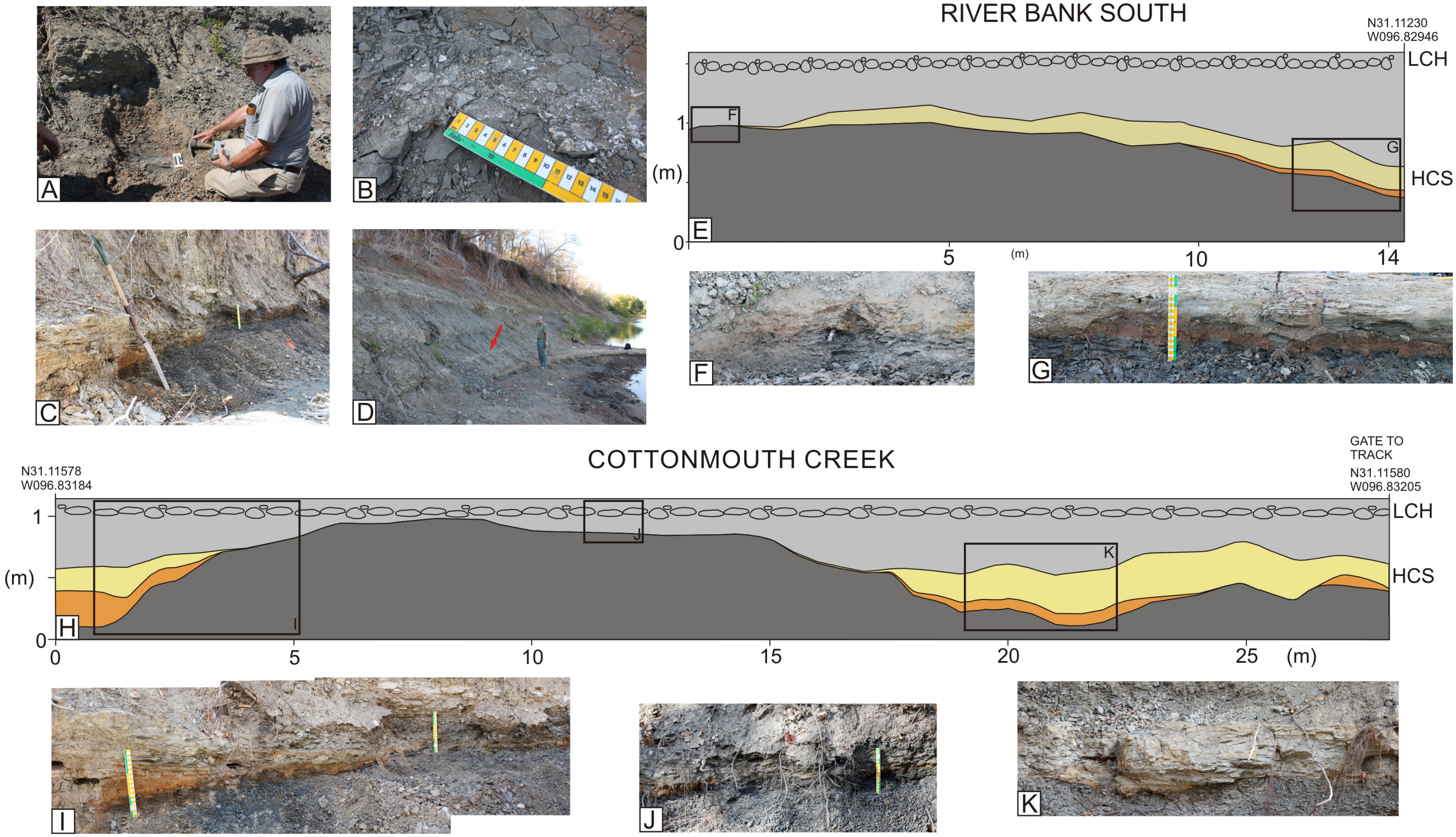

Figure 4. Thinning of the event bed and the Paleocene mudstones below the LCH horizon in the RBS and Cottonmouth Creek sections. (A) TEY indicating the level of the oyster pavement at the Maastrichtian/Paleocene interface. (B) Close-up of the oyster pavement (colored division on the ruler in cm). (C) Event bed between the Maastrichtian and Paleocene mudstones at the 10 m mark in profile E. The spherule bed is orange-colored, just below the blade of the spade. (D) MBH standing on the event bed with the LCH nodule bed marked by an arrow. (E) Measured profile along the section shown in D. The Maastrichtian mudstones are indicated by a dark gray color and the Paleocene mudstones and siltstones indicated in a paler gray color. (F) Photograph of the boundary between the Maastrichtian and Paleocene strata which is indicated by a chisel. (G) Photograph of the event bed showing the spherule rich horizon (orange color) and the HCS (pale colored) sandstones. (H) Measured profile along part of Cottonmouth Creek between the CM4 and CM1 sections with stratigraphic units in the same colors as profile E. (I–K) Photographic montages of the profile shown in H. The ruler is 30 cm long in all cases.

probably the remnants of larger burrows that have been infilled with pyrite and fine-grained sediment. The remaining ~90 cm to the top of the RBS section consists of finely laminated black claystones that contain abundant shell fragments, rare small bivalves and some pyrite concretions. The Paleocene succession is overlain by pink-colored terrestrial sediments of Pleistocene age (Fig. 2).

Erosion and Sea Floor Topography at the Base of the 'Event Deposit'

The exposure of the K/Pg contact in the RBS section shows an erosional relief of 0.5–1.0 m in that area (Fig. 4E). The seafloor feature was of sufficient relief to avoid being covered with the spherule-rich bed and the HCS sands that are recorded over most of the area. The event deposit sandstones are an upward-fining set of deposits that thin by progressive loss from the base upward, indicating that the lower, coarser sands were never deposited on the high and that thinning is not related to later removal by erosion (see Gale, 2006, his Figure 5). Erosion occurring prior to the HCS sand deposition removed all of the unconsolidated sea floor sediments and exposed cohesive muds resistant to wave action. This removal is related to erosion immediately prior to a time of mass-flow transport on the sea floor. Similar views of sea floor topography have been seen in sections DMC1, Brazos–1 and RB4, but continuing modern erosion and deposition of fluvial deposits has removed or covered most of these locales.

Another example of erosional relief on Cretaceous mudstones can be observed along Cottonmouth Creek between sections CM1 and CM4 (Fig. 1), where the event beds disappear from the succession against an erosional high of Maastrichtian mudstone (Figs. 4H, 4I, 4J, and 4K). At this location the LCH concretion horizon occurs directly above the K/Pg contact. Because of the confines of the creek we were unable to excavate this boundary and determine whether the shell pavement, described in the RBS section, is present. The Mullinax–2 and Mullinax–3 boreholes were placed near the Darting Minnow Creek exposure of the K/Pg boundary with the anticipation that the event bed would be recovered. The Mullinax–3 core (Adatte et al., 2011, their Figures 17, 29, and 31) recorded a hiatus between Maastrichtian mudstones and Paleocene siltstones, as we have described in the RBS section and in Cottonmouth Creek but that, at that time (2005), had not been described in the field. The Mullinax–3 site was also affected by Pleistocene weathering (including rootlets and neptunian dykes) that were, unfortunately, interpreted as a K/Pg paleosol (Adatte et al., 2011, their Figure 17).

A similar example of erosional relief on Cretaceous seafloor mudstones associated with the Chicxulub impact is presented in Olsson and Liu (1993) and Olsson et al. (1996) at the Millers Ferry excavation site in Alabama. Erosional low areas at the site contain a bed of sand matrix containing large blocks of chalk derived from the underlying chalk beds (Prairie Bluff Formation). The sandstones pinch out against the underlying chalk highs, revealing local erosional relief of at least 1 m (Olsson et al., 1996, p. 272). The eroded surface contains scour features oriented in an offshore direction (N–S), comparable to the offshore-directed (NW–SE) erosional features that are reported from the small number of Brazos River sites in Texas where these features have been observed.

INTERPRETATION AND DISCUSSION

The newly described RBS section has allowed a reinterpretation of both the Darting Minnow Creek and Cottonmouth Creek successions. This new look at the K/Pg boundary debate was also assisted by access to the three Mullinax cores. There are a number of questions that arise as a result of our investigations. These include the presence of volcanic-derived claystones in the succession, and the effects of impact disturbance at the K/Pg boundary.

Light-Colored Volcanic Claystone Layers

A thin (0.2–5.0 cm thick) layer (Figs. 5A and 5B) of light-colored claystone embedded within the dark gray Cretaceous mudstones exposed below the waterfall in Cottonmouth Creek is the subject of controversy as Keller et al. (2007, 2008) and Keller (2008) proposed that the layer records the Chicxulub impact (the "original Chicxulub impact spherule layer" [Keller et al. 2008, p. 164]) and that the overlying coarse-grained, spherule-bearing deposits are the products of later reworking of impact ejecta. Schulte et al. (2008, 2010) disputed this interpretation, noting that other workers had identified the layer as a bentonite and that the features mentioned in support of impact ejecta origin are inconclusive. Despite the strong rebuttal by Schulte et al. (2008), Adatte et al. (2011) invoked the same interpretation without pre-

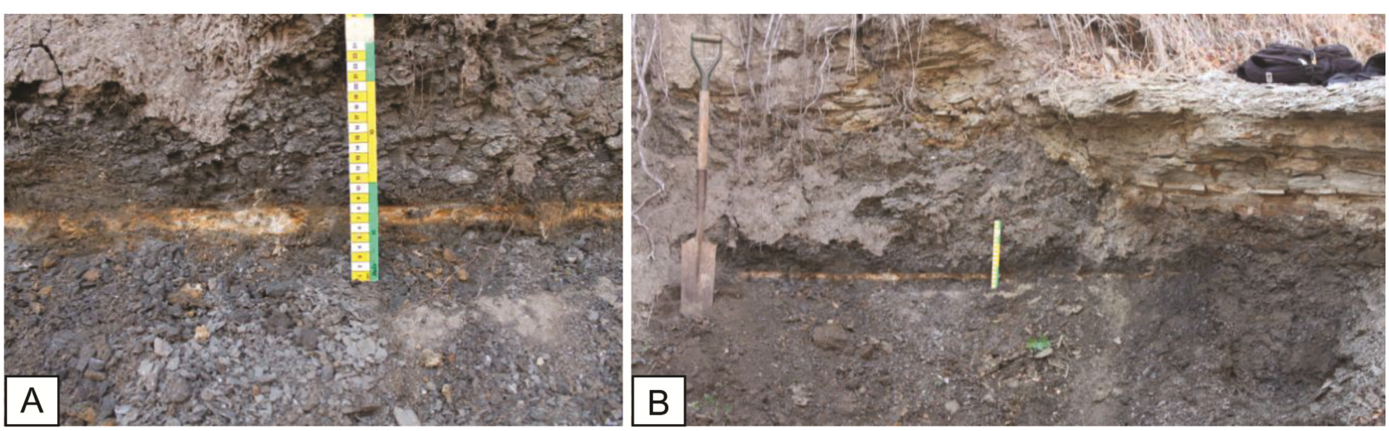

Figure 5. The volcanic-derived clay layer in Cottonmouth Creek, just below the waterfall. (A) Close-up view of the of the volcanic clay bed. Ruler is 30 cm long. (B) General view of the volcanic clay bed with the event bed to the right, though slightly displaced by a small fault.

senting new supporting evidence. More detailed study of the Cottonmouth Creek claystone layer and the discovery of a similar, well-defined claystone layer in the RBN section in 2010 provide the opportunity to test the concept of impact spherule composition versus that of volcanic ash.

The Cottonmouth Creek claystone layer, denoted as the 'yellow clay' in many discussions (see Keller et al. [2004a, 2004b], and Adatte et al. [2011] and references therein), is gray-white in fresh exposure or mottled where bioturbated, with many small burrows filled with dark mud from the surrounding sediment. The yellow coloration is an iron oxide stain on weathered surfaces that also contain abundant gypsum crystals. The claystone layer is laterally persistent over a 100 m outcrop in Cottonmouth Creek, but it has not been recorded elsewhere in the outcrop or in cores. The claystone is smectite in composition and contains common, angular, white crystals (Figs. 6A and 6B) with high potassium content set in a light gray-white ground mass. These crystals are phenocysts of partly altered potassium feldspar 30–50 µm in size (Fig. 6C). Other phenocrysts include rare quartz crystals of the same size, brown and white mica flakes <250 µm diameter and euhedral zircon crystals (Fig. 6D). Zircons and biotite recovered from the claystone show no sign of shock deformation and SEM images of the biotites show tensional fracture features with no evidence of shock-induced kinks (cf. Schneider, 1972) expected from compression.

Blocks of the claystone layer were examined in the microprobe laboratory of the Department of Geology & Geophysics at Texas A&M University to obtain additional data. EDS spectral maps show that elevated potassium occurs in conjunction with white, altered potassium feldspar crystals in the claystone, not in the general groundmass of smectite clay. Moreover the claystone layer contains euhedral feldspar phenocrysts and zircon crystals indicative of a magmatic origin. No ejecta spherules have been seen in the clean, well-prepared samples. In overall appearance, phenocryst content and lack of identifiable ejecta particles, this clay layer resembles many examples of airfall ash deposits. Preliminary U-Pb data from nine single-grain zircon analyses, all of which are indicative of a latest Cretaceous age, include three that are within error of 65.95 ± 0.04 Ma (Kuiper et al., 2008, including online supplement). This confirmation of a volcanic-derived claystone in the uppermost Maastrichtian succession removes the interpretation of an earlier deposition of impact ejecta in the Brazos sections.

A second volcanic ash bed has been located in the uppermost Maastrichtian strata in section RBN, at a level ~10 m below the event deposit. This, potentially older claystone layer, has sharp upper and lower boundaries and is a consistent 3 mm thickness across the area of exposure. Regular high water flow in the river has kept the riverbank cleared of soil cover and the surrounding mudstones are unweathered. Excavation ~30 cm into the riverbank exposed fresh samples that yield a zircon phenocryst assemblage similar to that in the Cottonmouth Creek clay layer, revealing that the deposit contains a dominance of euhedral magmatic zircon phenocrysts. The similarity of the two layers and presence of magmatic phenocrysts is convincing evidence of an origin as a bentonite.

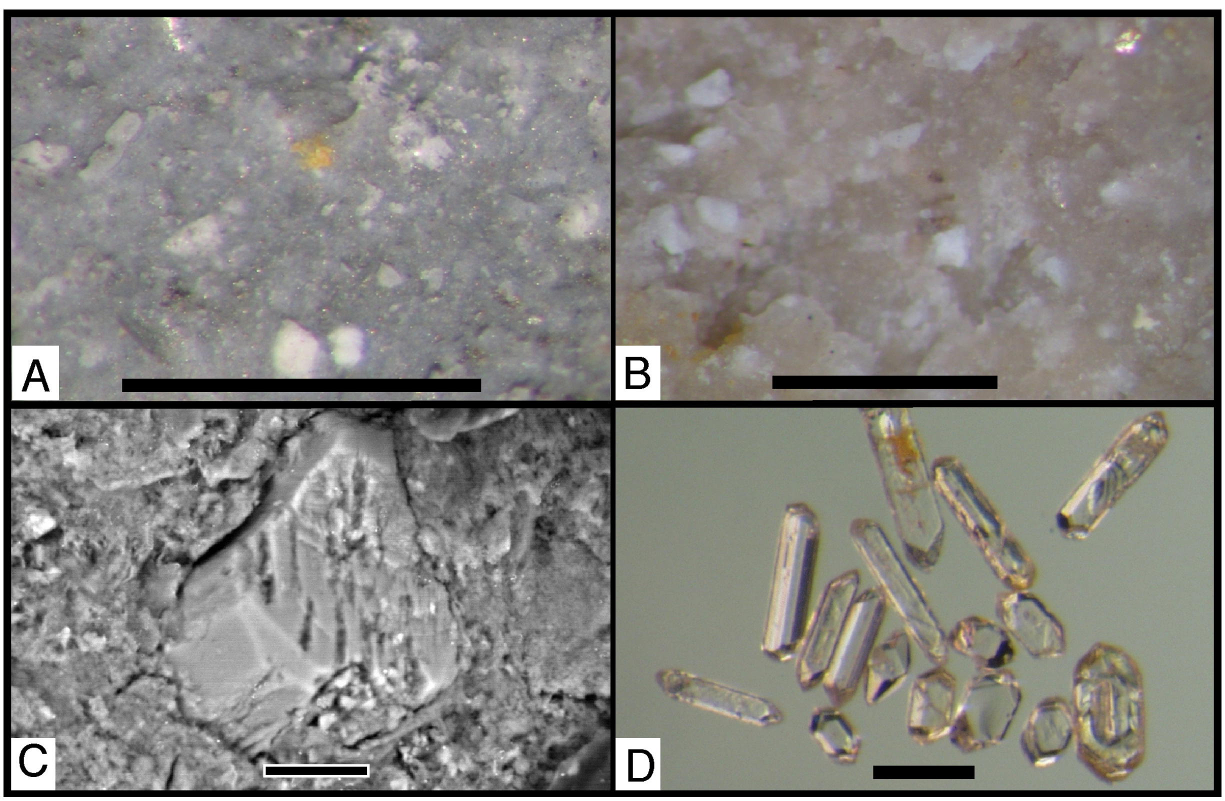

Figure 6. Mineralogy of the volcanic-derived clay layer. (A) Photomicrograph of volcanic ash (section CM1, Cottonmouth Creek), showing gray smectite groundmass with angular white inclusions of potassium feldspar, altered feldspar, and biotite. Quartz and zircon are present but not visible. Scale bar is 1 mm long. (B) Photomicrograph of volcanic ash (section RBN, Brazos River east bank), showing gray smectite groundmass with angular white inclusions of potassium feldspar and biotite. Scale bar is 1 mm long. (C) Backscattered electron image of subhedral potassium feldspar phenocryst with exsolution lamellae in volcanic ash (section CM1, Cottonmouth Creek). Scale bar is 10 µm long. (D) Photomicrograph of euhedral zircon phenocrysts (section CM1, Cottonmouth Creek). Scale bar is 100 µm long (photograph courtesy of Brent Miller).

The yellow-weathering bentonites seen in the outcrop have not been recorded in any of the Mullinax cores (Adatte et al., 2011) and were not visible in the cores when they were first drilled and photographed. However, close inspection of the cores in 2011, has shown the presence of a small number of possible, thin (0.5–3.0 cm), bentonites, all of which are presently under investigation.

Although there are no previous records known to us of bentonites in the Maastrichtian-Paleocene succession of central Texas, such horizons are well known in many areas of the Western Interior of the USA (Ryer et al., 1980; Elder, 1988; Kowallis et al., 1995; Fassett, 2000, 2009; Fassett et al., 2010). In a recent presentation, Sauvage et al. (2010) described the successions in the Denver Basin, including the presence of a prominent bentonite horizon (dated at 66.08 ± 0.02 Ma) just below the $\delta^{13}C$ isotope excursion at the K/Pg boundary. Given the compelling evidence for the volcanic origin of the yellow-weathering claystones in the Cottonmouth Creek and the RBN sections, the input of volcanic ash must be regarded as a normal part of the Maastrichtian to Paleocene sedimentation history of the area.

The Effects of Impact Disturbance

If the yellow claystone layer of Keller et al. (2007) is a bentonite, then the overlying event beds almost certainly rest on a surface coeval with the proposed Chicxulub impact and tsunami. The relationships described in the RBS and Cottonmouth Creek sections (Fig. 4E and 4H) indicate the presence of an erosional surface with <1 m amplitude that is overlain, in places, by a mass-flow deposit (Yancey, 1996, his Figures 5, 6, and 16). Following the original tsunami interpretation (Bourgeois et al., 1988) many workers have followed this model, although Gale (2006), Shanmugan (2006), and Dawson and Stewart (2007) have discussed the tempestite (= storms) versus tsunamite problem. Day and Maslin (2005) have also claimed that the shallow-water site at Chicxulub may not have generated a full-sized tsunami. Shanmugan (2006, his Figure 1) has suggested that, crossing the shelf of the Gulf Coastal area, the K/Pg tsunami would have decreased in velocity (from an initial ~180 m/sec), causing the wave height to rise. There would be no deposition at this stage, as this could only occur during the back-flow stage (Shanmugan, 2011).

Evidence from the 2004 Indian Ocean tsunami suggests that the tsunami waves (and reflected waves) would be over in a few (2–5) hours (G. Shapiro, 2012, pers. comm.), forming only the erosion surface and, potentially, some debris flows. Above the un-graded spherule-rich bed, which also contains abundant shell debris, bone fragments, and ichthyoliths, the sandstones and siltstones of the event bed display evidence (bioturbation, infaunal colonization) of deposition over a considerable period of time. The event bed cannot, therefore, have been deposited in the few hours represented by the tsunami and point to a series of extended storm events. This also appears to be the case in the Gulf Coast area of Mexico (Smit et al., 1996; Ekdale and Stinnesbeck, 1998).

The erosional boundary at the base of the event deposits is not in doubt: see Yancey (1996), Gale (2006), Bralower et al. (2010) and Hart et al. (2011). Gale suggests erosion in the form of discrete channels, but this is questioned in an area of open shelf that, despite the latest Maastrichtian shallowing recorded in other areas (Hart et al., 2005), may still have been 75–100 m deep. The interpretation of the RBS section, with its K/Pg boundary shell pavement, also casts doubt on the recent suggestion of a period of subaerial exposure (Adatte et al., 2011) at that time. The bioturbation (e.g., Savdra, 1993; Gale, 2000), colonization by bivalves, scaphopods, etc., and nature of the mudstone inter-beds, storm-induced hummocky cross-stratification capped by sets of ripple marks (some of which indicate west to east sediment movement) all point to a series of storm events interspersed by quiescence (Fig. 7). This sequence of events would have ensured that sediments (and their enclosed microfossils) were continually being re-suspended and re-deposited during the earliest Paleocene. When these events ended, sedimentation of the siltstones and mudstones of the Paleocene resumed with no further evidence of significant reworking of the sediment succession. The sandstones, lines of scattered nodules and cemented *Thalassinoides* burrow systems are all indicative of an in-situ succession with a diagnostic assemblage of foraminifera (including some large-sized individuals), ostracodes, bivalves and gastropods.

We can conclude, therefore, that our re-interpretation of the existing sections and the new data provided by the RBS succession allow us to demonstrate that the latest Maastrichtian shelf

Figure 7. The event bed at the waterfall in Darting Minnow Creek. The irregular contact between the spherule-rich base of the event bed and the underlying Maastrichtian mudstones can be seen low in the photograph (indicated by red dashed line). Several HCS sandstone units are present above and below the ruler (30 cm long), and a relatively thick (~30 cm) siltstone bed that contains bivalves, gastropods, scaphopods and large uniserial foraminifera is located immediately behind the ruler. The HCS sands are slightly inclined in an up-creek direction and capped by a ripple-marked surface.

sediments of the Corsicana Formation suffered disturbance close to the time of the Chicxulub impact event. The mixed assemblage of foraminifera above the erosion surface and the lack of a large iridium peak all point to a period of re-working and re-sedimentation. The majority of the event deposit consists of mixed seafloor sediment, impact ejecta and shallow water sands reworked and winnowed by deep-reaching waves. This is dissimilar to the graded air-fall, spherule-rich, sediments seen in places like the Demerara Rise (Erbacher et al., 2004; MacLeod et al., 2007; Schulte et al., 2009).

CONCLUSIONS

Fieldwork in the Brazos River area, Falls County, Texas, has identified a number of new sections that provide critical new information on the K/Pg boundary. With the identification of two bentonites in the uppermost Maastrichtian mudstones of the Brazos area, including the claystone previously identified as evidence of an impact event, the K/Pg boundary successions in the Brazos area can be re-interpreted as a series of sedimentary events caused by both a short-lived tsunami event and a series of subsequent storm events. The boundary complex is overlain by a Paleocene succession that contains an abundant and diverse assemblage of benthic foraminifera and a gradually increasing assemblage of post-extinction planktic foraminifera. The micropaleontological data (planktic and benthic foraminifera, ostracodes, calcareous nannofossils, and dinocysts) support all our paleoenvironmental interpretations and also provide a robust biostratigraphy of the boundary interval. These data strongly suggest that the microfossil extinction events are synchronous with a single impact event.

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