CRETACEOUS–TERTIARY MASS EXTINCTION IN MARGINAL AND OPEN MARINE ENVIRONMENTS: TEXAS, U.S.A., AND TUNISIA

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Abstract: The Cretaceous–Tertiary boundary (KTB) sequences along the Brazos River, Texas, U.S.A., have been controversial for over two decades. At issue is whether the KTB and the mass extinction should be placed at the base of a sandstone complex based on the presence of Chicxulub impact spherules or at the mass extinction. This issue goes to the very core of the KTB controversy—did the Chicxulub impact cause the KTB mass extinction? Faunal, stable isotope, platinum group elements (PGEs), and lithological analyses of six Brazos cores and outcrop sections, and comparison of these data with the Elles, Tunisia, parastratotype shed light on these issues. The KTB is well marked by the mass extinction of planktic foraminifera, the first appearance of Danian species, and the $\delta^{13}C$ negative shift, which occurs up to 1 m above the sandstone complex that contains two to three impact spherule layers at its base. There is no Ir anomaly at the KTB and mass extinction, but minor Ir enrichments are present in condensed intervals within and slightly above the sandstone complex. Clasts at the base of the sandstone complex contain impact spherules that reveal earlier deposition, lithification, erosion, and redeposition. The Chicxulub impact thus predates not only the KTB, but also the sandstone complex. A yellow clay layer consisting of altered impact glass 45–60 cm below the sandstone complex (zone CF1) may represent the original Chicxulub impact ejecta fallout.

The mass extinction pattern in the Brazos sections appears gradual or progressive compared with patterns documented from open-ocean environments. This is largely the result of high sediment accumulation rates in inner-neritic depositional settings coupled with the sea-level fall that culminated with deposition of the sandstone complex. Comparison of various extinction parameters, such as overall species richness, species abundances, life strategies, and separation into opportunists vs. specialists reveals that the shallow Brazos environment excluded the specialized larger and deeper-dwelling species (~ 40%) that suffered the most abrupt mass extinction at the KTB. The Brazos extinction pattern thus reflects the mass extinction in the most hardy and environmentally most tolerant assemblages, which include several KTB survivors. Similar patterns are observed in shallow-water environments of southern Tunisia, Egypt, Denmark, and Argentina. These data show that the Chicxulub impact predates the KTB and caused no species extinctions.

Key words: KTB Mass Extinction, Chicxulub Impact, Shallow Environment, high stress, Texas, Tunisia. Cretaceous–Tertiary, Evolution, $\delta^{13}C$ shift, Ir anomaly, Sea level, Sandstone complex, Depositional environment.

INTRODUCTION

The Cretaceous–Tertiary boundary (KTB) mass extinction is generally portrayed as a sudden, even instantaneous event resulting from a large extraterrestrial impact. But among all fossil groups only planktic foraminifera suffered a dramatic and relatively sudden mass extinction directly at the KT boundary (Keller et al., 1995; Keller et al., 2002). This microfossil group became the primary paleontological evidence supporting an extraterrestrial impact as the cause of the KTB mass extinction (Alvarez et al., 1980). Over the past three decades their demise has become the signature feature for the mass extinction.

In the impact exuberance of the 1980s all planktic foraminifera were claimed as wiped out instantaneously at the KTB as a result of a large impact, except for one species, *Guembelitria cretacea*, which was assumed to have given rise to the subsequent radiation of Danian species (Smit, 1982). Any data that did not fit this model were generally interpreted as compromised by reworking, bioturbation, preservation, or insufficient search for specimens, while ignoring the fact that these same imperfections affect sediments above and below the KTB (MacLeod, 1996a, 1996b). The Signor-Lipps effect (e.g., a bias towards recording shortened species ranges due to sporadic or rare occurrences; Signor and Lipps, 1982) became the misused and perverted catch-all phrase by which data that did not fit the idealized mass-extinction model was attributed to the difference between "apparent" and "real" biodiversity based on the assumption that "real" biodiversity would show all species ranging up to, but not beyond, the KTB.

The KTB stratotype section at El Kef provided the first test of this model extinction pattern. Instead of the instantaneous extinction of all but one species (Smit, 1982), it revealed the selective nature of extinctions with all larger, complex, ornamented, and specialized tropical and subtropical species (two-thirds of all species) disappearing at or near the KTB, and the short-term survival of small species more tolerant of environmental changes (one-third of the species; Keller, 1988; MacLeod, 1996b). Although controversial at the time (even leading to a blind test, e.g., MacLeod, 1996b; Canudo, 1997; Keller, 1997; Masters, 1997; Olsson, 1997), this pattern of species extinctions and survival is now generally accepted and documented in low to middle latitudes globally (e.g., MacLeod, 1996b; Luciani, 1997, 2002; Keller et al., 2002; Keller, 2004; Apellaniz et al., 1997; Obaidalla, 2005; Paul, 2005; Arenillas et al., 2006; Molina et al., 2005; Molina et al., 2006). Where patterns of instantaneous disappearance of all species are observed, these are generally the result of condensed or incomplete sections.

Less well known is the extinction pattern of planktic foraminifera in shallow marginal environments or higher latitudes. Only a few studies have documented such records, notably from Kazakhstan, Denmark, Tunisia, Argentina, Madagascar, India, and Texas (Fig. 1A; Keller et al., 1989a; Keller et al., 1989b; Keller et al., 1993; Keller et al., 1998; Keller et al., 2007a; Keller et al., 2007b; Keller et al., 2008; Keller et al., 2009a; Keller et al., 2009b; Keller et al., 2009c; Schmitz et al., 1992; Oberhänsli et al., 1998; Pardo and Keller, 1999; Abramovich et al., 2002; Hart et al., 2004; Hart et al., 2005). Across latitudes, these shallow-water assemblages are characterized by lower species diversity, gradual disappearance of species, dominance of small
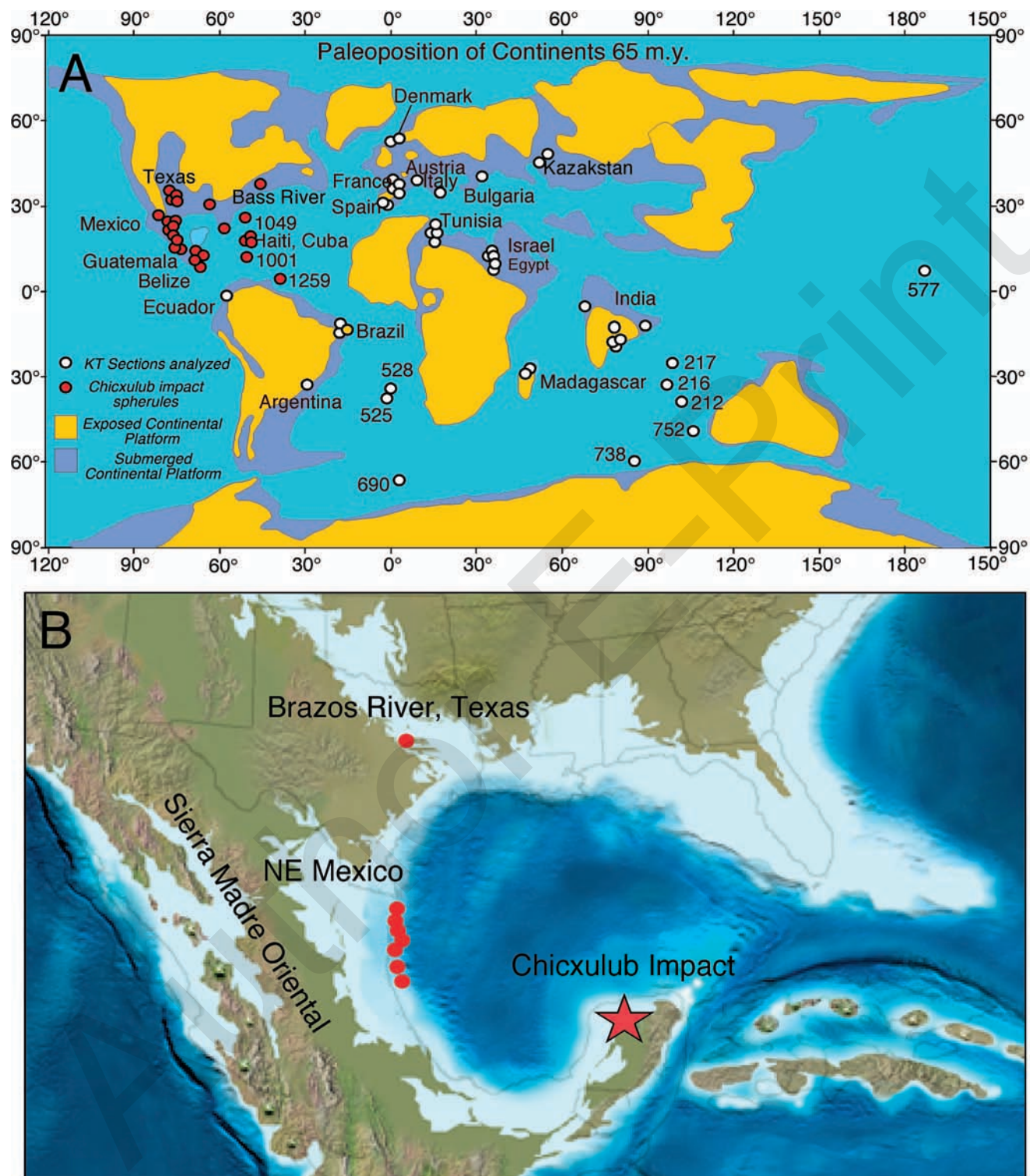
FIGURE 1.—A) Paleogeographic locations of over 150 KTB sequences studied by the author, students, and collaborators worldwide spanning from low to high latitudes and deep sea to marginal marine environments. Brazos River sections of Texas are similar to shallow marginal marine sequences in Egypt, Tunisia, Argentina, and Denmark. B) Paleogeographic location of the Brazos locality at the southern margin of the Western Interior Seaway.

species, dwarfing of species, and selective survivorship (Keller and Abramovich, 2009). As a result, planktic foraminiferal extinctions across the KTB appear much less severe and even gradual compared with open-ocean environments. Does this mean that the mass extinction was less severe in shallow-water environments than in the open ocean? Or does this simply mean that extinction-prone specialized species inhabited mostly open-ocean environments? What were the major environmental stresses limiting species diversity in shallow environments? Was dwarfing a viable survival strategy? Answers to these questions may help us understand the nature of the extinction pattern in shallow-water environments.

Brazos River sections in Falls County, Texas, U.S.A., offer an ideal location to investigate these questions. These sections have long been known as among the most complete KTB sequences worldwide and comparable to the El Kef stratotype and Elles parastratotype sections and point (GSSP) of Tunisia (Jiang and Gartner, 1986; Keller, 1989a, 1989b; Barrera and Keller, 1990). The Brazos sections have the added advantage of a sandstone complex with reworked Chicxulub impact-glass spherules up to 1.0 m below the KT boundary and the original impact-ejecta spherule layer in claystones between 45 and 60 cm below the sandstone complex (Keller et al., 2007a; Keller et al., 2009a; Keller et al., this volume). These deposits are thus unique in preserving three stratigraphically unique and well-separated events: the KTB, the sandstone complex with reworked impact spherules, and the primary Chicxulub impact-glass spherule ejecta. The temporal resolution provided by these sections permits unraveling the history of the KTB mass extinction in a shelf-margin environment.

This study examines the late Maastrichtian and KTB mass extinction pattern in five Brazos localities in a north–south transect. The results are compared with similarly shallow sequences from southern Tunisia to reveal the global nature of biotic stress, extinctions, and survival during the late Maastrichtian and the KTB transition.

No evaluation of the KTB transition in shallow-water environments can succeed without comparison with the open marine environment. For this purpose there is no better sequence than the Elles parastratotype section of Tunisia, which has a continuous and undisturbed sedimentary record from the Maastrichtian through the Paleocene. In contrast, the El Kef stratotype section has several faults in the late Maastrichtian where continuity is uncertain (Li and Keller, 1998a). The late Maastrichtian and KTB transition at Elles has been studied in great detail based on planktic foraminifera (Abramovich and Keller, 2002; Karoui-Yaakoub et al., 2002; Keller et al., 2002), stable isotopes, mineralogy, and sequence stratigraphy (Adatte et al., 2002; Stueben et al., 2002). Elements of these studies are combined to illustrate the characteristic patterns of extinctions and environmental change in open marine environments.

BRAZOS RIVER, FALLS COUNTY, TEXAS, U.S.A.

During the late Maastrichtian to early Paleogene the Brazos River area of Texas was located in the margin of the Western Interior Seaway with open access to the Atlantic Ocean (Fig. 1B). The dozen Brazos KT sequences analyzed are concentrated in three localities that span a north–south distance of about 3.5 km (Fig. 2) and paleodepths ranging from inner-neritic to estuarine environments. Each of the three localities has a complete late Maastrichtian through Danian record recovered from drill holes and outcrops, which were studied and illustrated (Keller et al., this volume). This duplication is necessary to avoid unique and nonrepresentative results, but also because of the contentious nature of the Brazos sections with long-running arguments regarding the placement of the KT boundary (e.g., Keller, 1989a; Hansen et al., 1993a; Hansen et al., 1993b; Yancey, 1996; Schulte et al., 2006; Schulte et al., 2008; Schulte et al., 2010; Keller et al., 2007a; Keller et al., 2008).

Lithology and Depositional Environment

Upper Maastrichtian below Sandstone Complex: Upper Maastrichtian sediments in all Brazos River sections show similar lithologies of bedded dark gray claystones and silty claystones with variable abundances of shells and burrows as seen in a north–south transect (Fig. 3). Only in the uppermost Maastrichtian part of this interval at Mullinax-3 is there a notable difference evident in abundant roots in the claystone that indicates southward shallowing to a marshy estuarine environment. In Cottonmouth Creek (CMAW) a 3-cm-thick yellow clay layer occurs 45–60 cm below the prominent sandstone complex that is present in most Brazos River sections (Fig. 4A). This yellow clay consists of altered glass (cheto smectite) similar to the altered impact glass at the base of the sandstone complex and appears to mark the primary Chicxulub impact-spherule ejecta in upper Maastrichtian sediments (Keller et al., 2007a; Keller et al., 2008). A primary impact spherule layer was also documented in upper Maastrichtian sediments in northeastern Mexico (Keller et al., 2009b).

Sandstone Complex and Reworked Spherules: A prominent sandstone complex with reworked impact spherules overlies a scoured base that marks a sequence boundary in Brazos River sections (Fig. 3; Gale, 2006; Keller et al., 2007a). This deposit is most pronounced and accessible in the Cottonmouth and Darting Minnow Creek tributaries of the Brazos River where the resistant sandstones form waterfalls (Fig. 4A, B). This sandstone complex has been at the center of an ongoing controversy over its origins. Its proximity to the KTB and the presence of impact spherules has led many to interpret this deposit as impact-generated tsunami event (Bourgeois et al., 1988; Hansen et al., 1987; Hansen et al., 1993a; Hansen et al., 1993b; Smit et al., 1996; Heymann et al., 1998; Schulte et al., 2006). Others have pointed to various sedimentary features to advocate seasonal storm deposits (Yancey, 1996), and to burrowing horizons and spherule-rich clasts to advocate a sea-level lowstand and subsequent early transgression well after the Chicxulub impact (e.g., Gale, 2006; Keller et al., 2007a; Keller et al., 2008).

The sandstone complex increases in thickness towards the south and is most developed in Darting Minnow Creek, where it reaches 1.0–1.6 m (Figs. 3, 4B). No sandstone is present in the nearby Mullinax-3 well, where a thick root zone indicates an estuarine environment (Fig. 3). Based on the average depth of downcutting by scouring, Gale (2006) estimated that channel excavation below the sandstone complex in the Brazos River is to a maximum depth of about 1 m. Large clasts of lithified claystone are common above the scoured base (Yancey, 1996). In the sections to the south (Cottonmouth and Darting Minnow Creeks) lithified clasts contain impact spherules and occasionally mud cracks that are infilled with spherules and truncated (Fig. 4E–G; Keller et al., 2007a). These clasts contain the history of an older impact-spherule deposit that was lithified and subaerially exposed prior to erosion and redeposition. The impact-glass layer altered to yellow clay below the sandstone complex also supports an older primary impact spherule layer (Figs. 3, 4C).

Above the spherule-bearing clasts are two to three upward-fining glauconite-, shell-, and spherule-rich layers topped by thin fine sand. These spherule-rich layers are reworked, as indicated by the presence of glauconite, shell hash, small clasts, and phosphate nodules. However, they mark discrete depositional events, possibly caused by seasonal storms. One or more hummocky cross-bedded sandstones (HCS; Fig. 4D) with large burrows of *Ophiomorpha nodosa, Thalassinoides* sp., and *Planolites* sp. truncated at the top, overlie the spherule-rich layers (Gale, 2006; Keller et al., 2007a). Laminated silty claystones or laminated sandstones with small burrows overlie the HCS and mark the top of the sandstone complex, which suggests decreasing hydrodynamic conditions.
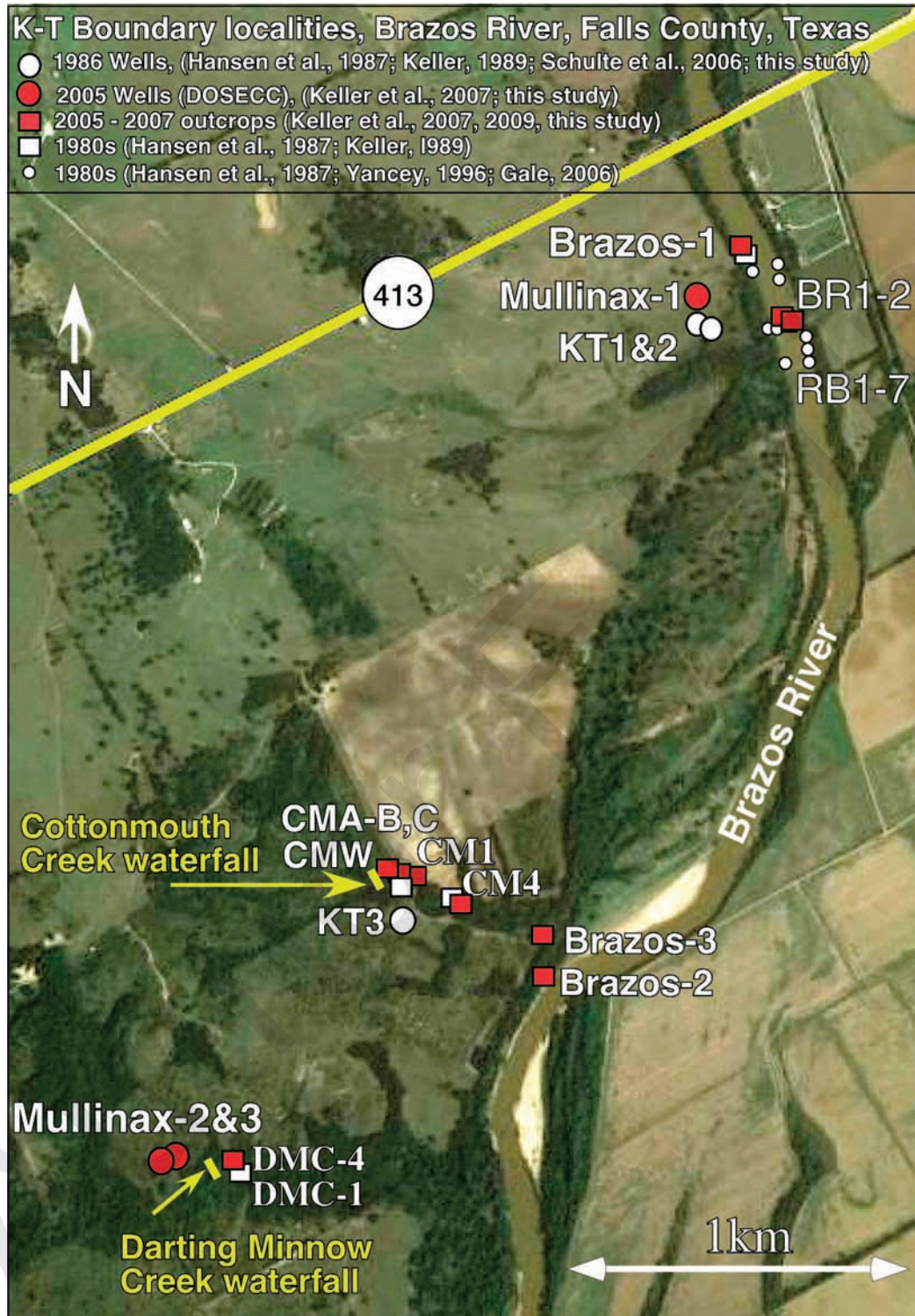
FIGURE 2.—Map of Cretaceous–Tertiary boundary outcrops collected and wells drilled and studied along the Brazos River, Cottonmouth, and Darting Minnow Creeks of Falls County, Texas.

Upper Maastrichtian above Sandstone Complex: Above the sandstone complex, deposition of gray to black upper Maastrichtian claystones with burrows, fewer small shells, and common framboidal pyrite resumes (Keller et al., 2007a). This indicates brackish, marshy water with high organic matter input and reduced oxygen conditions. In the Mullinax-1 and Brazos-1 sections, 0.8 m and 1.0 m of upper Maastrichtian sediments are between the sandstone complex and the KT boundary, respectively. The equivalent interval in Cottonmouth
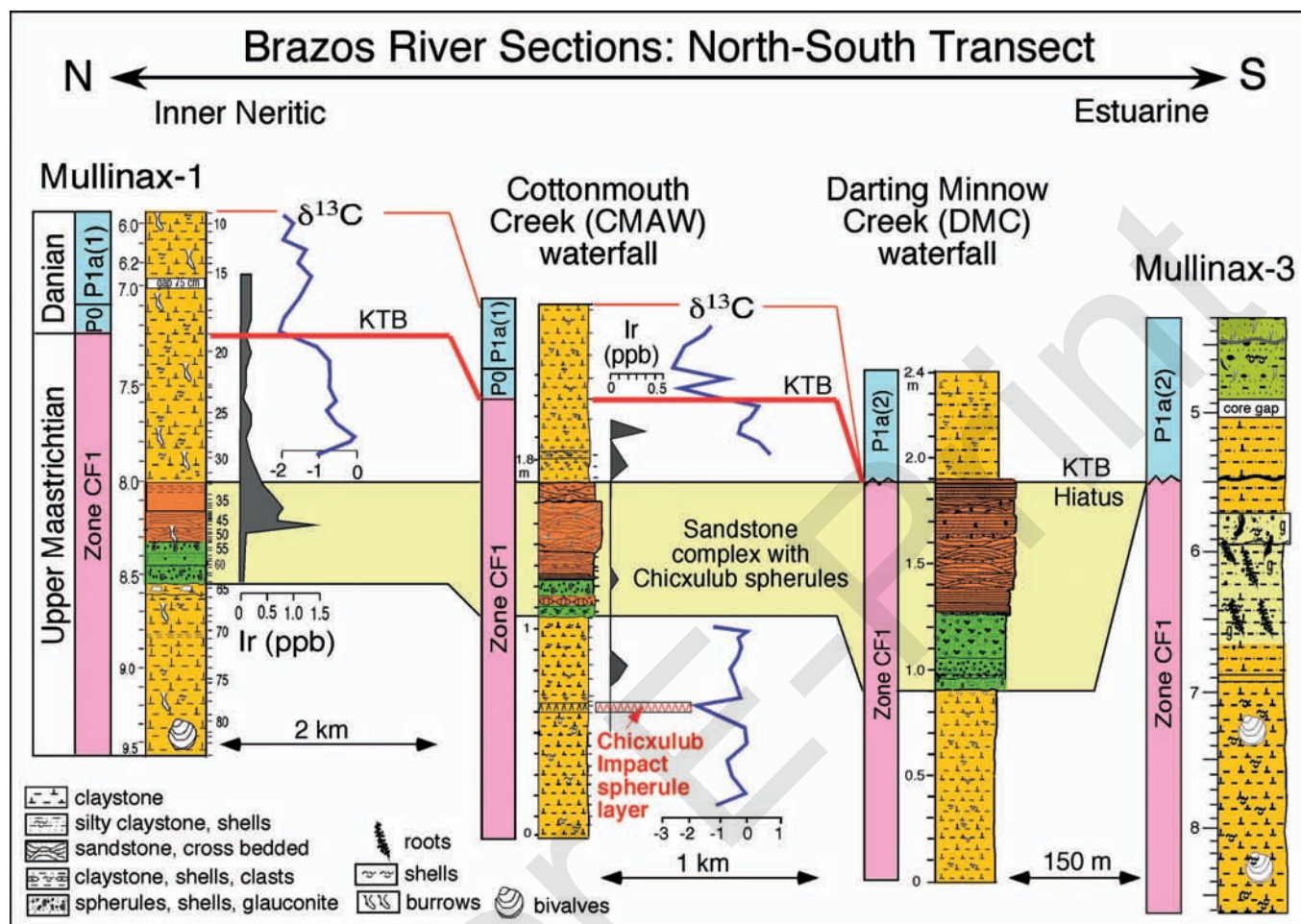
FIGURE 3.—Biostratigraphic and lithostratigraphic correlation of Brazos sequences from north to south. Note that the increasing thickness of the sandstone complex toward the south parallels shallowing from inner neritic to estuarine with subaerial erosion in Mullinax-3 at the Darting Minnow Creek. The southward shallowing trend is accompanied by increasing erosion. There is no Ir anomaly at the KTB and only minor enrichments at condensed intervals within and above the sandstone complex, except for Brazos-1.

Creek is 0.45 m but is absent in Darting Minnow Creek and Mullinax-3 due to erosion (Fig. 3). The decreasing thickness and erosion of upper Maastrichtian sediments from north to south parallels the increasing thickness of the sandstone complex and reflects the shallowing towards an estuarine environment.

KTB in Brazos Sections: There is no Ir anomaly, no lithologic change, or any interruption in the sedimentary regime apparent across the KT boundary in Mullinax-1 or the other sections analyzed, except for the Darting Minnow Creek and nearby well Mullinax-3 to the south. At this locality an unconformity marks the KTB interval. Below the unconformity in Mullinax-3 is a claystone with abundant roots, which indicates shallowing (Fig. 3). The absence of a KTB clay and Ir anomaly in the Brazos sections is puzzling. Ir concentrations are found well below the KTB and within the sandstone complex in Mullinax-1 (Gertsch et al., this volume), and 20 cm above it in Brazos-1 (Fig. 3; Rocchia et al., 1996).

Platinum group element (PGE) analysis by Gertsch et al. (this volume) revealed a similar pattern in all Brazos sections, with Ir and other PGEs concentrated in fine sand layers, suggesting postdepositional remobilization and concentration at redox boundaries. The

absence of an Ir anomaly and KTB clay layer can be explained by the high rate of sediment influx from nearby terrestrial runoff that diluted the Ir influx and prevented clay accumulation (Gertsch et al., this volume). Except for the absence of the KTB clay, the biostratigraphy and evolutionary transition in planktic foraminifera is the same as in more condensed continental shelf environments (Keller et al., this volume).

MATERIALS AND METHODS

Outcrops and cores were sampled at an average of 5–10 cm intervals and processed in the laboratory by standard techniques (Keller et al., 1995). Samples were soaked overnight in dilute (10%) H_2O_2, then gently washed through sieve sizes 38–63 μm and > 63 μm. The smaller sieve size recovered very small and dwarfed species that are common to abundant in some intervals and sections. The > 63 μm size fraction recovered the bulk of the assemblages for quantitative analysis. The washed residues were dried in the oven at 50°C (higher temperature may alter the shell carbonate composition for isotope analysis). Core sample size was generally restricted to 3–5 cm³, except for intervals where too few specimens were recovered for quantitative

FIGURE 4.—A) Cottonmouth Creek waterfall outcrop reveals a sandstone complex consisting mainly of a hummocky cross-bedded sandstone (D) with large *Thalassinoides* burrows truncated at the top. Below this unit are Chicxulub impact-spherule layers with altered impact glass (100% cheto smectite, A). The same geochemistry of altered impact glass is present in a yellow clay (C) layer between 45–60 cm below the sandstone complex. This yellow clay very likely is the original impact ejecta layer. B) The Darting Minnow Creek waterfall has an expanded and well-developed sandstone complex overlying a thick reworked glauconite, shell-hash, and impact-spherule unit. Clasts (E) at the base contain impact spherules (F, G) and yield further evidence that the primary ejecta fallout predates deposition of the sandstone complex.

analysis and therefore sample size was doubled. Much larger samples were collected and processed from outcrops, which significantly improved the chances of finding rare species and resulted in higher species richness for outcrop sections.

Quantitative analysis was conducted on two and sometimes three size fractions, 38–63 μm, > 63 μm and > 150 μm. For each size fraction and each sample an aliquot of 250–300 specimens was picked whenever possible, mounted on microslides, and identified. The remaining residue was examined for rare species, which were noted for data on species ranges. Benthic specimens were counted in the same aliquots of the > 63 μm size fraction as an indicator of sea-level changes. The > 63 μm size fraction was routinely analyzed because it represents the bulk of the faunal assemblages. However, because most species in the Brazos environment are small (< 150 μm), the larger species (> 150 μm) are underrepresented. For this reason the > 150 μm size fraction was also analyzed in order to evaluate the relative distribution of the larger species. The smallest size fraction (38–63 μm) was analyzed only where dwarfing reduced species size below 63 μm, which frequently occurs in the basal Danian (Keller and Abramovich, 2009). Preservation of foraminiferal tests is excellent with no recrystallization of foraminiferal tests. Danian species show some dissolution features (breakage and holes in tests). Stable isotope data from Brazos River KTB sections, quantitative data tables on planktic foraminifera, and supplemental material are available in Appendix I and II.

BIOSTRATIGRAPHY AND PLACEMENT OF THE KT BOUNDARY

The biostratigraphy of the Brazos sections is detailed in Keller et al. (this volume). Danian and Maastrichtian zonal schemes by Keller et al. (1995) and Li and Keller (1998a, 1998b) are applied in this study, which spans the KT transition from zones CF3 to P1a. Ages for Cretaceous biozones are calculated based on time scales of Cande and Kent (1995) and Gradstein et al. (2004), which place the KTB at 65.0 Ma and 65.5 Ma, respectively (Fig. 5). Because this time scale is still under revision, no preference is given and both zone durations are listed.

Zone CF3, *Pseudoguembelina hariaensis*: The interval from the first appearance of *P. hariaensis* (Plate 1) to the last appearance of *Gansserina gansseri* defines zone CF3 (65.45–66.83 Ma or 65.78–66.99 Ma; Fig. 5). This zone spans the nannofossil *Micula murus* zone. Among small planktic foraminifera (63–150 μm) in the Brazos sections zone CF3 is dominated by small *Heterohelix* species (e.g., *H. globulosa, H. navarroensis, H. planata*). *Heterohelix globulosa* also dominates the larger-species group (> 150 μm).

Zone CF2, *Pseudoguembelina palpebra*: Zone CF2 defines the interval from the last appearance of *Gansserina gansseri* to the first appearance of *Plummerita hantkeninoides* (5.30–65.45 Ma or 65.66–65.78 Ma) and corresponds to the lower part of the *Micula prinsii* zone.

FIGURE 5.—High-resolution late Maastrichtian–early Danian planktic foraminiferal biozones of Keller et al. (1995) Keller et al. (2002), Li and Keller (1998a) and Li and Keller (1998b) with comparison to the zonal scheme by Berggren et al. (1995) and the nannofossil zonation by Tantawy (2003). Biozone ages calculated based on Cande and Kent (1995) and Gradstein et al. (2004).

In the Brazos sections both size fractions (63–150 μm, >150 μm) in zone CF2 are dominated by *H. globulosa,* with common *H. planata* and *H. navarroensis*.

Zone CF1, *Plummerita hantkeninoides*: This zone defines the total range of the nominate species with its extinction at the KTB. Zone CF1 spans the end of the Maastrichtian (65.5–65.66 Ma or 65.0–65.3 Ma; Fig. 5). The zone duration based on Gradstein et al. (2004) is 160,000 years compared with 300,000 years based on Cande and Kent (1995), and hence is considerably shorter than the age used in previous studies which placed the KTB at 65.0 Ma. In the Brazos sections, *P. hantkeninoides* is rare and zone CF1 spans up to 4 m of the uppermost Maastrichtian.

Zone P0 marks the KT boundary and is defined as the interval between the mass extinction of Cretaceous species and the first appearance of *Parvularugoglobigerina eugubina* and/or *P. longiapertura*. The negative $\delta^{13}C$ shift, the mass extinction of all specialized Cretaceous species, and the first appearance of Danian species (*Parvularugoglobigerina extensa, Globoconusa daubjergensis, Woodringina hornerstownensis, W. claytonensis*) identify this interval in the Brazos sections. The age of zone P0 is uncertain, with estimates ranging from a few thousand years to tens of thousands of years. The difficulty lies in estimating the rate of clay sedimentation in boundary clays that frequently show very condensed sedimentation or nondeposition. It is likely that zone P0 spans at a minimum 10,000 years and probably more.

Early Danian: Zone P1a is defined by the range of *Parvularugoglobigerina eugubina* and/or *P. longiapertura*. Zone P1a can be subdivided based on the first appearance of *Parasubbotina pseudobulloides* and *Subbotina triloculinoides*. Zone P1a is characterized by *Parvularugoglobigerina longiapertura, P. eugubina, P. extensa, Subbotina triloculinoides, P. pseudobulloides, Chiloguembelina midwayensis*, and increasing abundance of *Globoconusa daubjergensis*. Zones P0 and P1a span 260,000 years based on the time scale of Cande and Kent (1995) and 380,000 years based on Gradstein et al. (2004) (Fig. 5).

Placement of KT Boundary

The KT boundary is one of the most extensively documented stratigraphic intervals in marine environments based on lithologic, paleontologic, and geochemical markers. Originally proposed for the El Kef stratotype, these markers include: (1) a dark organic-rich boundary clay with a 3–4 mm thin oxidized red layer at the base, (2) an iridium anomaly largely concentrated in the red layer, (3) the mass extinction of all tropical and subtropical planktic foraminiferal species, (4) the first appearance of Danian species within a few centimeters above the extinction horizon, and (5) a 2–3‰ negative shift in $\delta^{13}C$ values of marine carbonate (Keller et al., l995; Keller et al., 2002; Remane et al., 1999). These KTB identifying criteria have remained remarkably consistent in hundreds of marine sequences analyzed worldwide, although the Ir anomaly and the clay layer may not be present. In the Brazos River sections, there is no lithologic change and no Ir anomaly at the KTB. However, the KTB can be placed confidently and consistently based on the mass extinction of Cretaceous species, the evolution of the first Danian species, and the global $\delta^{13}C$ shift.

Despite this, placement of the KTB in the Brazos River sections has been controversial since the late 1980s. Ever since its discovery, the Chicxulub impact is believed to have caused the KTB mass extinction. Therefore, many have assumed that any impact signal must define the KTB. By this reasoning, the sandstone complex with its impact spherules in the Brazos sections represents an impact-generated tsunami deposit and therefore must be the KTB (Bourgeois et al., 1988; Hansen et al., 1987; Hansen et al., 1993a; Smit et al., 1996; Heymann et al., 1998; Schulte et al., 2006; Schulte et al., 2008; Schulte

et al., 2010). This has resulted in circular reasoning—the Chicxulub impact is KT in age, therefore the impact defines the KT boundary (see Schulte et al., 2008 and reply by Keller et al., 2008).

This circular reasoning inadvertently gained support when Gradstein et al. (2004) proposed to reduce KTB-defining criteria to just the "Ir anomaly associated with a major extinction horizon", and Molina et al. (2006) proposed to include any Chicxulub impact markers as KTB-defining criteria (e.g., Ir, spherules, shocked quartz, tsunami deposits, breccia). The inadvertent effect has been the elevation of any impact signal to a key defining KTB criterion. In a recent article by a consortium of scientists, this reasoning was the basis for asserting that the Chicxulub impact is KTB in age and the sole cause for the mass extinction (Schulte et al., 2010).

This "impact stratigraphy" seemed like a paleontologist's dream come true. A global instantaneous event leaves a unique signal worldwide that can now be traced and used as an age marker with absolute certainty—or can it? Like any other sediment markers, impact signals are subject to erosion, reworking, and redeposition (see review by Keller, 2008). For example, the most widespread and prominent Chicxulub ejecta, the impact-glass spherules, are documented from the Danian in Guatemala, Belize, and southern Mexico (Keller et al., 2003a; Keller et al., 2003b), from the KTB in deep-sea sites (Norris et al., 1999; Norris et al., 2000; Arenillas et al., 2006; MacLeod et al., 2007), from the upper Maastrichtian sandstone complex in northeastern Mexico and Texas (Keller et al., 2003a; Keller et al., 2007a), and from still older upper Maastrichtian sediments in northeastern Mexico and Texas (Keller et al., 2007a; Keller et al., 2009a; Keller et al., 2009b).

Where should the KT boundary be placed based on these stratigraphic occurrences? At the base of the spherule layer, as in Blake Nose and Demerara Rise? Or at the base of the sandstone complex with impact spherules in northeastern Mexico and the Brazos River sections of Texas? Or at the stratigraphically oldest impact-glass spherule layer below the sandstone complex? Clearly, Chicxulub impact spherules (or impact breccia) are not a KTB-defining marker horizon. In fact, based on the law of superposition, the stratigraphically oldest Chicxulub impact-glass spherule layer dates this impact as older than the KT boundary (see review by Keller, 2008). Impact markers are useful in stratigraphy, but they must be used with caution and in corroboration with other independent age markers rather than in isolation.

KTB MASS EXTINCTION IN BRAZOS SECTIONS

Those who are looking for the deep-sea mass-extinction pattern in the Brazos River sections will find similarities, but also significant differences by virtue of its shallow-marine environment. During the late Maastrichtian, sediment deposition occurred in a middle-neritic environment that rapidly shallowed to inner-neritic depth by about the middle of zone CF1, culminating in scoured channels (incised valleys) that were infilled by the sandstone complex during the early transgression (Gale, 2006; Keller et al., 2007a). The mass-extinction pattern mirrors this shallow shelf environment and drop in sea level below critical depth sustaining diverse assemblages.

Brazos River Sections

The upper Maastrichtian to early Danian record was recovered in the new well Mullinax-1, situated on a meadow about 300 m south of the Highway 413 Bridge and at the same locality as the old Brazos wells KT1 and KT2 ("core"of Hansen et al., 1987; "Brazos core 1" of Schulte et al., 2006). These wells are about 200 m west from the Brazos-1 section (Fig. 2). All three localities were analyzed (Keller et al., this volume). Mullinax-1 and Brazos-1 are illustrated here.

Brazos-1: No other Brazos section has been analyzed by as many people and varied disciplines as this outcrop (e.g., Hansen et al., l987; Hansen et al., 1993a; Hansen et al., 1993b; Jiang and Gartner, l986; Keller, 1989; Keller, 1989b; Keller, 1992; Montgomery et al., 1992; Beeson, 1992; Yancey, l996; Heymann et al., l998; Gale, 2006). It reached fame with the discovery of an iridium anomaly about 20 cm above the sandstone complex (Ganapathy et al., 1981; Asaro et al., 1982; Rocchia et al., 1996), and the KTB was generally placed at this anomaly or at the base of the sandstone complex. Restudy of this section does not justify either of these two KTB placements (Fig. 6).

The Brazos-1 outcrop is restricted to about 1.8 m from the sandstone complex upward. Twenty-seven species are present just below the unconformity at the base of the sandstone complex. In the 1.2 m interval above it, there is a gradual decrease to 14 species, with an abrupt drop to eight survivor species at 1.2 m (*G. cretacea, H. globulosa, H. planata, H. navarroensis, H. monmouthensis, H. holmdelensis, P. costulata, G. aspera*; Fig. 6). KTB survivors are recognized based on their ubiquitous presence in early Danian zone P1a(1) deposits, small dwarfed size, good preservation, and Danian $\delta^{13}C$ isotope signals (Barrera and Keller, 1990; Pardo and Keller, 2008). Below the KTB, *Heterohelix globulosa* dominates ($\sim$ 50%), gradually decreases, and drops to $<$ 5% in the earliest Danian. *Guembelitria cretacea* is the second most abundant species with 30%, but increasing to 50–60% as *H. globulosa* decreases. All other survivor species are $<$ 3% (Fig. 6).

In this assemblage pattern, there is no indication that the KTB is at the sandstone complex or at the Ir anomaly. Indeed, there is no significant change in the species assemblage, relative abundances of species, and no species extinctions associated with the sandstone complex or Ir anomaly. And there is no evidence to support the interpretation that the Ir anomaly and Cretaceous species above the sandstone complex resulted from settling through the water column after the impact-tsunami event (e.g., Smit et al., 1996; Schulte et al., 2006; see Adatte et al., this volume). There is no lithologic change in the 1.2 m interval above the sandstone complex. The Ir anomaly coincides with a 1 cm thin Fe-stained sandy layer. Otherwise the lithology gradually changes from dark gray to lighter gray claystone with increasing bioturbation. Characteristic Cretaceous $\delta^{13}C$ values and planktic foraminiferal assemblages mark this interval as uppermost Maastrichtian.

A major faunal turnover coincides with the $\sim$ 3‰ negative shift in $\delta^{13}C$ and $\delta^{18}O$ isotopes 1.0 m above the sandstone complex (Fig. 6). The first Danian species appear with the onset of this isotopic shift (e.g., *Woodringina hornerstownensis, W. claytonensis, Globoconusa daubjergensis, Parvularugoglobigerina extensa*), followed by *P. eugubina* and *P. longiapertura* which mark the P0-P1a boundary 10 cm above the onset of the isotope shift. In the same interval all but six of the surviving Cretaceous species disappear. The same pattern of extinctions, survivors, evolution, and $\delta^{13}C$ shift is observed in KTB sections globally and serves as a very reliable KTB marker horizon (Keller et al., 1995; Keller et al., 2002; Molina et al., 2006).

Mullinax-1: The proximity of Brazos-1 and Mullinax-1 (just 200 m apart) permit these two sections to be regarded as representing the
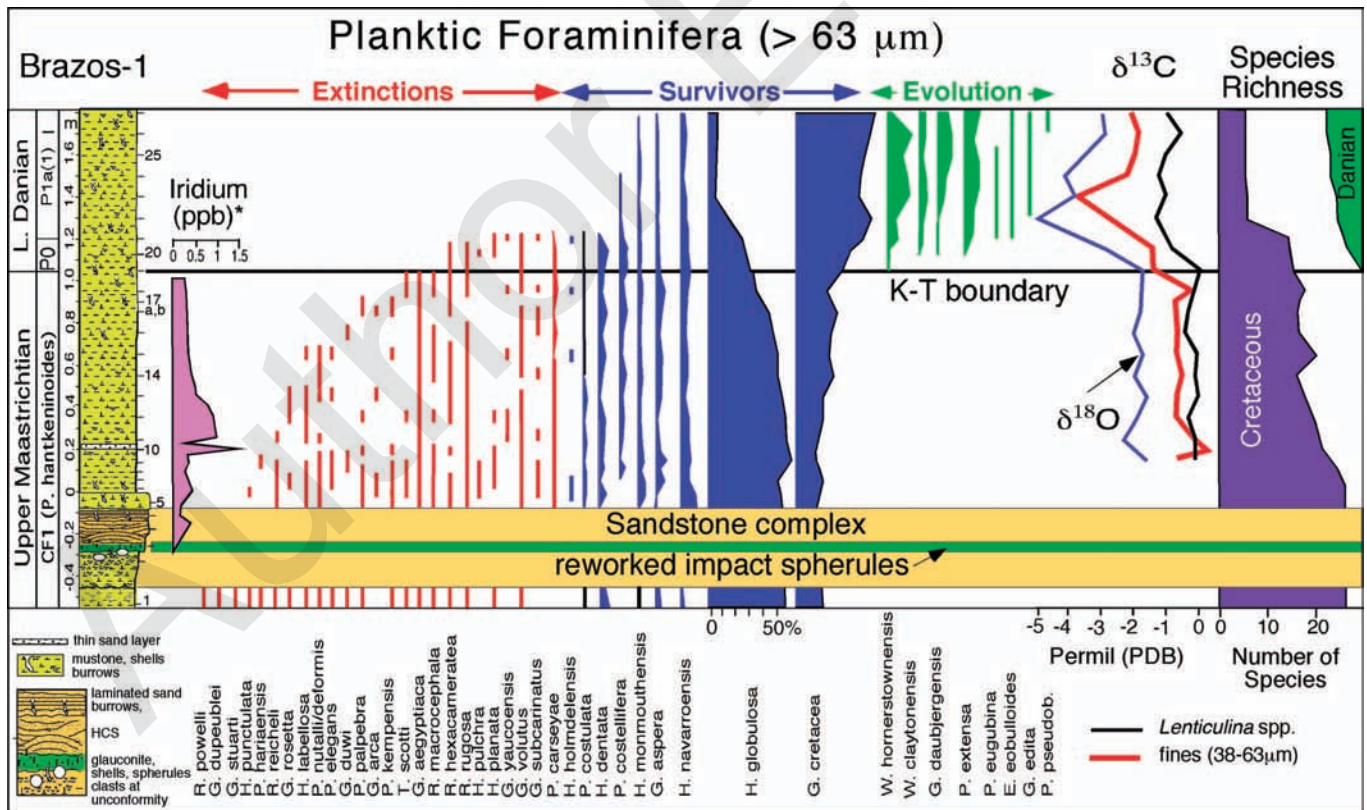

FIGURE 6.—Lithology, relative abundance of planktic foraminifera ($>$ 63 μm), stable isotopes and Ir concentrations at Brazos-1. Note that the mass extinction, the first Danian species, and $\delta^{13}C$ shift occur 1 m above the sandstone complex, whereas the Ir anomaly is within upper Maastrichtian sediments well below the KTB. The gradual decline in species richness reflects the exclusion of deeper-dwelling species in this shallow inner-neritic environment.

same environment. Brazos-1 has a better faunal record above the sandstone complex because larger samples were available and processed from the outcrop for analysis, and therefore rare species are well represented. In Mullinax-1 only small core samples (5 cm^3) were available, leading to underrepresentation of rare species, particularly above the sandstone complex. Despite this difference, the similarities are evident in the same gradual decrease in species richness, the same overall species pattern, with the same relative abundances, and the same evolution pattern coincident with the δ^{13}C shift that marks the KTB 80 cm above the sandstone complex in Mullinax-1 (Fig. 7) (Keller et al., 2009a).

The major difference between the two sections is the stratigraphic position of the Ir anomaly, which is at the base of a laminated silty mudstone above the HCS of the sandstone complex in Mullinax-1, but 20 cm higher up in Brazos-1 (Fig. 6). As in Brazos-1, there is no lithologic change at the KTB. The interval between the sandstone complex and the KTB is characterized by Cretaceous δ^{13}C signals and consists of burrowed claystone with some burrows infilled with framboidal pyrite (Keller et al., 2007a). A core gap is present in zone P1a above the KTB and truncates the Danian range of the survivor species.

The Mullinax-1 well provides an excellent record of the upper Maastrichtian zone CF1 below the sandstone complex that marks the sea-level fall correlative with major climate cooling evident in the stable isotope record (Fig. 7). Species richness averages 30 species

with an occasional maximum of 37 species. *Heterohelix globulosa* and *Guembelitria cretacea* dominate below and above the sandstone complex, though there is also an intriguing peak in *G. cretacea* at the base of zone CF1 that suggests increased stress conditions correlative with the onset of major climate warming. Apart from small biserial species all other species are present in abundances of < 1%, rare or sporadically present in the > 63 μm size fraction. Compared with deeper open marine environments of the latest Maastrichtian zone CF1, the most dramatic difference is the ∼ 40% lower species diversity and the gradual decrease in species richness, particularly in the 1 m below the sandstone complex. The main reason for this pattern appears to be the relatively shallow middle neritic shelf, which excludes many of the deeper-dwelling species and the continued shallowing due to the sea-level fall that culminated at the unconformity at the base of the sandstone complex.

One of the characteristics of Brazos foraminiferal assemblages is the dwarfed size of species, with most specimens smaller than 150 μm. Dwarfing increases with increased shallowing and is particularly acute above the sea-level drop (sandstone complex), as quantified for some species by MacLeod et al. (2000). To assess the underrepresentation of large species, the > 150 μm size fraction was also quantified. All specimens were generally picked from this size fraction to obtain a representative assemblage distribution. In most samples 200–300 specimens were recovered, though some samples have less than 100
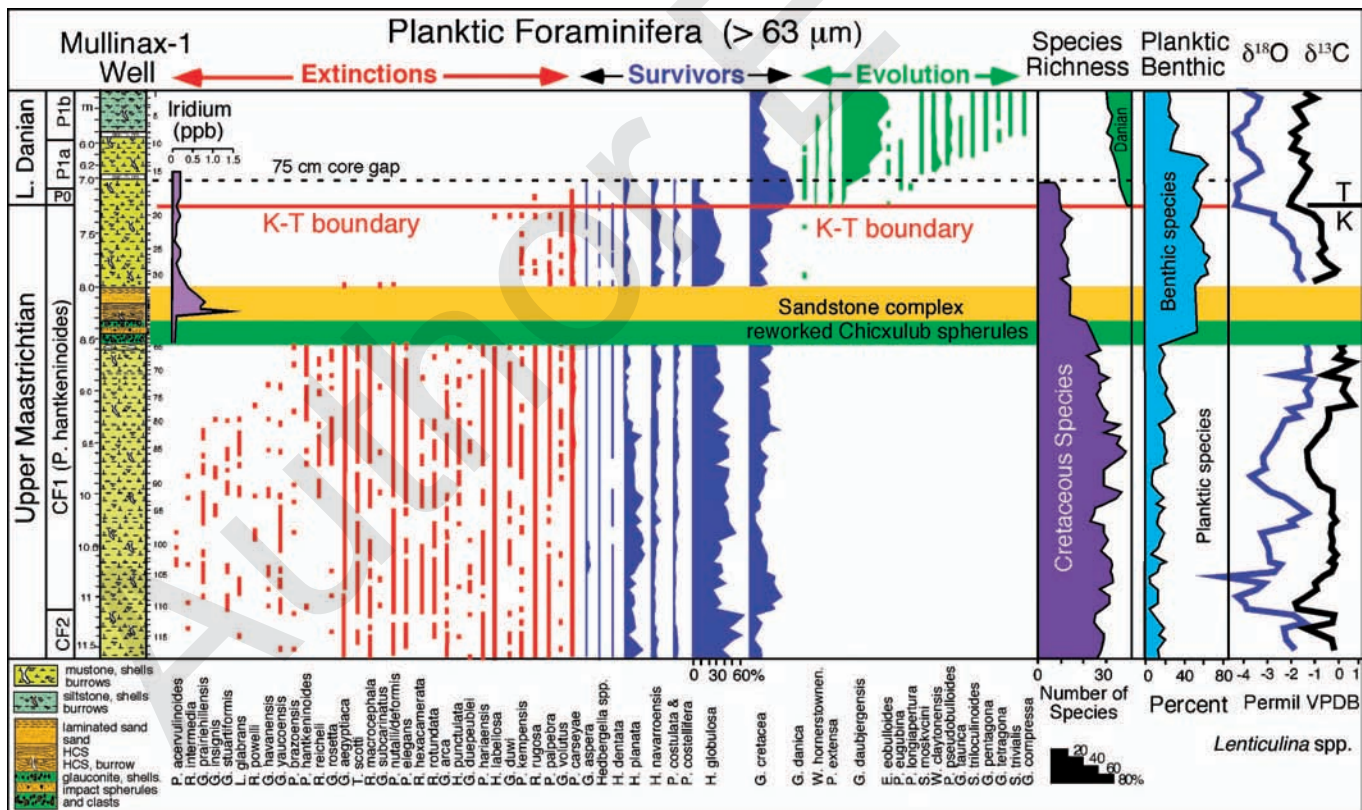

FIGURE 7.—Lithology, relative abundance of planktic foraminifera (> 63 μm), stable isotopes, and Ir concentrations in the upper Maastrichtian to Danian sediments in well Mullinax-1. As in all other sequences, the KTB is marked by the δ^{13}C shift, the first Danian species and species extinctions. Cretaceous species diversity is very low above the sandstone complex because the shallow inner-neritic environment excludes all deeper subsurface dwellers. Note the absence of any significant changes in diversity or abundance of species. The Ir concentration is at its maximum in a laminated fine sandstone near the top of the sandstone complex.

TABLE 1.—Stable isotope depth ranking of Late Maastrichtian planktic foraminifera in open marine and inner-neritic Brazos environments. Boldface species mark ecological opportunists interpreted as *r*-strategists. All others are assumed to be *K*-strategist species. (Modified after Abramovich et al., this volume). Open ocean data from Abramovich et al. (2003) and Abramovich et al. (2010), and Brazos River data from Barrera and Keller (1990) and Pardo and Keller (2008).

Mixed layer		Thermocine	Subthermocline
Surface	**Subsurface**	**Intermediate**	**Deep**
Pseudoguembelina excolata	*Globotruncana aegyptiaca*	*Globotruncana arca*	*Planoglobulina multicamerata*
P. kempensis	*G. mariei*	*G. dupeublei*	*Heterohelix rajagopalani*
P. costulata	*G. rosetta*	*G. falsostuarti*	*Abathomphalus mayaroensis*
P. hariaensis	*Rosita walfishensis*	*G. mariei*	*Gublerina cuvilieri*
P. palpebra	*Rugoglobigerina rugosa*	*G. orientalis*	*Globotruncana stuartiformis*
*Rugoglobigerina pennyi***	*R. hexacamerata*	*G. ventricosa*	*Gansserina gansseri*
R. hexacamerata	*R. milamensis*	*Globotruncanita angulata*	*Lipsonia lipsonae*
*Planoglobulina acervulinoides**	*R. rotundata*	*G. stuarti*	
	Globigerinelloides asper	*Rosita patelliformis*	
	G. subcarinatus	*Racemiguembelina fructicosa*	
	Gublerina acuta	*R. intermedia*	
	Pseudotextularia deformis	*R. powelli*	
	P. elegans	*Rugoglobigerina pennyi*	
	Heterohelix globulosa	*Globotruncanella havanensis*	
	H. labellosa		
	Planoglobulina carseyae		
** also listed in thermocline	*P. brazoensis*		
* also listed in subsurface	* also listed in thermocline		

Species also present in Brazos area (this study)

Paraspiroplecta navarroensis	*Globotruncana duwi*	*Globotruncanella petaloidea*	
Guembelitria cretacea	*G. esnehensis*	*Globotruncanella havanensis*	
Guembelitria irregularis	*G. insignis*		
Guembelitria trifolia	*Rugoglobigerina macrocephala*		
Guembelitria danica	*R. scotti*		
Paraspiroplecta navarroensis	*R. reicheli*		
	Plummerita hantkeninoides		
	Heterohelix planata		
	H. dentata		
	H. globulosa		
	Globigerinelloides multispina		
	G. rosebudensis		
	G. volutus		
	G. yaucoensis		
	Hedbergella monmouthensis		
	H. holmdelensis		

and sometimes even less than 50 specimens in the > 150 μm fraction. These were not included in the abundance plots.

The relative abundance data of the larger species is revealing. The number of species present averages 20 in the lower part of zone CF1 and decreases to an average of 15 in the 1 m below the sandstone complex (Fig. 8). *Heterohelix globulosa* is the sole dominant species, with maximum abundances during peak warming, and a significant increase in rugoglobigerinids at these times also. During cooler intervals, other biserial taxa increased and *H. globulosa* decreased. All other taxa are rare or sporadically present. Conspicuously absent are the specimens in the larger size fraction above the sandstone complex. This pattern repeats itself in all Brazos sections. It reveals increasingly high stress conditions in the Brazos area due to the shallowing

environment leading to exclusion of subsurface dwellers and dwarfing of survivors (see Discussion).

Cottonmouth Creek

CMAW-CMB Waterfall: Just 2 km to the south of Mullinax-1 are the Cottonmouth Creek outcrops, with the best ones at and near the waterfall (CMAW and CMB) (Fig. 2). On a meadow nearby is the location of the old well KT3 that was first analyzed by Keller (1989a) and reanalyzed with species concepts updated for this study. Cottonmouth Creek sections are important for their excellent exposures of the sandstone complex with reworked impact spherules, the presence of the thin yellow clay layer (altered impact glass) in
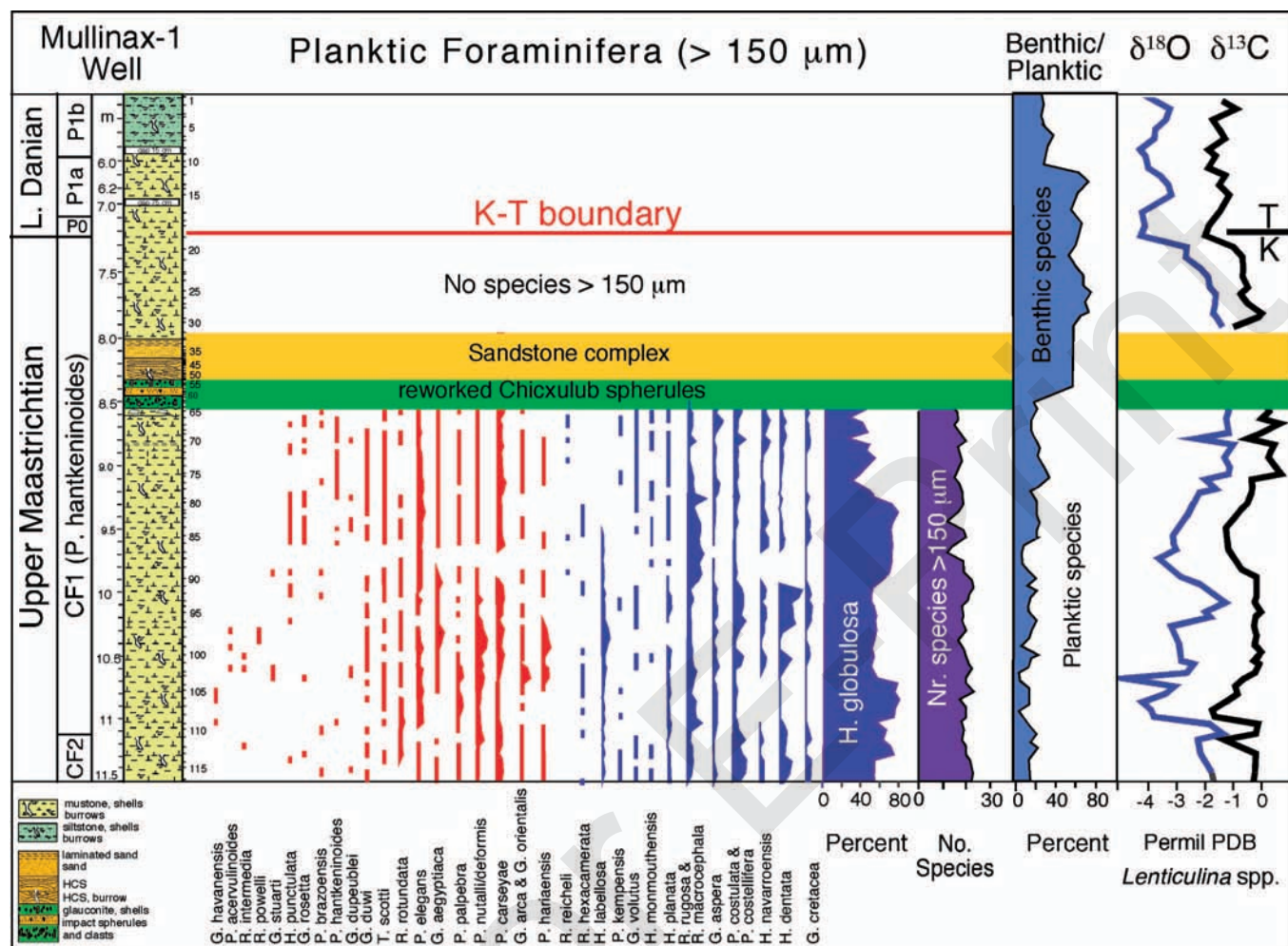
FIGURE 8.—Lithology, relative abundance of planktic foraminifera (> 150 μm) and stable isotopes in the upper Maastrichtian to Danian sediments in well Mullinax-1. Note that there are no species or specimens > 150 μm above the sandstone complex. This is a result of the high-stress conditions in the shallower environment after the sea-level drop that marks the sandstone complex. The exclusion of the larger, deeper-dwelling species results in significantly reduced diversity and a more gradual extinction pattern (Fig. 7).

claystone 45–60 cm below the sandstone complex, and clasts with impact spherules (also present in the Darting Minnow Creek; Fig. 4) (Keller et al., 2007a). Cottonmouth Creek waterfall sections thus demonstrate the pre-KTB age of the Chicxulub impact in four ways:

1. reworked Chicxulub impact spherules in the sandstone complex,

2. Chicxulub impact spherules in lithified clasts,

3. altered impact glass in the yellow clay layer below the sandstone complex, and

4. stratigraphic position of the sandstone complex and all Chicxulub impact-spherule evidence well below the KTB.

Cottonmouth Creek waterfall (CMAW) exposes an interval from 1 m below to about 0.5 m above the sandstone complex. The CMB section, situated about 20 m from the waterfall, exposes a reduced sandstone complex and about 2 m above it (Keller et al., this volume). The two sections are here combined, with CMAW representing the interval up to the sandstone complex and CMB the interval above it (Fig. 9).

Compared with Brazos-1 and Mullinax-1, the Cottonmouth Creek sections are more condensed due to minor hiatuses or nondeposition. This is evident in the north–south transect, which reveals a shallowing trend towards the shoreline to the south (Fig. 3).

Despite the shallower environment, planktic foraminiferal assemblages (> 63 μm) in Cottonmouth Creek sections are strikingly similar to the northern sections. Maximum species richness in zone CF1 below the sandstone complex varies between 30–35 species and decreases to 20–22 species between the sandstone complex and the KTB (Fig. 9). Cretaceous δ13C signals characterize these intervals. The KTB is marked by the onset of the δ13C shift, the first appearances of Danian species, and the disappearance of most Cretaceous species within 10 cm of these datum events. Survivor species continue into the lower part of the P. eugubina subzone P1a(1) and are truncated by a short hiatus. Relative species abundances are also similar to the northern sections, with H. globulosa and G. cretacea dominating and other small biserial species common. There is no significant assemblage change across the yellow clay layer or the sandstone complex. A minor Ir enrichment of 0.4 ppb occurs about 25 cm above the sandstone complex, and more
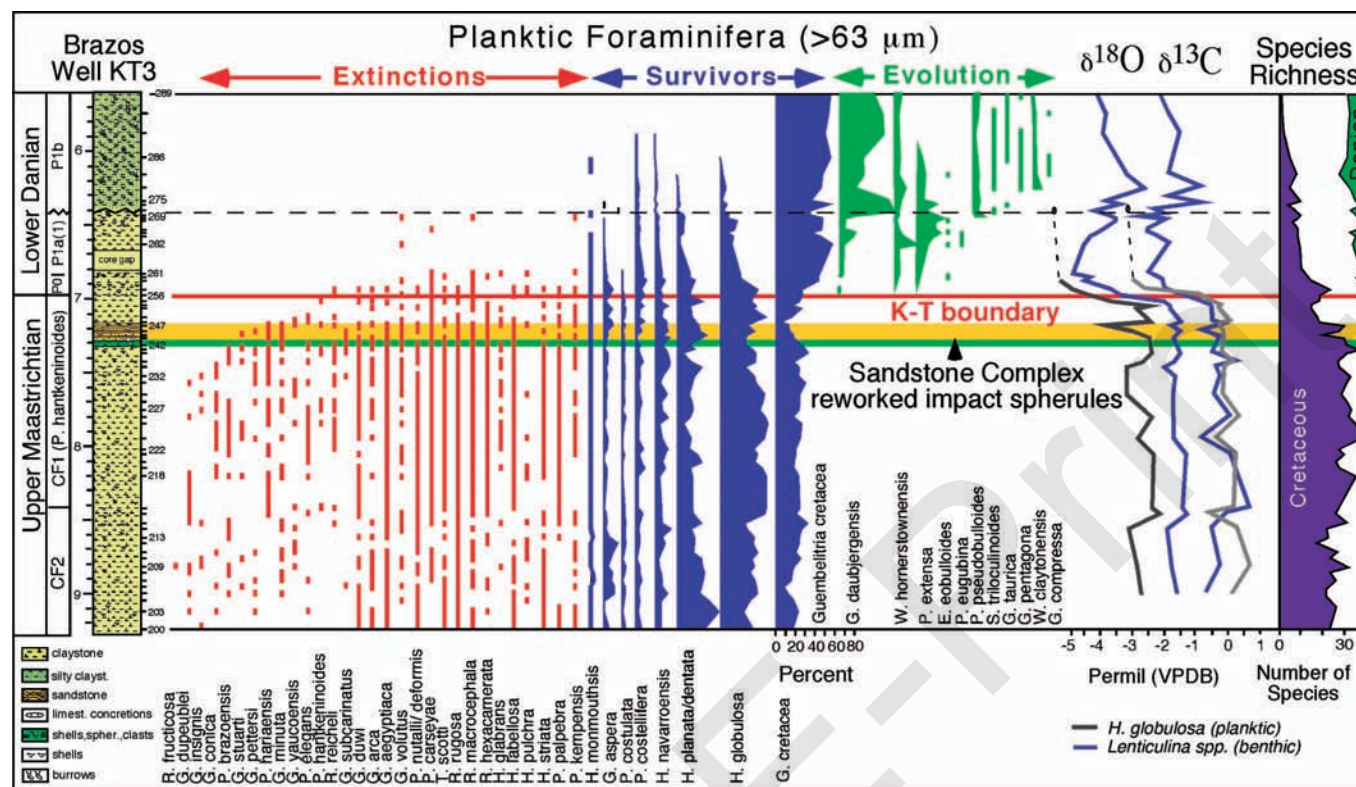
FIGURE 9.—Lithology, relative abundance of planktic foraminifera (> 63 μm), stable isotopes and Ir concentrations in the Cottonmouth Creek waterfall CMAW and CMB composite section (CMB is 20 m down the creek). As in all other sequences the KTB, marked by the δ¹³C shift, the first Danian species, and species extinctions, is above the sandstone complex, Cretaceous species diversity is low due to the shallow inner-neritic environment. A sharp negative isotope excursion in the yellow clay is due to diagenetic alteration of the impact-glass layer. Note the absence of any significant changes in diversity or abundance of species across the impact layer. A minor increase in Ir concentration occurs between the KTB and the sandstone complex.

FIGURE 10.—Lithology, relative abundance of planktic foraminifera (> 150 μm) and stable isotopes in the upper Maastrichtian to Danian sediments in CMAW and CMB. As in Mullinax-1, there are no species or specimens > 150 μm above the sandstone complex as a result of the high-stress conditions induced by the shallower environment after the sea-level drop that marks the sandstone complex. The exclusion of the larger, deeper-dwelling species results in significantly reduced diversity and a more gradual extinction pattern (Fig. 9).

FIGURE 11.—Lithology, relative abundance of planktic foraminifera (> 63 µm) and stable isotopes in Cottonmouth Creek well KT3. As in all other sequences the KTB, marked by the δ^{13}C shift, first Danian species and species extinctions, is above the sandstone complex; Cretaceous species diversity is low due to the shallow inner-neritic environment.

minor enrichments are detected between the yellow clay and the base of the sandstone complex (Fig. 9).

The larger size fraction (> 150 µm) also shows the same pattern as in the northern sections. No foraminiferal species larger than 150 µm are present above the sandstone complex (Fig. 10). Below the sandstone complex, species richness averages 20 species. *Heterohelix globulosa* dominates, other small species are common along with rugoglobigerinids. There is no significant change across the yellow clay layer.

Well KT3: Well KT3 was drilled in 1986 by Thor Hansen and Earl Kauffman on a meadow about 200 m from the waterfall (Fig. 2). Keller (1989a) published a description of the planktic foraminifera of this section and reanalyzed and updated taxonomic concepts for this report. Stable isotopes were analyzed by Barrera and Keller (1990) (Fig. 11). Well KT3 is very similar to Mullinax-1 and CMAW. Species richness averages 25 in zone CF2, 30 species in CF1, with peaks to 37 species, and drops to 15 species above the 15-cm-thick sandstone complex. With the exception of an increase to 20 species at the KTB, probably due to reworking, species richness drops to eight survivor species at the P0-P1a(1) boundary 10 cm above the KTB.

As in all Brazos sections, the KTB is marked by the δ^{13}C shift, the first appearances of Danian species, and the mass extinction of all but survivor species within 10 cm above the onset of the δ^{13}C shift. Relative species abundances (> 63 µm) also follow the same pattern with *H. globulosa* and *G. cretacea* dominating and with other small biserial species common (Fig. 11). Other species are rare (< 1%), sporadically present, and gradually disappearing. Stable isotope

patterns below the sandstone complex are not comparable with Mullinax-1 because the sample spacing at KT3 is too large (20 to 50 cm as compared with 5 cm intervals at Mullinax-1).

Darting Minnow Creek

Darting Minnow Creek Waterfall and Mullinax-3: About 1 km south of Cottonmouth Creek is the Darting Minnow Creek (DMC), which has the thickest and most prominent sandstone complex, forming a small waterfall (Fig. 4B). Biostratigraphy reveals a hiatus with subzone P1a(1), zone P0, and the uppermost Maastrichtian above the sandstone complex missing (Fig. 3). The same hiatus was observed on a meadow above the waterfall where well Mullinax-3 was drilled.

Mullinax-3: In Mullinax-3, less than 200 m from the DMC waterfall, no sandstone complex is present. Instead roots are common in the upper Maastrichtian claystone of zone CF1, revealing a marshy estuarine environment with erosion surfaces marking temporary emergence (Fig. 12). We tend to think that planktic foraminifera would not survive in such a shallow environment. But this is evidently wrong. Planktic foraminifera are common through the late Maastrichtian zones CF2-CF1 and into the early Danian, and so are calcareous nannofossils, which indicate deposition occurred during the latest Maastrichtian *Micula prinsii* zone and early Danian zone NP1a-NP1b (Tantawy, this volume).

Planktic foraminifera show low species richness (15 to 25 species) in zone CF2, increase to 25 with peaks to 30 species in zone CF1 below the root zone, and gradually decrease to between 10 to 14 species in the
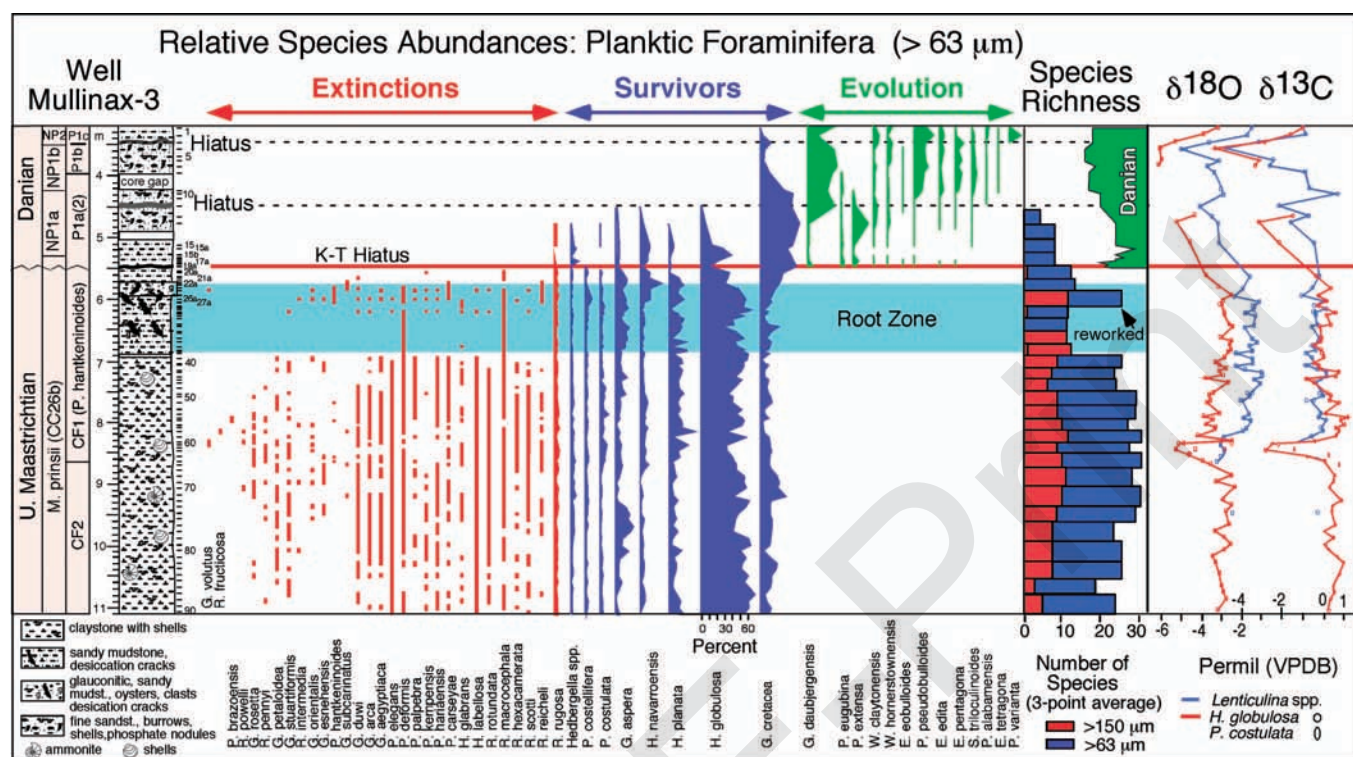
FIGURE 12.—Lithology, stable isotopes of benthic and planktic foraminifera and relative abundance of planktic foraminifera (> 63 μm) are shown for well Mullinax-3. Note the presence of a major KTB hiatus but no sandstone complex. Instead, root traces below the KTB indicate an estuarine to marshy environment below the KTB and probably correlative with the sandstone complex in the Darting Minnow Creek (Fig. 4). Within this shallow interval only the most environmentally tolerant species are present, and in very low numbers. Reworking accounts for the influx of additional Cretaceous species in the 0.5 m below the KTB.

root zone, except for one peak of 25 species that represents reworked species at an erosion surface (Fig. 12). Above the KTB hiatus, survivor species persist into subzone P1a(2). Relative abundances of species > 63 μm also remain similar, with *H. globulosa* dominant and other small biserial species common. The main difference is that *G. cretacea* is less abundant during the late Maastrichtian.

The > 150 μm size fraction is restricted to below the root zone interval. Although rare specimens are present within the root zone, these are sporadic and may be reworked. Below the root zone the assemblages are also similar to the > 150 μm size fraction of Mullinax-1 (Figs. 8, 13). For example, there are major abundance fluctuations in *H. globulosa* between 40–80% in both wells in zones CF1 and CF2, which appear to be coeval. But there are also major differences that cannot be attributed to reworking or analytical error. For example, the high abundance of *R. rugosa* and *H. labellosa*, and the relatively high presence of *G. arca, G. aspera*, and *P. elegans* in zones CF2 and CF1 prior to the end-Maastrichtian sea-level fall (Fig. 13). It is unclear whether this is related to special niche habitats in the area. In addition, many species make only isolated appearances in zone CF1 in both size fractions, which may be related to climate warming, sea-level rise, and associated influx of species. Similarly, the low species richness observed in zone CF2, which is also observed in well KT3 and

Mullinax-1, likely correlates with the global sea-level fall that precedes the CF1 global warming (Li and Keller, 1998c; Li et al., 1999; Adatte et al., 2002).

Stable isotope data from planktic and benthic foraminifera also reflect the shallow water environment in Mullinax-3 (Fig. 12). δ^{13}C values for the benthic *Lenticulina* spp. and planktic *Heterohelix globulosa* and *Pseudoguembelina costulata* are largely overlapping with minimal surface-to-deep gradient, as would be expected in very shallow water environments. A minor though distinct surface-to-deep gradient apparent in the δ^{18}O values likely reflects salinity effects and possibly warmer surface waters. There are two major δ^{13}C excursions. One is near the base of zone CF1 and stratigraphically corresponds to a similar excursion in CMAW associated with the yellow clay that represents the primary Chicxulub impact-spherule layer now altered to cheto smectite (Fig. 9). The second excursion is across the KTB and begins in the root zone interval and continues across the KTB above where δ^{13}C and δ^{18}O values decrease by 3 permil in planktic foraminifera and to a lesser extent in benthic foraminifera. This negative δ^{13}C shift partly represents the productivity drop across the KTB, but may be amplified by the shallow water conditions and multiple emersions (e.g., salinity effects and paleosol formation).
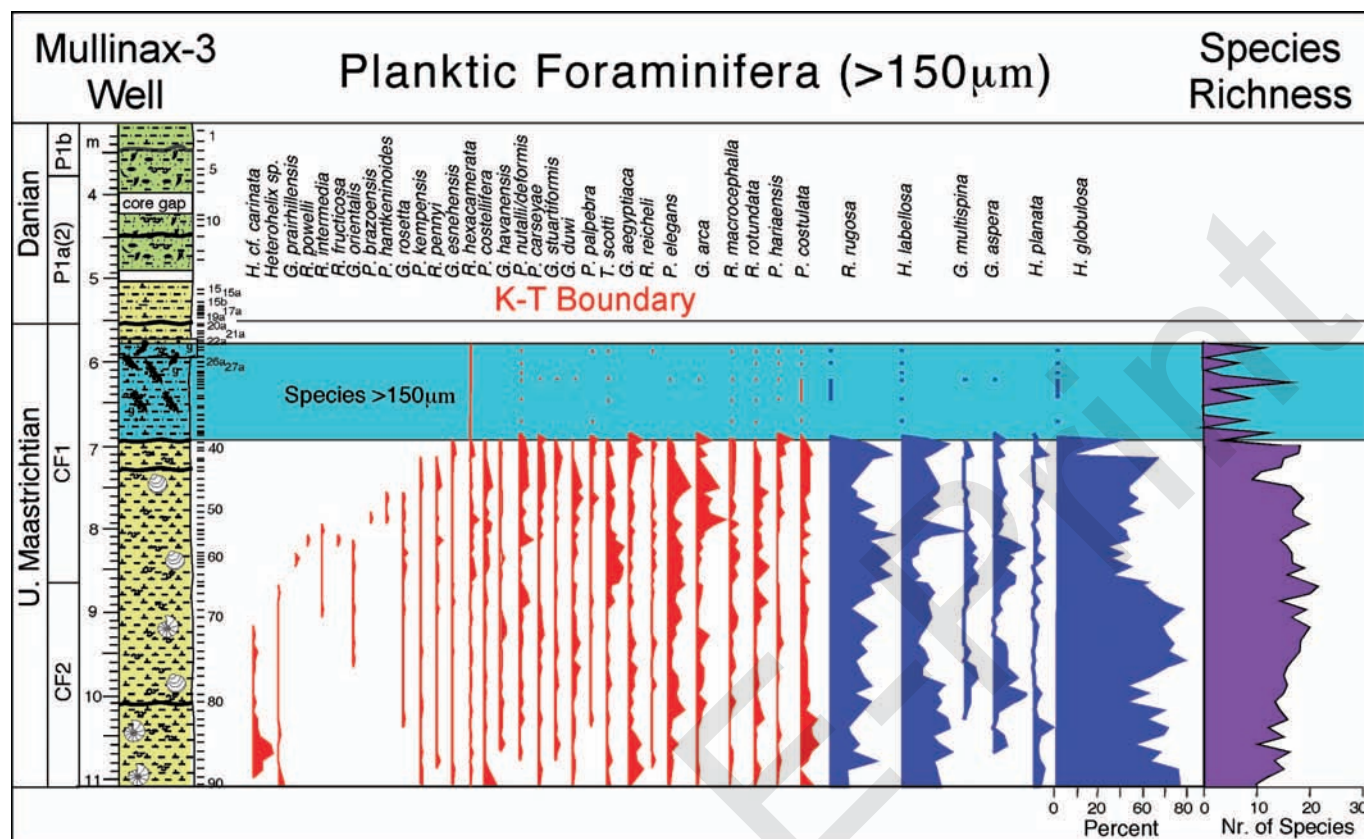
FIGURE 13.—Lithology and relative abundance of planktic foraminifera (> 150 μm) in well Mullinax-3. Note that only very rare specimens are present in the root zone that marks shallowing to an estuarine environment with the sea-level drop that marks the sandstone complex in the nearby (~ 200 m) Darting Minnow Creek.

Recovery in subzone P1a(2) reflects the global trend. The negative shift near the top of the analyzed interval coincides with a hiatus.

SAHARA PLATFORM, TUNISIA

One of the shallowest marginal-sea KTB sequences is known from the Gafsa Basin of southern Tunsisia, located in the Qued Seldja, about 10 km west of the city of Metlaoui (Keller et al., 1998). During the latest Maastrichtian zone CF1, sediment deposition at Seldja occurred at the edge of the Saharan platform in an inner-neritic (littoral) environment that shallowed to a nearshore brackish environment during the last 100–200 ky of the Maastrichtian. In this environment planktic foraminifera averaged 17 species, although 25 species are present in one sample before decreasing to 11 species at the KTB (Fig. 15). Assemblages are dominated by small heterohelicids (e.g., *H. planata, H. navarroensis, H. globulosa, P. costulata*) and *Guembelitria cretacea*. In contrast to Brazos and Danish KT sections, *H. globulosa* is less abundant at Seldja.

There is no pronounced mass extinction at the KTB because all but two of the remaining 11 species are survivors and disappear gradually in zone P1a. The KT boundary is marked by an undulating erosional contact, which is overlain by a 10-cm-thick sandstone (Keller et al., 1998). The absence of a boundary clay, a red layer, or an Ir anomaly suggests a short hiatus. Another hiatus is present at the subzone P1a(1)-P1a(2) boundary. These two short hiatuses are commonly present in KT sequences worldwide (MacLeod and Keller, 1991a, 1991b; Adatte

et al., 2002). *Guembelitria cretacea* rapidly increased across the KTB from 40% to over 90%, with all other survivor species decreasing (Fig. 14). Above the KTB, *Guembelitria* spp. dominate almost exclusively and survivor taxa are rare. No Danian species are observed in the > 63 μm size fraction, although they may be present in the smaller size fraction, which was not analyzed.

Between 0.4 and 1.2 m above the KTB, $CaCO_3$ drops below 5% and carbonate dissolution seems to have eliminated the fragile planktic foraminiferal tests. Rare specimens of the zone P1a index species *Parvularugoglobigerina eugubina* are present in the upper part of this interval and suggest subzone P1a(1). Carbonate deposition increased just below the unconformity at the base of a 20-cm-thick phosphate layer which represents a short hiatus. Above this interval most Danian subzone P1a(2) species are present, including the marker species *Parasubbotina pseudobulloides* and *Subbotina triloculinoides,* which indicates subzone P1a(2) (Fig. 14).

Based on planktic and benthic foraminifera, calcareous nannofossils, and mineralogical and stable isotope analyses, the paleoenvironment of the Saharan platform during zone CF1 was interpreted as shallow nearshore with a warm/humid climate, increased rainfall, lower salinity, and decreased productivity and biodiversity (Keller et al., 1998). A sea-level fall culminated in erosion of uppermost Maastrichtian sediments and deposition of the sandstone layer at the KTB. Low sea levels prevailed into the early Danian zone P1a accompanied by high rainfall, low salinity, low oxygen, and increased terrigenous influx and low-oxygen-tolerant species. These conditions ended with
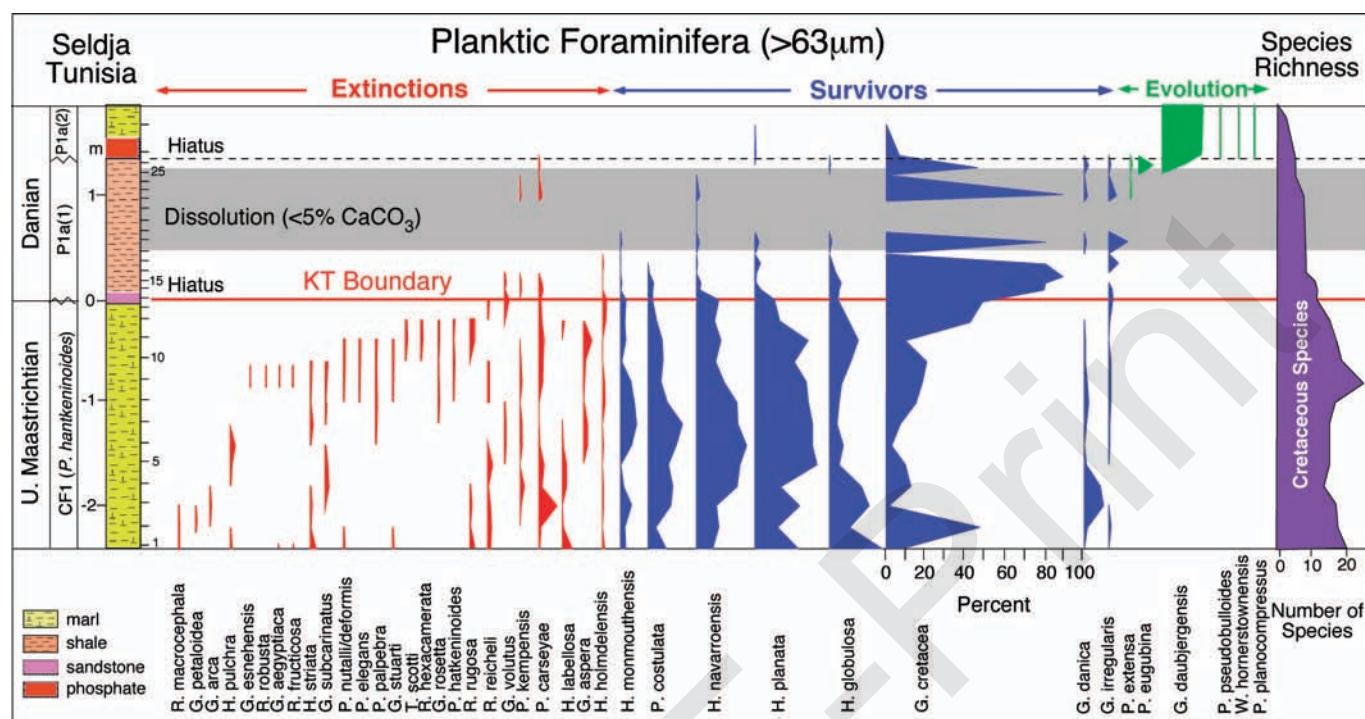
FIGURE 14.—Lithology and relative abundance of planktic foraminifera (> 63 μm) at Seldja, southern Tunisia. Note that the low species richness and *Guembelitria* blooms below the KTB reflect high-stress environments. Short hiatuses are present at the KTB and P1a(1)-P1a(2) boundary, correlative with similar hiatuses in the Brazos sections and elsewhere (MacLeod and Keller, 1991a, 1991b; Adatte et al., 2002). (Modified from Keller et al., 1998.)

erosion followed by deposition of the phosphatic sandstone that represents condensed sedimentation in a deepening open marine environment.

MASS EXTINCTION IN OPEN MARINE ENVIRONMENTS

Any study of the KTB mass extinction must take into account the records of the Tunisian KTB sections, including Ain Settara and the El Kef stratotype and parastratotype sections at Elles, with the latter situated 75 km to the southeast of El Kef (e.g., Molina et al., 2006; Adatte et al., 2002; Karoui et al., 2002; Keller et al., 2002; Luciani, 2002; Stueben et al., 2002). These sections are recognized as the best and most complete KTB sequences worldwide, but only Elles contains an undisturbed Maastrichtian through Paleocene record and is therefore the most preferable section for the long-term KT transition (Keller et al., 1995; Keller et al., 2002). The late Maastrichtian to early Danian of the Elles section was analyzed at 5 cm sample intervals, with closer sampling across the KTB (Abramovich and Keller, 2002; Keller et al., 2002; Stueben et al., 2002). During the late Maastrichtian, Elles was located in a middle- to outer-shelf environment of the Tethys Ocean.

Late Maastrichtian

Abramovich and Keller (2002) identified a total of 75 planktic foraminiferal species in the late Maastrichtian of Elles. But eliminating isolated single occurrences reduces the total to 63 viable species for the Elles environment (Fig. 15). Among these the actual number of species present in any given sample varies from 32 to 49, and there is a distinct

fluctuating trend that seems related to climate changes. In particular, climate warming and decreased productivity between the upper zones CF2 to middle CF1 correlate with a marked decrease in species richness, whereas the end-Maastrichtian cooling and increased productivity correlate with a marked increase in species richness. However, in zone CF3 the trend seems reversed, with maximum warming correlating with maximum species richness, which decreased rapidly with climate cooling (Fig. 15). Apparently temperature and productivity are important but not the sole factors controlling species richness during the late Maastrichtian. Other factors, including ecology, sediment deposition, and preservation, may play key roles. The latter two can be excluded at Elles because preservation is generally very good to excellent and sediment deposition is nearly invariant. This leaves non-optimum or high-stress ecologic conditions leading to rare or sporadic occurrences and dwarfing that result in shortened species ranges, also known as the Signor-Lipps effect (Signor and Lipps, 1982).

The main factors influencing the species richness pattern at Elles are shortened species ranges and sporadic occurrences. A total of just 21 species (33%) are consistently or nearly consistently present during the late Maastrichtian (Fig. 15). All other species are intermittently or sporadically present, and many of these have shortened species ranges. For example, 18 species gradually disappeared between 3 m and 28 m below the KT boundary, but only six of these are known to disappear prior to the KTB (e.g., *Gansserina gansseri*, *Rosita walfischensis*, *Globotruncna ventricosa*, *G. falsostuarti*, *Archeoglobigerina blowi*, *A. cretacea*). About 12 of the disappearing species reappear in the 1 m below the KT boundary (Fig. 15), an interval that has been identified as a sea-level lowstand accompanied by increased detrital influx followed by deposition of a foraminiferal packstone (Adatte et al., 2002). This
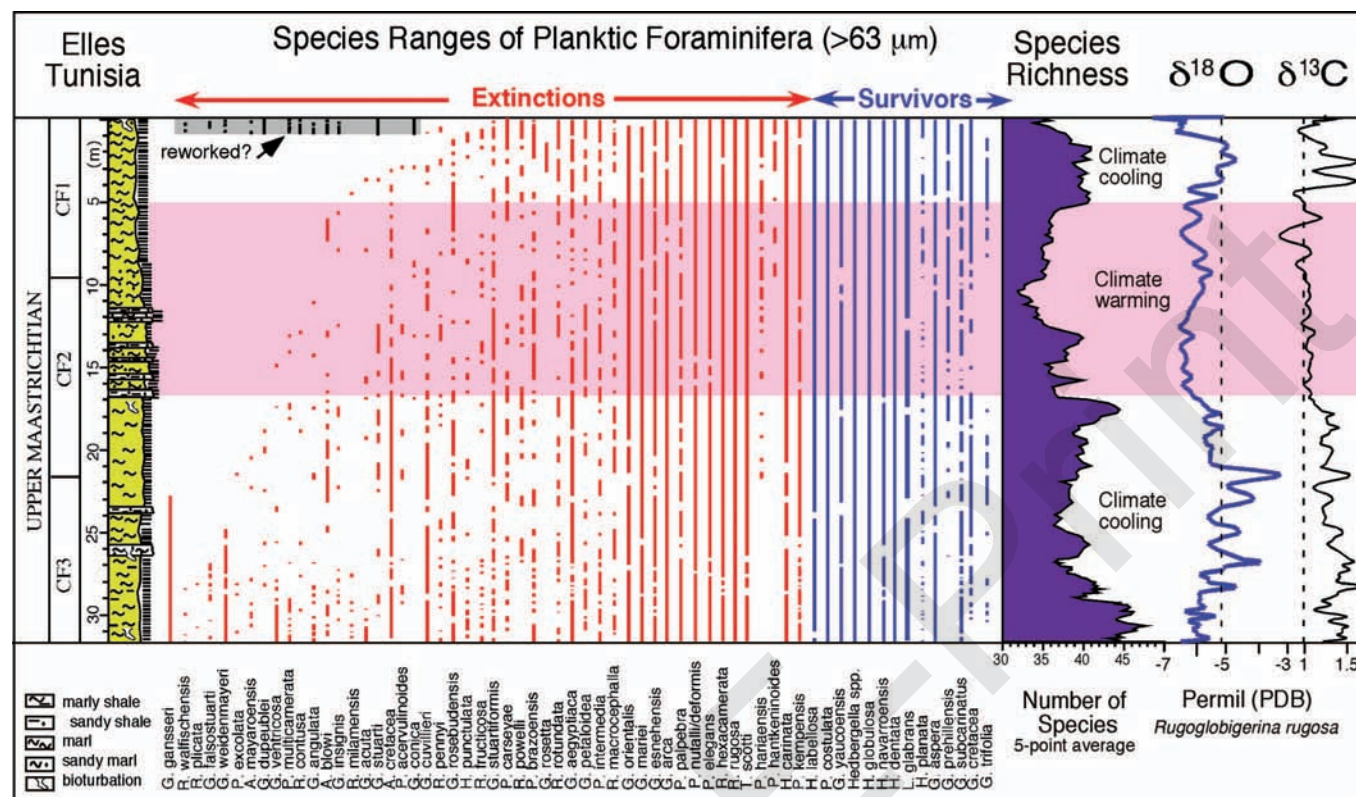
FIGURE 15.—Lithology, stable isotopes, species richness, and species ranges in the middle- to outer-shelf environment during the late Maastrichtian at Elles, Tunisia. Species richness is significantly higher than in the inner-neritic environment of Seldja or the Brazos sections but fluctuates strongly with the changing climate. Lowest species richness coincides with the end-Maastrichtian warming. Note the significant number of reworked species present at the KTB. (Modified from Abramovich and Keller, 2002.)

sudden reappearance is therefore suspect and may be due to reworking. However, with the exception of just six species the optimal upper range of most Maastrichtian species is through the late Maastrichtian (except for the evolution of *Pseudoguembelina hariaensis* and *Plummerita hantkeninoides*), though not necessarily ending at the KTB. Their absence and/or sporadic occurrences must be attributed to adverse ecological conditions. Similar decreases in species richness were observed at El Kef, Israel, and Mexico (Abramovich et al., 1998; Li and Keller, 1998a, 1998b; Lopez-Oliva and Keller, 1996; Keller, 2004; Adatte et al., 2005).

Quantitative species data (relative abundances) provide a better index of environmental conditions than species census data. In any well-preserved assemblages the bulk of the specimens are in the 63–150 μm size fraction, which at Elles total of 32 species. Just four species dominate 80% of the assemblages (Fig. 16). Among these, *H. globulosa* dominates, with maximum abundances (50%) during warm climate intervals, whereas *H. dentata* increases in abundance during climate cooling (Fig. 16). *Heterohelix navarroensis* and *Pseudoguembelina costulata* are very common but show no consistent pattern with climate change. Another eight species are intermittently common (5–10%), though the remaining 19 species (60%) are rare or sporadically present.

This assemblage is tentatively grouped into *K*-strategists and *r*-strategists (Pardo and Keller, 2008; Keller and Abramovich, 2009), which are concepts adapted from biology (Pianka, 1972; Begon et al., 2006). *K*-strategist planktic foraminifera are generally restricted to lower latitudes, consist of specialized, large and ornamented species

with generally low species abundance. They tend to require specialized food sources and ecologic niches, have few offspring, and live longer relative to *r*-strategists. In the > 63 μm size fraction at Elles, 13 species (41%) can be classified as *K*-strategists, with a combined relative abundance of about 5% (Fig. 16).

In contrast, species identified as *r*-strategists are ecologic generalists, with most species able to thrive in a wide range of environmental fluctuations. They are characterized by small species size and simple unornamented morphologies. They tend to be omnivorous, have short life spans, produce many offspring, and have large species populations (Pardo and Keller, 2008; Keller and Abramovich, 2009). At Elles 17 species are placed into this group, including all common to abundant species totaling 95% of the individuals in the assemblages. This reveals an assemblage dominated by surface (*Pseudoguembelina costulata*) and subsurface dwellers (*Rugoglobigerina rugosa*, *Hedbergella* spp., and small biserial species) able to tolerate temperature, salinity, oxygen, and nutrient fluctuations.

Most *K*-strategist species are > 150 μm and therefore their well-being during the late Maastrichtian must be evaluated in the larger size fraction. A total of 44 species are in this size fraction, with 29 or 68% *K*-strategists and 14 or 32% *r*-strategists (Fig. 17). The most dominant species is still *H. globulosa,* with a maximum of 50%, and common *Pseudoguembelina costulata* and *R. rugosa*. *K*-strategists total about 30% of the assemblages, with globotruncanids and *Pseudotextularia nutalli* common in the lower part of the upper Maastrichtian and *Pseudotextularia elegans* in the upper part (Fig. 17). Since most *K*-strategists are subsurface dwellers, this suggests a change in the water-
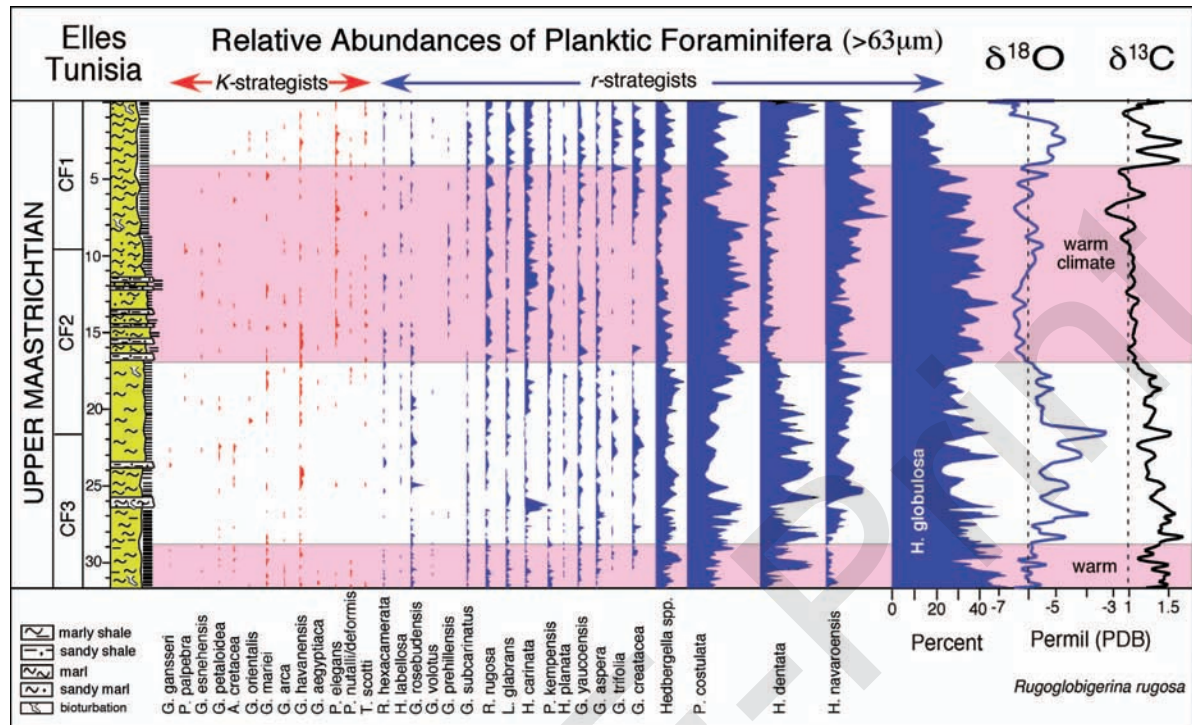
FIGURE 16.—Lithology, stable isotopes, and relative abundance of planktic foraminifera (> 63 μm) at Elles, Tunisia. Heterohelicids dominate the assemblages, with *H. globulosa* most abundant. Despite the deeper environment (middle to outer shelf), there are few large, specialized species (*K*-strategists), whereas small species tolerant of environmental fluctuations (*r*-strategists) dominate the assemblages. (Modified from Abramovich and Keller, 2002.)
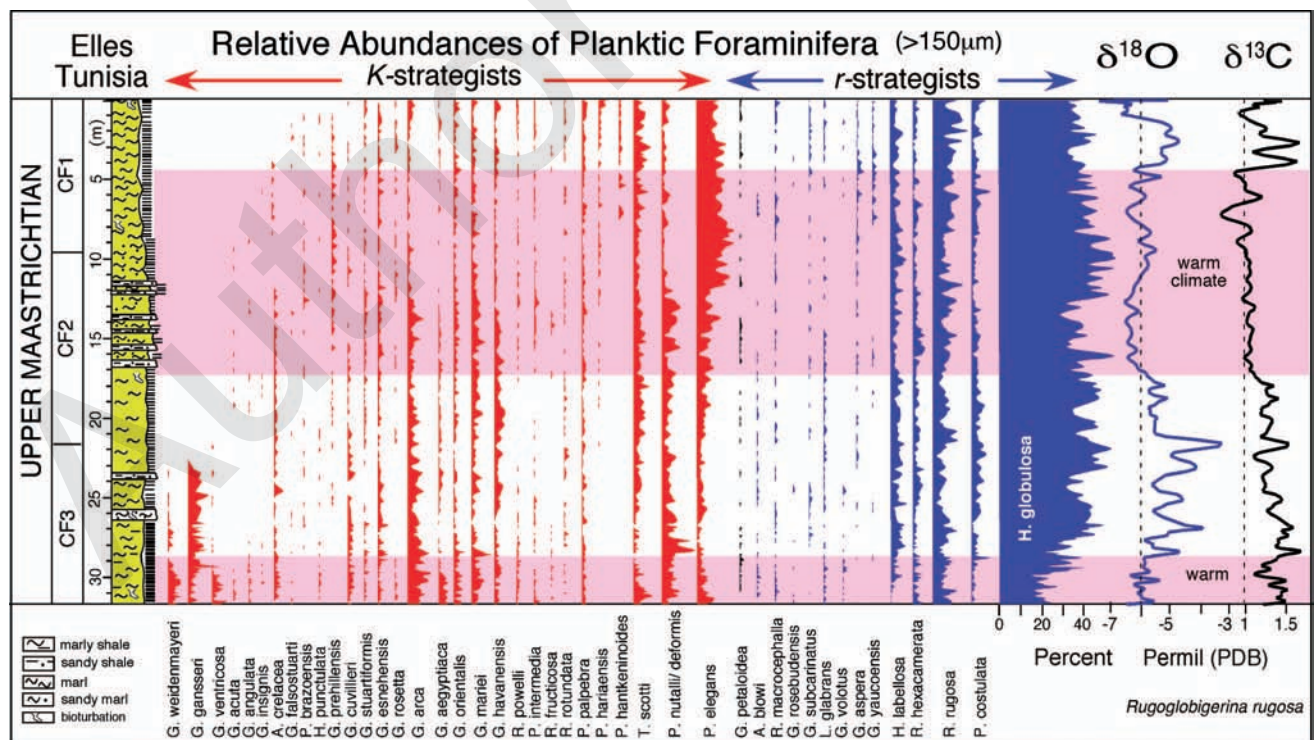

FIGURE 17.—Lithology, stable isotopes, and relative abundance of planktic foraminifera (> 150 μm) at Elles, Tunisia. Large specialized species (*K*-strategists) dominate the larger size fraction, although *H. globulosa* is still the most abundant species. Note that a minor extinction event marks the end of zone CF3, correlative with the coldest climate of the Maastrichtian.

mass stratification associated with the climate warming in zones CF2 to CF1 near the end of the Maastrichtian.

KT Boundary

Closer examination of species richness across the KTB yields further clues. The total number of species recorded, including potentially reworked specimens from the 40-cm-thick foraminiferal packstone and 60 cm below reveals between 40 and 50 species (Fig. 18; data from Keller et al., 2002). However, 9–10 species included in this tally may be reworked, judging from their rare and sporadic occurrences. Consequently, their long-term record (Fig. 15), excluding the isolated occurrences of the last meter, may be more representative (Abramovich and Keller, 2002). Above the KTB, 15 species are present in the basal 10 cm of the boundary clay, and some or all of these may be reworked. But 11 species are present well into subzone P1a(1) and are likely survivors because the same species are found to range into zone P1a in shallow and open marine environments everywhere.

Evolution of the first Danian species (*P. extensa, E. eobulloides, E. edita, G. daubjergensis*) begins near the base of the KTB clay, and the zone P1a index species (*P. eugubina*) first appears at 30 cm above the KTB (Fig. 18). The KTB is also marked by a thin red layer enriched in iridium at the base of the boundary clay and the onset of the δ^{13}C shift that reaches minimum values at the P0-P1a zone boundary.

In the > 63 μm size fraction none of the 25 (43%) *K*-strategists exceed 1% in abundance. *R*-strategists dominate, particularly small biserial species and hedbergellids, and all rapidly decrease in the basal 10 cm of the KTB clay, where the disaster opportunist *Guembelitria cretacea* floods (80%) the environment (Fig. 19). Surprisingly, between 10 and 80 cm above the KTB only very rare Cretaceous survivors are present and no Danian species in the > 63 μm size fraction. This has been observed in many other early Danian sequences, including Seldja, Mullinax-3, and Walvis Ridge DSDP Site 738 (Keller et al., 1993, 1998, this volume) and indicates dwarfing due to high-stress conditions (Keller and Abramovich, 2009). At the Elles, Seldja, and Brazos sections the high-stress intervals have very low CaCO₃ contents (~ 5%) coupled with high-nutrient and low-oxygen conditions (Adatte et al., 2002; Keller et al., 2007a). Danian specimens reappear in the $>$ 63 μm size fraction in subzone P1a(1) when CaCO₃ content increased (> 10%; Fig. 19).

Environmental conditions during the high-stress interval can be evaluated by analyzing the 38–63 μm size fraction, which was done across the KTB (Fig. 20). Just 12 species are present below the KTB. Among these *Guembelitria* spp. (~ 30%) and small *Heterohelix* spp. (~ 50%) dominate. Above the KTB, *Guembelitria* spp. (*G. cretacea, G. irregularis, G. trifolia*) dominate almost exclusively (~ 95%) through the high-stress, low-CaCO₃ interval. Interestingly, evolution of early Danian species occurred during these high-stress conditions (Fig.
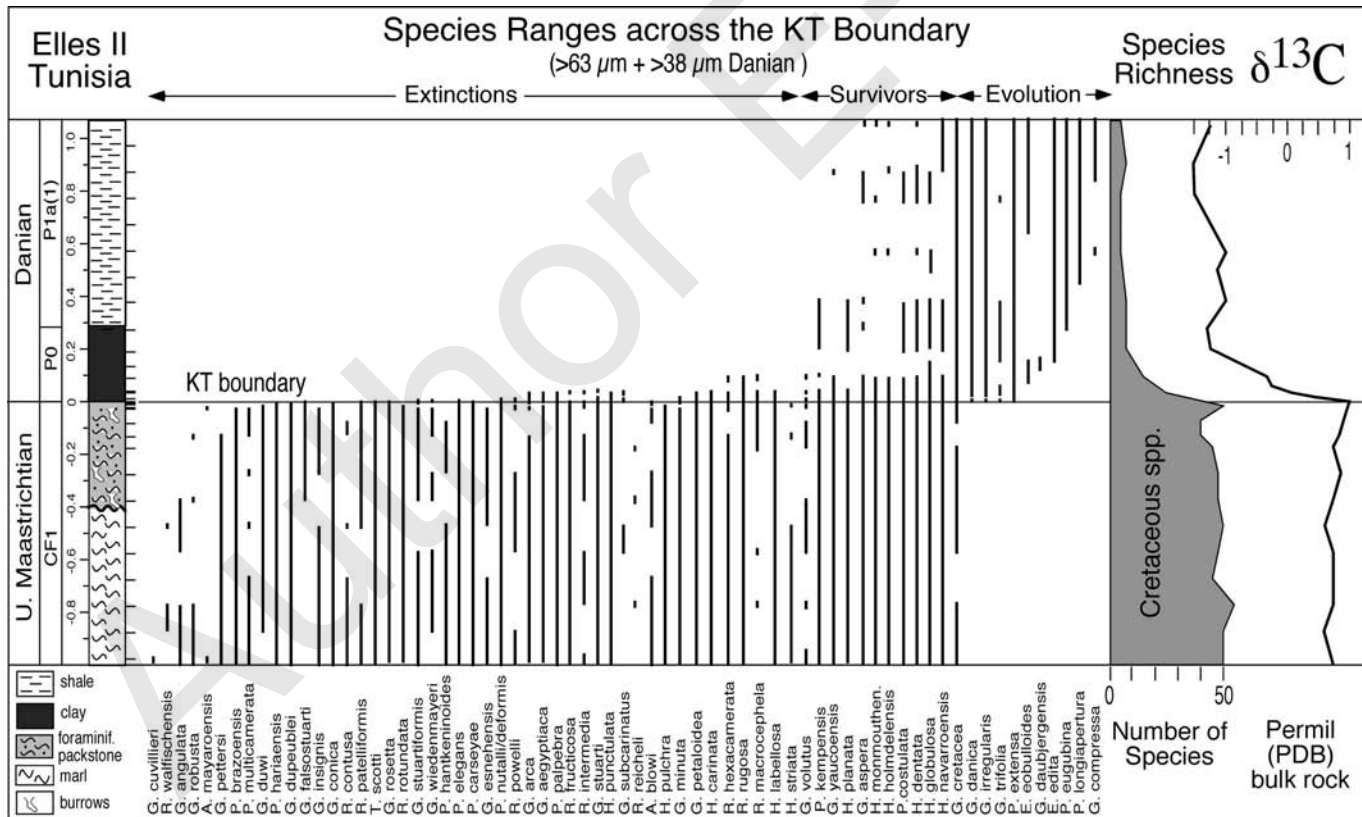

FIGURE 18.—Lithology, stable isotopes, and species ranges of planktic foraminifera across the KT boundary event at Elles, Tunisia. Note that the abrupt disappearance of most species at the KTB is characteristic of deeper open marine environments because of the high diversity of large, specialized species (*K*-strategists) intolerant of environmental changes. Only species tolerant of environmental changes (*r*-strategists) survived into the Danian. (Modified from Keller et al., 2002.)

20). Cretaceous survivors are rare and sporadically present, and some species not generally found in the early Danian are likely reworked.

DISCUSSION

Mass Extinction in Shallow vs. Deeper Marine Environments

The difference between patterns of extinctions in shallow and deeper marine environments is a major clue for understanding the nature of the KTB mass extinction. The idealized mass-extinction pattern of nearly all species becoming extinct suddenly at the KTB is based on deep-sea marine sequences, where species diversity is highest and sediment deposition is generally condensed or incomplete. Shallow continental shelf environments show a very different mass-extinction pattern because of their low species diversity, high-stress conditions, and generally much higher sediment accumulation rates. This is particularly evident in the Brazos sections, where the KTB placement has been controversial for over two decades largely because of a sandstone complex with Chixculub impact spherules that is assumed to represent the KTB. Analyses of five Brazos sequences compared with the Elles parastratotype section of Tunisia reveal the differences between open marine and shallow nearshore environments.

At Elles, the mass-extinction pattern is representative of deep shelf and open marine environments (Fig. 18). Through the latest Maastrichtian zone CF1 just a few species disappeared, although these may be local disappearances rather than true extinctions (Figs. 15–18).

Based on the maximum species richness (50), including survivors (10), a total of 80% became extinct and just 20% survived (Fig. 21A, B). All survivors are smaller species (heterohelicids, hedbergellids, globiger-inellids, guembelitrids), and only one is a long-term survivor with thriving populations (*Guembelitria cretacea*).

The contrast with the mass-extinction pattern in the shallow neritic Brazos environment is stunning, but not unexpected. Open-ocean and nearshore environments support very different planktic foraminiferal assemblages, with vastly reduced numbers of extinction-prone species in the latter. In addition, the effect of the latest Maastrichtian (zone CF1) sea-level drop in shallow environments accelerates the faunal turnover prior to the KTB. Therefore, instead of the abrupt mass extinction, species disappeared gradually through zone CF1 in Brazos (Fig. 22A, B). Among these a total of 25% of the larger species (> 150 μm) and 30% of the smaller species (> 63 μm) disappeared in the latest Maastrichtian zone CF1 below the sandstone complex, correlative with the sea-level fall. No larger species are present above the sandstone complex, and none reach the KTB (Fig. 22B). Above the sandstone complex another 20% gradually disappeared, followed by a relatively minor concentration of extinctions (~ 25%) at the KTB and 30% survivors (Fig. 22A). The survivor species are the same as in the open ocean (heterohelicids, hedbergellids, globigerinellids, guembelitrids). They reach 30% of the total assemblage because of the overall reduced total number of species in nearshore environments.

The overall extinction pattern at Brazos is gradual through zone CF1 and into the early Danian (Fig. 22A). Although significant (15–18%) variations occur among the five Brazos localities in the disappearances
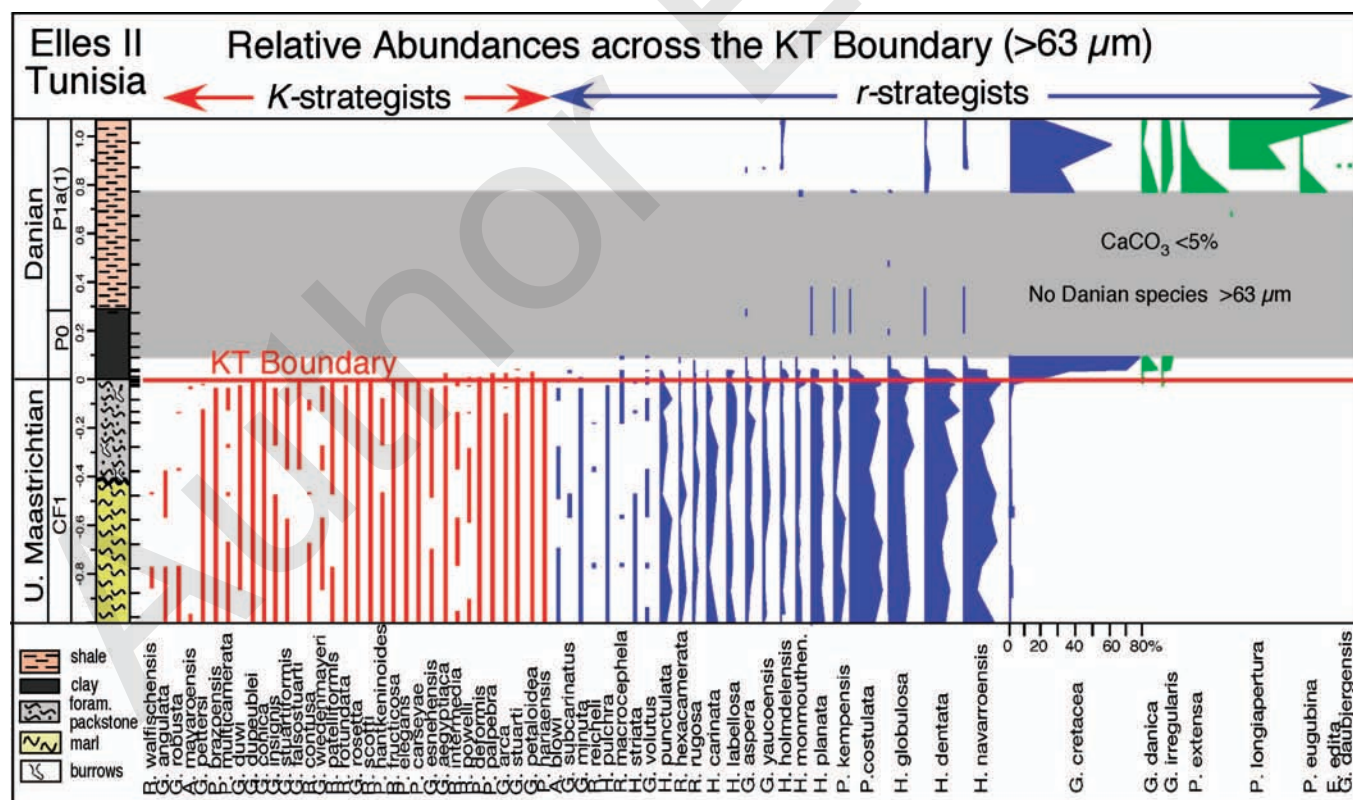

FIGURE 19.—Lithology and relative abundance of planktic foraminifera (> 63 μm) across the KTB at Elles, Tunisia. Note that just four heterohelicids dominate the uppermost Maastrichtian assemblages. Surprisingly, no Danian species > 63μm thrived in the aftermath of the KT catastrophe P0-P1a(1). However, species thrived in the smaller (38–63 μm) size fraction, indicating dwarfing as a response to high-stress conditions. (Modified from Keller et al., 2002.)

of species, primarily due to artifacts of small sample size from cores and increased shallowing towards the south, this does not change the overall gradual pattern of extinction. This gradual-extinction pattern and the stark difference between shallow and deep marine environments is also apparent at Seldja, located at the edge of the Sahara in southern Tunisia (Fig. 14) and at Nye Klov in Denmark (Keller et al., 1993; Keller et al., 1998).

Differences in the extinction patterns of deep vs. shallow marine environments are due to optimum vs. non-optimum conditions for planktic foraminiferal assemblages, rather than the actual cause of the mass extinction. Deep marine environments tend to be stable with limited nutrients—oligotrophic conditions—that favor high species diversity among foraminiferal communities, smaller populations, specialized species adapted to specific niches, slow reproduction cycles, fewer offspring, and large size (*K*-strategists) (Pardo and Keller, 2008; Keller and Abramovich, 2009). Shallow nearshore environments are inherently unstable and high stress with variations in salinity, oxygen and nutrients—dystrophic to eutrophic conditions. These environments foster low diversity assemblages of opportunistic species, usually with one or two dominant taxa in the assemblages, rapid reproduction, many offspring, large populations, and small size (*r*-strategists). In planktic foraminiferal assemblages, the main difference is thus the exclusion of the diverse, large specialized species, which are most prone to extinction and characterize the abrupt extinction pattern in the deep sea. The gradual-extinction pattern commonly observed in the shallow depositional setting is the result of climate and sea-level changes.

A number of parameters summarize the extinction patterns, including species richness, assemblage associations (*K*- and *r*-strategists), and dominant species populations. A comparison of these parameters in smaller > 63 μm and larger > 150 μm species assemblages and between shallow and deep marine environments reveals the key differences in the respective patterns of the KTB mass extinction.

Species Richness

Species richness, as well as the temporal range of species from evolution to extinction, is influenced by many factors, including ecology, shallow vs. deep water, optimum or high-stress conditions, the nature of sediment deposition, and preservation. Species living in non-optimum or high-stress environments may exhibit rare or sporadic occurrences and dwarfing that result in shortened species ranges (Signor and Lipps, 1982). Bias resulting in extended species ranges is generally associated with sediment reworking and redeposition into younger sediments by storms and currents, particularly during sea-level falls. Reworked specimens can usually be recognized by poorer preservation and discoloration of tests compared with *in situ* material.

Species richness thus reflects the environment that sustains a planktic foraminiferal community. In any given sample, species richness is generally less than the total number of species over a given interval. For example, in the middle- to outer-shelf environment during the latest Maastrichtian zone CF1 at Elles, Tunisia, the maximum number of species in the > 63 μm size fraction totals 57 species, whereas species richness per sample varies between a low of 40 and a high of 55 (Fig. 18). Thus, in the upper part of zone CF1 species richness averages 50 species, abruptly drops to 25 species at the KTB, and to just 9 or 10 survivor species within the basal 10 cm of the
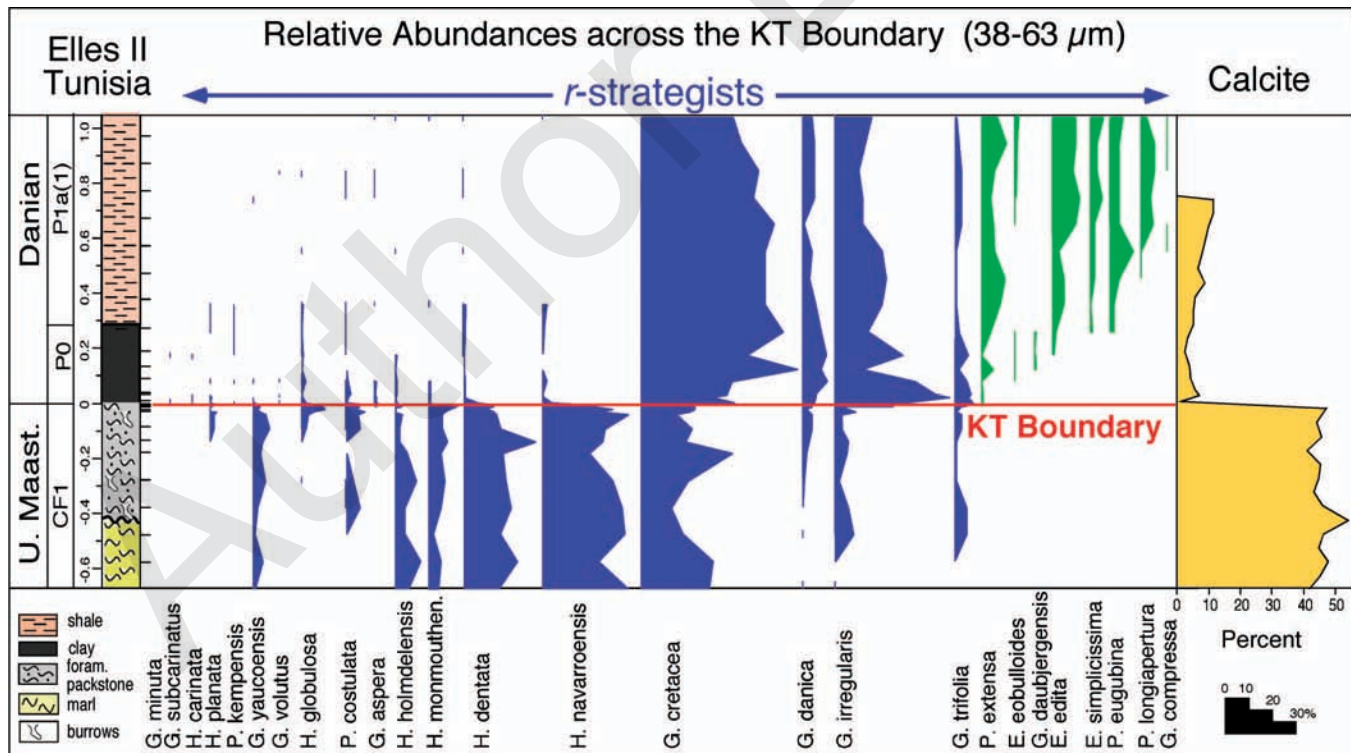

FIGURE 20.—Lithology and relative abundance of planktic foraminifera in the 38–63 μm size fraction across the KTB at Elles, Tunisia. Note the presence of abundant tiny planktic foraminifera dominated by blooms of the disaster opportunist *Guembelitria cretacea* and *G. irregularis* in the early Danian. The presence of this dwarfed faunal assemblage and exclusion of larger morphotypes indicates high-stress conditions. (Modified from Keller et al., 2002.)
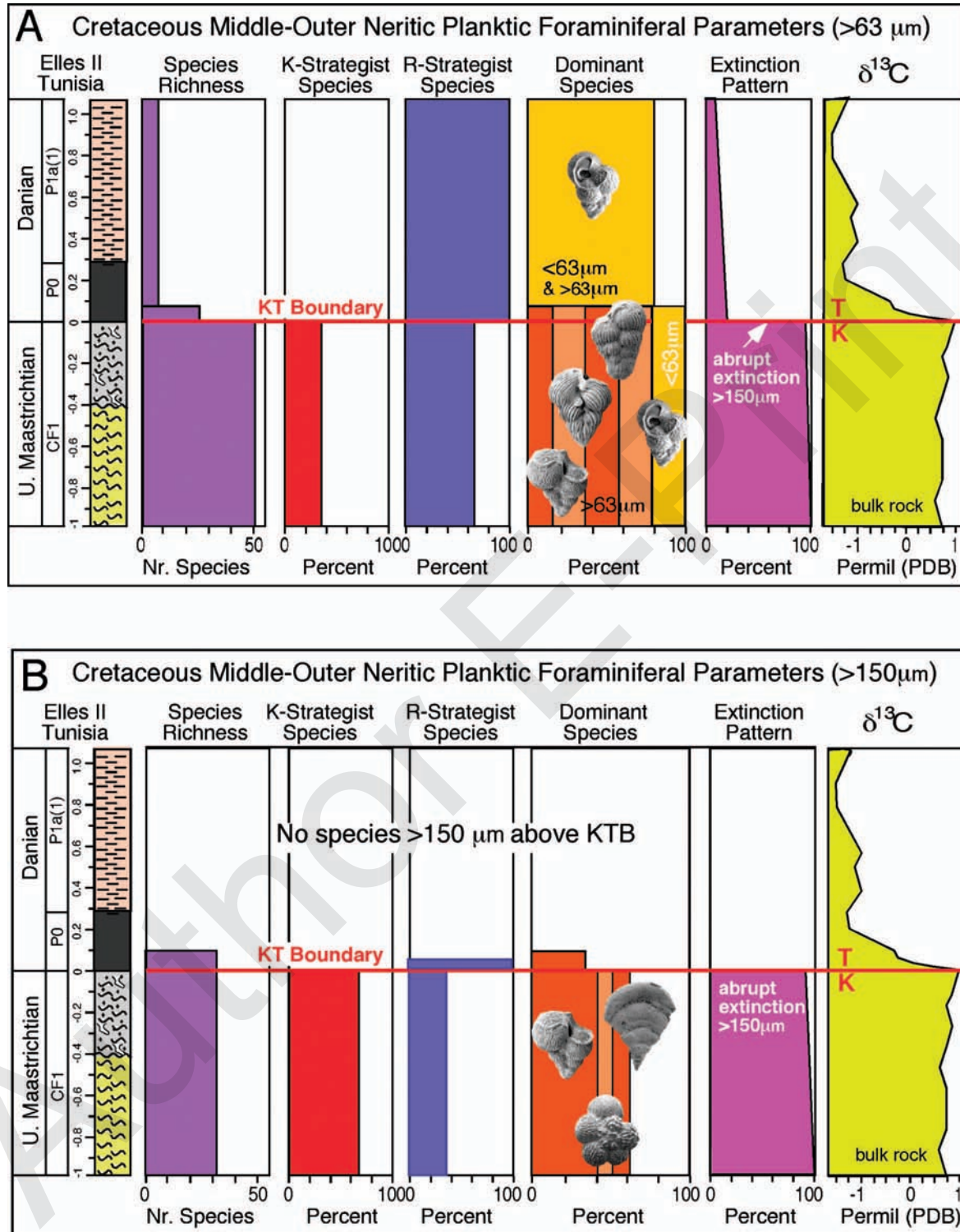
FIGURE 21.—A & B. Summary of Cretaceous species parameters in the middle- to outer-nertitic environment of Tunisia. All specialized species (*K*-strategists) went extinct at the KTB, whether in the large or small size fractions (A, B). Only smaller, ecologically tolerant (*r*-strategy) species survived for a short time, and only the disaster opportunist *G. cretacea* thrived. All species adapted to high-stress conditions by dwarfing and rapid reproduction. The mass extinction appears sudden and catastrophic.
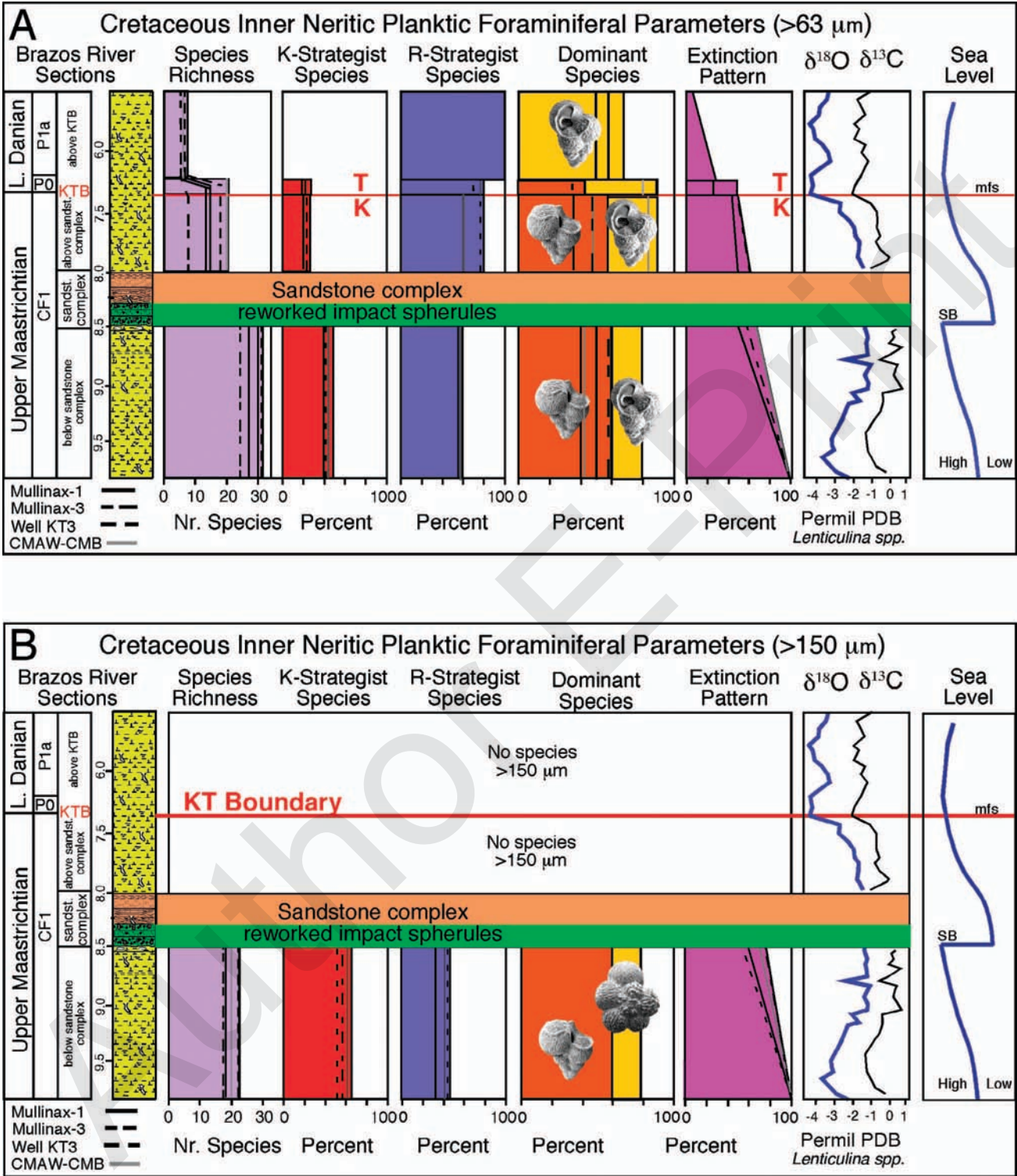
FIGURE 22.—A & B. Summary of Cretaceous species parameters in the inner-nertitic environment of Texas. (A) All larger species $>$ 150 μm (*K*-strategists and *r*-strategists) disappeared at the sea level fall ∼ 100 ky prior to the KT boundary. (B) Smaller species ($<$ 150 μm) survived and most adapted to stress conditions with dwarfed morphologies. Only the disaster opportunist *G. cretacea* and small heterohelicids thrived. The mass extinction is gradual.

boundary clay which persist into the early Danian zone P1a (Fig. 21A). In contrast, species richness in the > 150 μm size fraction averages 31 species, all of which persist to the KTB where they abruptly disappeared (Fig. 21B).

In the shallow Brazos sections the species richness pattern is significantly different and at a minimum 40% lower. Maximum species richness in zone CF1 averages between 25 and 31 species (> 63 μm) below the sandstone complex, drops to between 15–18 species between the sandstone complex and the KTB, where they persist for 10–20 cm into the early Danian, and then drop to 9 survivor species that persist into zone P1a (Fig. 22A). In the > 150 μm size fraction species richness averages between 18–22 species, all of which disappear at the unconformity at the base of the sandstone complex that contains reworked Chicxulub impact spherules. This has led some workers to place the KTB at the base of the sandstone complex based on the assumption that the Chicxulub impact hit Yucatán at the KTB and caused the mass extinction (e.g., Schulte et al., 2006; Schulte et al., 2008; Schulte et al., 2010).

By this interpretation the presence of the late Maastrichtian assemblages above the sandstone complex is interpreted as settling from the water column after the impact tsunami. This interpretation does not take into account the substantial sea-level fall during the late Maastrichtian (< 80 m, from middle- to inner-neritic depths) that culminates with the unconformity and incised valleys that are subsequently infilled with the sandstone complex (Fig. 22B; Gale, 2006; Keller et al., 2007a; Hart et al., this volume). At this time, water depth in the Brazos area reached a low of just tens of meters at the deepest with temporary emergence at Mullinax-3 to the south (Fig. 1). Only small species that tolerate unstable conditions survived in such environments (MacLeod et al., 2000; Keller and Abramovich, 2009).

Life Strategies: Opportunists and Specialists

Opportunists are species with the ability to increase their populations rapidly and dominate ecological communities when the environment changes from stable to unstable conditions. They are known as *r*-strategy species due to their reproductive strategy, consisting of early maturation and fast reproductive cycles. Few species in the planktic foraminiferal assemblages can be considered *r*-strategists (Table 1). Stable isotope depth ranking of planktic foraminifera shows that *r*-strategists lived in the ocean's surface mixed layer, which is subdivided into surface and subsurface environments (Barrera and Keller, 1990; Abramovich et al., 2003; Abramovich et al., 2010; Pardo and Keller, 2008). The most extreme opportunistic species is *Guembelitria cretacea*, a surface dweller that bloomed in high-stress environments of the late Maastrichtian and is best known from the aftermath of the KTB mass extinction (review in Pardo and Keller, 2008; Abramovich et al., 2010). Other common opportunistic species include small heterohelicids, hedbergellids, and globigerinellids (Table 1). Most *r*-strategy species tend to have large populations, dominate at times of high environmental stress, and are most abundant in shallow marine settings with unstable fluctuating conditions.

There is a continuum between *r*-strategy opportunist and *K*-strategy specialist species, from small to larger size, and simple to complex morphologies (Fig. 23). *K*-strategists are typically large (> 150 μm), with complex morphologies and surface ornamentation and low tolerance for environmental changes (e.g., globotruncanids, planoglobulinids, racemiguembelinids, and pseudoguembelinids), although many smaller species also seem to be *K*-strategists (e.g., rugoglobigerinids, globotruncanellids, and some globigerinellids and heterohelicids; Table 1). Most *K*-strategists lived in subsurface, thermocline, and subthermocline depths, and only a few were surface dwellers. Maximum diversity is observed in stable tropical–subtropical deep-sea or deep-shelf environments, where they occupied specialized ecological niches, utilized particular food sources, and reproduced

slowly with small numbers of offspring. *K*-strategists have small populations because of their narrow adaptation and low tolerance to environmental changes.

Separation of planktic foraminiferal assemblages into *r*- and *K*-strategist species provides further clues to the nature of the mass extinction in shallow vs. deep environments. At Elles in zone CF1, 66% of the larger species (> 150 μm) are *K*-strategists and all disappear at the KTB, and 34% are *r*-strategists (Figs. 17, 21B). In the smaller size fraction (> 63 μm) 36% are *K*-strategists and all of them are rare and sporadically present and disappear at or below the KTB (Figs. 19, 21A). In contrast, *r*-strategists comprise 64% of the assemblages in zone CF1 and 100% in the early Danian zone Pla (Fig. 21A). The absence of *K*-strategists in the Danian reflects the continued high-stress environment after the mass extinction.

In the shallow Brazos sections the proportions of *K*- and *r*-strategists are surprisingly similar. Between 55–66% in the > 150 μm are *K*-strategists, and between 33–45% are *r*-strategists below the sandstone complex, where they disappear (Fig. 22B). In the smaller species (> 63 μm) below the sandstone complex 40–44% are *K*-strategists and 56–60% are *r*-strategists. Above the sandstone complex 20–22% are *K*-strategists and 78–80% are *r*-strategists, and these proportions remain up to the KTB. Above the KTB all species are *r*-strategists (Fig. 22A, B).

The similarities in percentage of *r*- and *K*-strategists between the deep-shelf Elles and shallow-neritic Brazos sections during the latest Maastrichtian is misleading. At Elles, most *K*-strategists are consistently present and relatively common, indicating optimum habitats (Figs. 16–18). In contrast, at Brazos they are very rare, sporadically present with shortened ranges, and generally small, dwarfed, or immature specimens (Figs. 6–13). This can be explained by high stress conditions in the absence of optimum (deep water) habitats for *K*-strategists. Their presence in inner-neritic environments may be due to current transport into the shallow Brazos environment.

Dominant Species Populations

Relative abundance patterns of planktic foraminiferal species are primary indicators of environmental conditions. Dominant species tend to thrive in optimum conditions. By their very nature, rapid reproduction, and large numbers of offspring, ecological generalists (*r*-strategists) dominate assemblages. Once optimum conditions pass, generally due to depletion of nutrients, populations decline rapidly. In general, planktic foraminiferal assemblages of small (> 63 μm) or larger (> 150 μm) species across latitudes and in shallow to deep-sea environments are dominated by 1–4 *r*-strategist species. The specialized niches of *K*-strategists consistently allow only small populations in their optimum deep-sea environments and across latitudes.

For example, at Elles *H. globulosa* is the dominant species in the larger (> 150 μm, 40%) size fraction (Fig. 21B). Among *K*-strategists only *R. rugosa* and *P. nutalli* reach 10% and 15%, respectively (Fig. 17). All other *K*-strategists have very small populations (1% to 5%) in CF1, although some are more common in CF2 and CF3 (*G. gansseri, G. arca, G. mariei, T. scotti, P. deformis*) reflecting more optimum conditions in the early late Maastrichtian (Fig. 17). In the > 63 μm size fraction, four *r*-strategists dominate, though with significant long-term variations (*H. globulosa, H. navarroensis, H. dentate/planata, P. costulata)* that reflect environmental changes (Fig. 16). In zone CF1, *H. globulosa* averages 15% and the other three species 20% each (Fig. 19), and all decreased abruptly at the KTB, coincident with the onset of *Guembelitria* blooms (80%). Very rare foraminifera are present in the interval from 10–80 cm above the KTB, which contains only 5% $CaCO_3$. Dramatically reduced test sizes caused by species dwarfing suggest that the reason is not dissolution or poor preservation, but rather high-stress conditions. This is evident in the abundance of
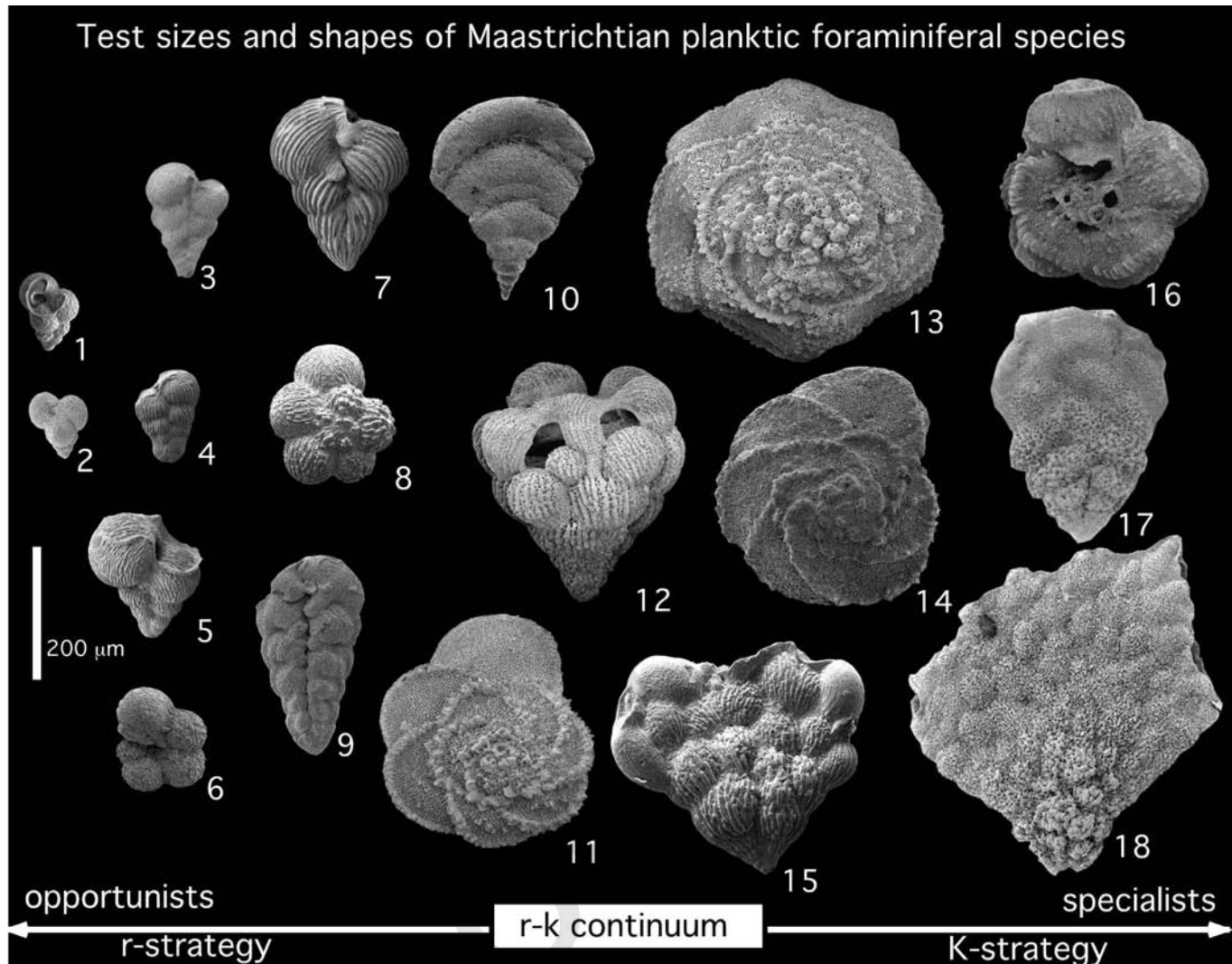
FIGURE 23.—Test sizes and shapes of Maastrichtian planktic foraminifera form a continuum from the small opportunistic *r*-strategy species to the large and highly specialized *K*-strategists. The extinction of the latter marks the KTB event, whereas some *r*-strategists survived into the Danian with *G. cretacea* the sole long-term survivor. (Modified from Keller and Abramovich, 2009.)

planktic foraminifera in the smaller size fraction (38–63 μm), where *Guembelitria* blooms average 80%. But *Guembelitria* are also common in the smaller size fraction in zone CF1, where they reach 30% of the assemblages, along with *H. navarroensis* (30%) and *H. dentata* (20%) (Figs. 20, 21A). Thus, planktic foraminifera at Elles show distinctly different abundance patterns among *K*- and *r*-strategists in small and larger species assemblages, with *r*-strategists always dominant, as would be expected given the opportunistic nature of these species.

Dominant species of the shallow Brazos sections show strong similarities with the deeper Elles section although abundances of opportunistic species tend to be significantly higher (Fig. 22A, B). In the > 150 μm fraction, *H. globulosa* averages 60%, as compared with 40% at Elles, and *R. rugosa* averages 20% as compared with 10% at Elles (Figs. 21B, 22B). In the > 63 μm fraction, *H. globulosa* averages between 40–60% at Brazos, but only 15% at Elles, where *H. navarroensis, H. dentate, H. planate*, and *P. costulata* are slightly more abundant. In both shallow and deep environments, however, *Guembelitria* blooms average 20–30% in zone CF1 and become the

dominant opportunistic species in the early Danian. Dominant populations thus highlight the similarities in opportunistic species in shallow and deep environments.

Chicxulub Impact and KTB Mass Extinction

Three decades of strong media support for the impact-kill theory has firmly entrenched the popular belief that the Chicxulub impact caused the mass extinction of dinosaurs and many other organisms. Most recently, this claim was reaffirmed by a group of 41 scientists, though none of them experts in many of the organismal groups that their claim encompassed. They concluded that the original theory of 1980 was right—a large asteroid impact on Yucatán was the sole cause of the KT catastrophe (Schulte et al., 2010). To arrive at this conclusion, these authors used a rather selective review of data and interpretations offered by proponents of this viewpoint, but they ignored the vast body of evidence accumulated by scientists across disciplines (paleontology,

stratigraphy, sedimentology, geochemistry, geophysics, volcanology) that documents a complex long-term scenario involving impacts, volcanism, and climate change that is inconsistent with their conclusion. How did they arrive at this conclusion?

The underlying basis for this conclusion is the *assumption* that the iridium anomaly at the KT boundary and Chicxulub are genetically linked and therefore the same age. There is no evidence to support this assertion. No Ir anomaly has ever been identified in association with undisputed Chicxulub impact ejecta (impact glass spherules) and no impact spherules have ever been identified in the Ir-enriched KTB clay in Mexico or elsewhere (review in Keller, 2008). In fact, impact-spherule layers are found in early Danian zone P1a sediments in the Caribbean, Haiti, Belize, Guatemala, and southern Mexico, in the submarine channel sandstone complex in northeastern Mexico and Texas, with an additional (original) impact-spherule layer in still deeper late Maastrichtian sediments in northeastern Mexico and Texas, but never at the KTB mass extinction (Keller et al., 2001; Keller et al., 2003a; Keller et al., 2003b; Keller et al., 2007a; Keller et al., 2009a; Keller et al., 2009b). Additional evidence for a pre-KTB age of the Chicxulub impact is also found in the lithified clasts with impact spherules found at the base of the sandstone complex in Brazos, Texas, sections (Keller et al., 2007a). In rare deep-sea sites (e.g., Blake Nose, Bass River, Demerara Rise; Olsson et al., 1998; Norris et al., 1999; Norris et al., 2000; MacLeod et al., 2007) where the Ir anomaly is just above impact spherules, this is due to condensed sedimentation, nondeposition, and/or erosion. For example, on Blake Nose Site 1049 and probably also Bass River, New Jersey, early Danian zone P1a assemblages are present in the spherule layer, which indicates that the impact spherules are reworked from an older deposit and redeposited in early Danian sediments. A major KTB hiatus is present in these localities with the lower Danian, P0 and P1a(1), and the uppermost Maastichtian zones CF1 and CF2 missing (Keller et al., in prep.). Impact spherules are commonly found reworked in early Danian sediments throughout the Caribbean, Haiti, Cuba, Belize, Guatemala, and southern Mexico (Keller et al., 2003; Keller, 2008). Therefore, the juxtaposition of impact spherules with Danian sediments does not support a KTB age for the Chicxulub spherules or an impact-mass extinction scenario.

Indeed, how could such a complex pattern of multiple impact spherules in Danian and late Maastrichtian sediments be explained as an impact at the KTB? The underlying basis is the definition of the Chicxulub impact as KTB in age and assumption that any impact ejecta therefore marks the KTB. This circular reasoning was then justified by pseudo-empirically correlating the impact-spherule layer with the Ir anomaly at the El Kef stratotype, a correlation that is demonstrably unjustified on any scientific grounds (Arenillas et al., 2006; Molina et al., 2006; Schulte et al., 2006; Schulte et al., 2008; Schulte et al., 2010). Which of the multiple spherule layers in the late Maastrichtian and early Danian would satisfy such a correlation? Some workers chose an early Danian zone P1a spherule layer in southern Mexico (Bochil section), others chose the multiple spherule layers at the base of the sandstone complex in northeastern Mexico. The former was justified on the basis of correlation of the overlying Danian zone P1a assemblages with El Kef and the latter based on the impact-tsunami interpretation. Neither represents the KTB. The impact-tsunami interpretation has long been shown to be unsupportable based on multiple horizons of bioturbation within the sandstone complex and a limestone layer that separates two impact-spherule layers at the base. Both sedimentary features indicate long-term deposition rather than a tsunami event. Older Maastrichtian spherule layers 4–9 m below the sandstone complex were dismissed as slumps or liquefaction (e.g., sinking of spherules into deeper sediments), although the spherule layer parallels horizontal stratification traceable over 90 m and no large slumps are present (Keller et al., 2009b).

Evidence for the age of the Chicxulub impact is consistent from the impact-crater core Yaxcopoil-1 on Yucatán to northeastern Mexico and Texas. In each locality, Chicxulub impact ejecta (glass spherules, suevite breccia in the crater core) underlies the KTB in zone CF1 (Ward et al., 1995; Keller et al., 2004a; Keller et al., 2004b; Keller et al., 2007a; Keller et al., 2009a; Keller et al., 2009b). This triple confirmation cannot be accidental—the Chicxulub impact predates the KTB mass extinction. Faunal analysis across the late Maastrichtian impact-spherule layer at El Peñon and in Brazos sections reveals that not a single species went extinct and no significant abundance changes occurred in species populations as a result of the Chicxulub impact (Fig. 9; Keller et al., 2009a).

This result is surprising only because we have assumed that the Chicxulub impact caused the mass extinction. Was it reasonable to assume that an impact that left a crater 150–175 km in diameter would cause a major mass extinction, when impact craters of 100 km (Popigai and Chesapeake) and larger (Alamo, Woodleigh, Manicouagan) caused no extinctions whatsoever (see review in Keller, 2005)? Consider also that there is no evidence that impacts caused any of the other four major Phanerozoic mass extinctions, but massive volcanic eruptions are associated with four of them, including the KTB mass extinction (Courtillot, 1999; Wignall, 2001; Keller, 2005; Keller et al., 2009c; Keller et al., 2009d). The sum total of a vast database on the Chicxulub impact does not support either a KTB age for this impact or major extinctions and global environmental destruction. Deccan volcanism is the only other known catastrophe at the end of the Maastrichtian, and emerging evidence strongly indicates that this underestimated catastrophe was the real killer.

CONCLUSIONS

- *KT boundary:* The Brazos sections contain some of the most complete and continuous sedimentary records equivalent to the El Kef stratotype, with the added advantage of Chicxulub impact spherules, which permit dating of this event relative to the KTB mass extinction. The KT boundary is identified based on the mass extinction, the first appearance of Danian species, and the $\delta^{13}C$ shift. No clay layer, Ir anomaly, or impact spherules mark the KTB in the Brazos sections. Minor Ir concentrations are associated with condensed sedimentation within or above the sandstone complex.

- *Sandstone complex:* The sandstone complex infills submarine channels, or incised valleys, and varies in thickness depending on the position within the channel. A well-developed complex contains two to three upward-fining glauconite-rich impact-spherule layers grading into fine sand. A hummocky cross-bedded sandstone with large burrows truncated at the top overlies the spherule unit. Laminated fine sand-silt layers mark the top and may contain minor Ir concentrations. Up to 1 m of dark gray claystone with late Maastrichtian zone CF1 planktic foraminiferal assemblages separates the sandstone complex from the KT boundary.

- *Impact spherules:* The two to three upward-fining glauconite-rich impact-spherule layers overlie a scoured base with lithified clasts containing impact spherules eroded from an older spherule deposit. This indicates primary fallout of impact ejecta occurred at an earlier time, followed by lithification, erosion, and redeposition at the base of the sandstone complex. These clasts provide very strong evidence that the Chicxulub impact hit Yucatán well before the KTB. A yellow clay consisting of altered impact glass (cheto smectite) may represent the original impact layer in the Cottonmouth Creek section in claystone 45–60 cm below the sandstone complex. The estimated age of the Chicxulub impact is early to middle zone CF1.

- *Mass extinction:* Analysis of the shallow-water Brazos sequences across the KTB reveals a very gradual mass-extinction pattern in planktic foraminifera. This pattern contrasts strongly with the mass extinction in open marine environments, such as the parastratotype

section at Elles in Tunisia. Comparison of various extinction parameters, such as overall species richness, species abundances, life strategies, and separation into opportunists vs. specialists, reveals that the high-stress conditions of shallow nearshore environments excluded the specialized larger and deeper-dwelling species that suffered the most abrupt mass extinction at the KTB. As a result the mass extinction appears much less severe and even gradual compared with open ocean environments.

• *Age and effects of Chicxulub?* Brazos sections show that the Chicxulub impact predates the KTB, corroborating the earlier results from northeastern Mexico and the Chicxulub impact-crater core. There is no evidence that Chicxulub contributed to the KTB mass extinction. Faunal analysis across the primary impact-spherule layer in Texas and Mexico reveal that this impact caused no species extinctions, no significant species population changes, or any long-term environmental changes.

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