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Cretaceous-Tertiary boundary planktic foraminiferal mass extinction and biochronology at La Ceiba and Bochil, Mexico, and El Kef, Tunisia

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ABSTRACT

Micropaleontology studies across the Cretaceous-Tertiary (K-T) boundary from sections at La Ceiba, Bochil, Mexico, and El Kef, Tunisia, suggest a close cause and effect relationship between the Chicxulub impact and the K-T planktic foraminiferal mass extinction. The K-T planktic foraminiferal biostratigraphy and assemblage turnover in Mexico was examined and the approximate deposition timing of K-T-related material (clastic unit) was estimated. On the basis of established biomagnetochronologic calibrations, the first appearance datum (FAD) of *Parvularugoglobigerina longiapertura* occurred ~3.5–5 k.y. after the K-T boundary, and the FADs of *Parvularugoglobigerina eugubina*, *Eoglobigerina simplicissima*, and *Parasubbotina pseudobulloides* occurred ~15–17.5 k.y., ~28–31 k.y., and ~45–55 k.y., respectively, after the K-T boundary. According to estimated average sedimentation rates and estimated age, the K-T red layer at El Kef was probably formed in <20 yr and the deposition of the K-T clastic unit in the Gulf of Mexico was geologically instantaneous. The last appearance of most Maastrichtian species is just below the K-T impact-generated bed, clearly implying a catastrophic planktic foraminiferal mass extinction.

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INTRODUCTION

The Cretaceous-Tertiary (K-T) boundary Global Stratotype Section and Point (GSSP) was officially defined at the El Kef section (Tunisia) at the base of a clay layer anomalously rich in iridium (Cowie et al., 1989). The placement of the K-T boundary in Europe and in North Africa is clear because the base of the boundary clay and the impact evidence coincide with the mass extinction of Maastrichtian planktic foraminifera. Most specialists agree that planktic foraminifera at the K-T boundary underwent a mass extinction. However, there is still a controversy about whether the extinction occurred instantaneously or more gradually. Nevertheless, the main planktic foraminiferal extinction coincides biostratigraphically with the K-T boundary in addition to the impact evidence at Tethyan sections (Alvarez et al., 1980; Smit and Hertogen, 1980; Smit, 1982), where the placement of the K-T boundary is unambiguous.

The placement of the K-T boundary in the Gulf of Mexico is more difficult because the deposits in this area are more complex and the boundary is marked by a clastic deposit, the nature and timing of which are controversial. The base of the clastic deposit is usually marked by a layer rich in millimeter-size microspherules, normally interpreted as altered microtektites from the Chicxulub impact crater (Smit et al., 1992a, 1992b, 1996). For this reason, most specialists place the K-T boundary at the base of the clastic bed (Hansen et al., 1987; Bourgeois et al., 1988; Smit et al., 1992b, 1994, 1996). However, others place it above the clastic deposits because the boundary clay and Ir anomaly—one of the main criteria used for K-T boundary placement—are also above them (Keller et al., 1993, 1994a; Stinnesbeck et al., 1993, 1994; Stinnesbeck and Keller, 1996). These last authors interpret that the main planktic foraminiferal extinction also occurs in this horizon, suggesting that the Chicxulub impact and K-T mass extinction do not coincide. Using sedimentological, micropaleontological, and paleoichnological criteria, they proposed that the clastic deposits are the result of successive sea-level lowstands over several thousands of years.

The timing of clastic deposition must be clarified in order to establish whether the clastic deposits were deposited in one event (Smit et al., 1996) or several different events (Stinnesbeck et al., 1993; Keller et al., 1994a; Stinnesbeck and Keller, 1996). Previous studies of planktic foraminiferal biostratigraphy at the most expanded and continuous K-T boundary sections in Spain (Caravaca, Agost, Zumaya) and Tunisia (El Kef, Aïn Settara, Elles) helped to evaluate the continuity and thickness of the K-T sections and correlate biozones and sections (Molina et al., 1998; Arenillas et al., 2000a). In this chapter we consider the K-T boundary at La Ceiba and Bochil in order to examine K-T planktic foraminiferal biostratigraphy and assemblage turnover in Mexico and approximately calibrate the timing of clastic deposition. We compared the findings with the El Kef stratotype (Tunisia) in order to analyze the planktic foraminiferal extinction pattern across the K-T boundary and its possible cause and effect relationship to the Chicxulub impact event.

LOCATION AND STRATIGRAPHY

La Ceiba, Mexico

The La Ceiba section crops out ~7 km south of La Ceiba (Avila Camacho), along the road from La Ceiba to Tlaxcalantongo, in the State of Veracruz (central-eastern Mexico). Here, the K-T boundary is marked by a >1-m-thick clastic unit, intercalated between two pelagic marly units (Méndez and Velasco Formations). Arz et al. (2001) divided this clastic unit into four different subunits according to their texture and architectural characteristics. (1) A basal subunit of calcareous marls is rich in shocked quartz and millimeter-size spherules, altered to clay minerals, most likely representing microtektites (Smit et al., 1992a, 1992b, 1996) as well as bioclasts of shallow-water origin. (2) A second subunit is a 25-cm-thick body of medium-grained sandstone of tabular geometry and a slightly channeled base that displays abundant parallel lamination. (3) The third subunit is composed of a single body of medium- to fine-grained sandstone that has tabular geometry; some internal erosive surfaces separate ~15–20-cm-thick tabular strata, and the subunit exhibits parallel- and cross-lamination, trough cross-stratification, current ripples, and climbing ripples. (4) An upper subunit is a tabular body of fine-grained sandstones, exhibiting parallel and low-angle cross-lamination, asymmetric ripples, and burrow traces on the top. The second and third subunits could correspond to the Unit II in Smit et al. (1996) and fourth subunit to the Unit III. Just above the last clastic bed is a 20-cm-thick subunit of marl, clay, or silt alternating with millimeter-size fine sands. This subunit has Paleocene planktic foraminifera and must be included in the Velasco Formation.

The clastic unit displays a general fining upward, similar to a turbidite sequence (i.e., tends to fine upward) (Fig 1). The sedimentological features support an impact-generated sediment gravity flow at lower bathyal depths, deeper than 1000 m according to benthic foraminiferal assemblages. The clastic unit was deposited under a high sedimentation rate in upper flow regimes and placed in a single-pulse event as turbidites (Arz et al., 2001).

Bochil, Mexico

The Bochil section is ~9 km northeast of the town of Bochil along the road to the PEMEX Soyalo-1 well, in the State of Chiapas (southern Mexico). Here, the K-T boundary has an upward-fining clastic sequence that can be subdivided into three main subunits (Fig 1): (1) a >60-m-thick basal clast-supported coarse carbonate breccia containing blocks of as much as 2 m in diameter, followed by (2) a 4-m-thick medium-grained breccia, including a 2-m-thick bed containing round calcareous objects in a whitish matrix (altered ejecta?), and (3) an ~2-m-thick sandstone to claystone subunit. This section is similar to the one in Guayal, Tabasco, described by Grajales-Nishimura et al. (2000).

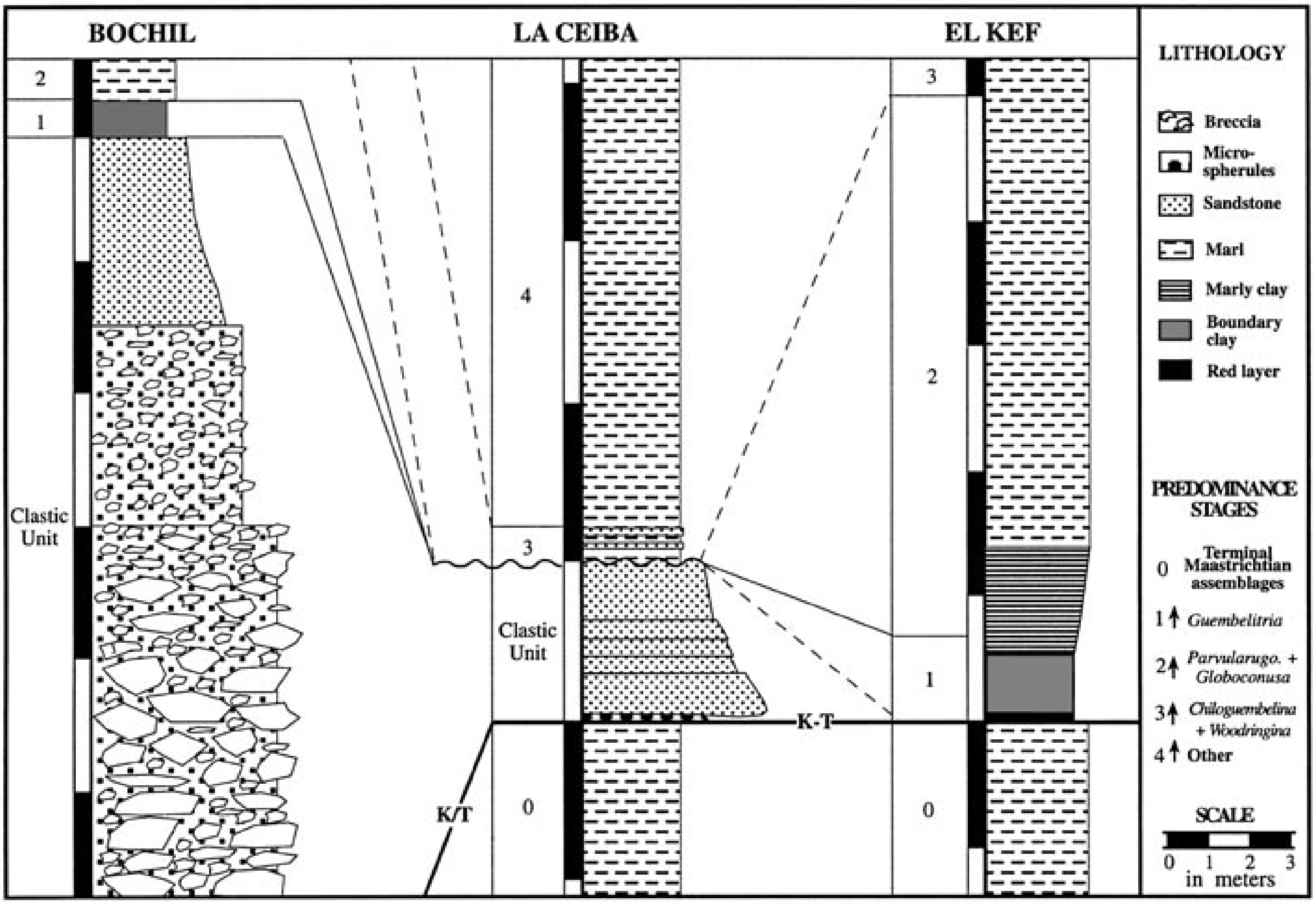

Figure 1. Stratigraphic columns of Bochil, La Ceiba, and El Kef sections across Cretaceous-Tertiary (K-T) boundary, showing planktic foraminiferal predominance stages.

The source of the particles forming the breccia and sandstone units is variable. The lower part of the breccia of subunit 1 is made of clasts containing rudist fragments and larger foraminifera such as *Vaughanina cubensis*, *Orbitoides media*, *Asterorbis aguayoi*, *Sulcoperculina globosa*, *Smoutina* spp., and *Aktinorbitoides* spp., typical of platform margins (Rosales-Domínguez et al., 1997). Some fragments appear to be rip-ups of Maastrichtian sediments eroded during the deposition of clasts from the platform. The clasts of the upper part of this subunit contain alveolinids such as *Chubbina jamaicensis* and miliolids typical of lagoonal environments. Even though the matrix is very scarce, we identified *Globotruncana mariei*, *Rugoglobigerina* spp., *Heterohelix* spp., and the larger foraminifera *Chubbina jamaicensis* and *Orbitoides media*. The breccia of subunit 2 comprises fragments with mostly alveolinids and miliolids, similar to the upper part of subunit 1. The sandstone of subunit 3 has many fragments of loose benthic foraminifera, altered glass fragments, and shocked quartz (Grajales-Nishimura et al., 2000). An Ir anomaly was found in the clay on the top part of this subunit (Montanari et al., 1994).

We interpret that the basal coarse breccia (subunit 1) represent a gravity-flow deposit formed by seismic shacking, triggered by the impact at Chicxulub. Fragments of the platform margin were deposited first, followed by fragments from the inner platform, lagoon environments. Subunits 2 and 3 were originated by a combination of mechanisms, including ballistic sedimentation (ejecta deposits), later reworked and mixed with local material by the backwash of the tsunamis. The Ir-bearing uppermost part of subunit 3 represents the waning stage of turbulent flow when sediments were deposited by the settling of fine-grained suspensions. Stratigraphic and micropaleontological studies support this interpretation.

El Kef, Tunisia

The El Kef section is ~7 km west of El Kef, northwestern Tunisia. This section was officially designated the Cretaceous-Paleogene (K-P) boundary GSSP (Cowie et al., 1989). The K-T boundary was defined at the base of a 50–60-cm-thick marly clay layer (Fig 1), which is intercalated between Maastrichtian and Danian pelagic marly sediments (El Haria Formation). The clay layer has a drop in $CaCO_3$, a maximum of organic carbon, and a negative excursion in $\delta^{13}C$ (Keller and Lidinger, 1989). A 2–3-mm-thick rust-red layer at the base of this clay unit marks the boundary event. This red layer also has an Ir anomaly, crystalline microspherules (altered microkrystites), Ni-rich spinels, and shocked minerals (Smit and Klaver, 1981; Smit, 1982; Robin et al., 1991; Robin and Rocchia, 1998).

The red lamina represents the direct fallout layer of the impact event (Smit, 1982). Small microkrystites identified at El Kef and in other Tethyan sections are finely crystallized, altered to K-feldspar or goethite spherules (Smit and Klaver, 1981; Smit et al., 1992a; Martínez-Ruiz et al., 1997), and were probably derived from the Chicxulub impact. Biostratigraphic data indicate that the red layer with microkrystites from Tethyan sections and the microtektite layer from Gulf Coast sections are geologically isochronous (Arenillas et al., 2000d). Moreover, K-T boundary impact glass in Beloc (Haiti) and El Mimbral (Mexico) sections and melt rock from the Chicxulub impact structures are geochemically and isotopically similar (Sigurdsson et al., 1991; Smit et al., 1992b; Blum et al., 1993), indicating a similar origin. The $^{40}Ar/^{39}Ar$ dating shows that the Chicxulub crater melt rock and K-T boundary microtektites have the same age and that the age of the K-T boundary is 65 Ma (Swisher et al., 1992).

BIOSTRATIGRAPHY AND ASSEMBLAGE TURNOVER

We considered five biozones: *Abathomphalus mayaroensis*, *Plummerita hantkeninoides* (Cretaceous), *Guembelitria cretacea*, Parvularugoglobigerina *eugubina*, and *Parasubbotina pseudobulloides* (Tertiary). The base of each of these biozones is placed at the FAD of the eponymous species, except for the base of *G. cretacea*, which was placed at the last appearance datum (LAD) of *A. mayaroensis*, precisely at the K-T boundary (Molina et al., 1996). Because *P. eugubina* and *P. longiapertura* are considered synonyms by some authors (Smit, 1982; Berggren et al., 1995), the *P. longiapertura* FAD has frequently been used to situate the top of the P0, which is not completely equivalent to the *P. eugubina* biozone used by Arenillas and Arz (2000). These five biozones were recognized at El Kef. At La Ceiba, a hiatus affects the lower part of the Danian (Arz et al., 2001), including the *Guembelitria cretacea* and *Parvularugoglobigerina eugubina* biozones and the lower part of the *Parasubbotina pseudobulloides* biozone. At Bochil, we only studied the lower part of the *G. cretacea* biozone (approximately the P0 zone and the lower part of P1 zone).

Terminal Maastrichtian planktic foraminiferal assemblages were very abundant and diverse at La Ceiba (Gulf of Mexico) and El Kef (Tunisia, Tethys). There are 67 species at El Kef and 63 species at La Ceiba (Arenillas et al., 2000b; Arz et al., 2001). One species (1.6%) at El Kef disappears in the last meter of the Maastrichtian, 46 (74.1%) species extinct at the K-P boundary, and 15 (24.2%) range into the earliest Danian (Arenillas et al., 2000b). At La Ceiba, nearly all Maastrichtian planktic foraminiferal species are found in the last Maastrichtian sample, with no support for a gradual mass extinction pattern in the terminal Cretaceous (Arz et al., 2001). At Bochil, the contact between upper Maastrichtian hemipelagic marl and limestone and basal coarse carbonate breccia (subunit 1) could not be observed. As a result, we could not analyze the planktic foraminiferal biostratigraphy and extinction pattern across the uppermost part of the Maastrichtian.

This catastrophic mass extinction is the largest and most sudden extinction event in the history of planktic foraminifera. It also consistently coincides with the possible catastrophic effects caused by the impact of a large asteroid (Smit, 1982; Molina et al., 1998). Furthermore, there is an evolutionary radiation of planktic foraminifera in the earliest Danian. This radiation always begins above the K-T boundary and never below, which is very consistent with the impact theory. Figure 2 shows planktic foraminiferal ranges from subtropical-temperate sections (Molina et al., 1998; Arz, 2000; Arenillas, 2000) and indicates the probable worldwide model of planktic foraminiferal mass extinction across the K-T boundary. The only species that went extinct just below the K-T boundary were probably *Archaeoglobigerina cretacea* and *Gublerina acuta*. Other Cretaceous species, such as *Archaeoglobigerina blowi* or *Contusotruncana walfischensis*, seem to disappear in some sections before the K-T boundary. However, these pre-K-T disappearances may be local or the remaining Signor-Lipps effect (Molina et al., 1998; Arz, 2000; Arenillas et al., 2000c).

Danian planktic foraminifera evolve sequentially in continuous sections of the K-T boundary. Because these gradual Tertiary species appear over an extensive stratigraphic interval in the lower Danian from El Kef, this section is considered one of the most continuous and expanded marine K-T boundary sections known at the Tethys (Cowie et al., 1989; Keller et al., 1995). A comparison of Tethyan and Gulf coast sections helps to identify four stages in the planktic foraminiferal population in the lowermost Danian (see Arenillas et al., 2000a, 2000c). The lowermost assemblages were dominated successively by *Guembelitria* (stage 1), Parvularugoglobigerina and *Globoconusa* (stage 2), *Chiloguembelina* and *Woodringina* (stage 3), and *Eoglobigerina*, *Parasubbotina*, *Praemurica*, and *Globanomalina* (stage 4). Figure 3 shows the correlation between planktic foraminiferal stages and biozones. The infaunal benthic foraminiferal species underwent a general Lazarus effect across stages 1 and 2 (Alegret et al., 2001). The identification of these stages may help to quantify the size of the hiatus across the K-T boundary because they do not involve problematic taxonomic species assignments.

All stages were identified in the El Kef stratotype (Fig. 4; Arenillas et al., 2000b). However, stages 1 and 2 were not identified at La Ceiba (Fig. 5; Arz et al., 2001) and stages 3 and 4 were not studied at Bochil. The simultaneous first appearances of Tertiary planktic foraminifera at La Ceiba mark a hiatus that affects the lower part of the Danian, impeding investigation of the FADs and LADs of possible Maastrichtian survivors and

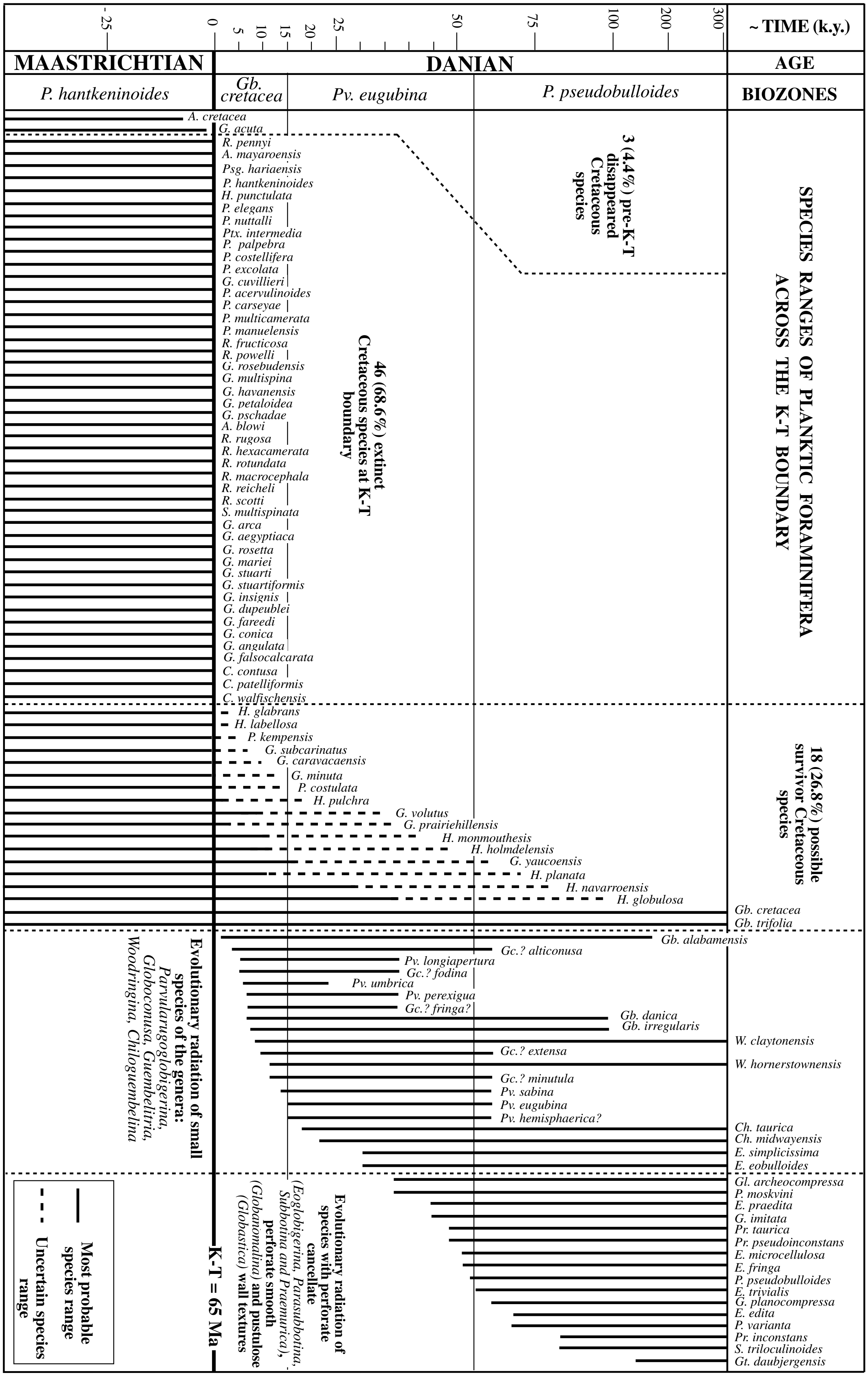

Figure 2. Planktic foraminiferal ranges from subtropical-temperate sections by Arenillas (2000), Arz (2000), and Molina et al. (1998), and probable Cretaceous-Tertiary (K-T) planktic foraminiferal extinction and evolutionary models.

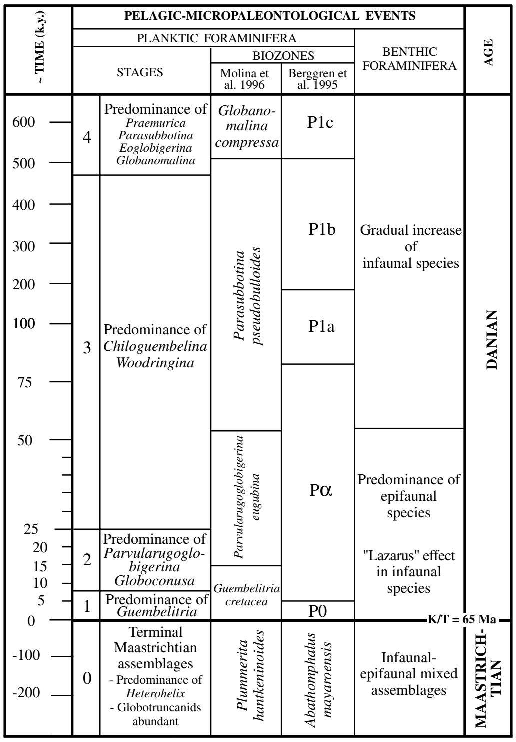

Figure 3. Correlation among planktic foraminiferal predominance stages, biozones, and benthic foraminiferal events. K-T is Cretaceous-Tertiary.

new Danian species. A shorter hiatus has been also identified at other Mexican sections such as El Mimbral and El Mulato (López-Oliva and Keller, 1996; López-Oliva et al., 1998). However, the two first Danian stages were identified at Bochil just above the clastic sequence (Fig. 6). Here, stage 1 and the P0 biozone (lower part of *G. cretacea* biozone) approximately coincide with the clay—anomalously rich in Ir—at the top of impact-derived breccia and sandstone.

BIOMAGNETOCHRONOLOGY

The biomagnetostratigraphic correlation of planktic foraminifera with geomagnetic polarity scales was used to develop a geologic time scale and, ultimately, a magnetobiochronology framework. Using this we approximated the sedimentation rate of the sections and absolute age of the FADs of index taxa (Kent, 1977; Smit et al., 1996). The K-T boundary is near the upper middle part of C29r (Lowrie and Alvarez, 1981) and is ca. 65 Ma (Swisher et al., 1992). According to biomagnetochronology studies by Robaszynski and Caron (1995), Gradstein et al. (1995), and Berggren et al. (1995), the base of C29r is 578 k.y. before the K-T boundary, ca. 65.578 Ma, and the top of C29r is 255 k.y. after the K-T boundary, ca. 64.745 Ma. The base of the three first Tertiary biozones is between the K-T boundary and the top of C29r. A biomagnetostratigraphic calibration of the K-T events is possible by correlating the magnetostratigraphic studies of the most expanded and continuous sections in Spain, such as Caravaca, Agost, and Zumaya (Roggenthen, 1976; Smit, 1982; Groot et al., 1989): the sedimentation rates in the basal part of the Danian were ~2.00 cm/k.y., 0.85 cm/k.y., and 1.31 cm/k.y., respectively. The sedimentation rates in the upper part of the Maastrichtian at Caravaca and Agost were ~2.02 cm/k.y. and 1.00 cm/k.y. respectively. Nevertheless, the sedimentation rate in the boundary clay of the three sections must be very similar, probably <0.8 cm/k.y., because the boundary clay has a similar thickness in the three sections (Kaiho et al., 1999; Arenillas, 2000).

It is obvious that the sedimentation rate fluctuated with time. The boundary clay sedimentation was slower than normal Maastrichtian and Danian pelagic marly sediments in Spain, Tunisia, and Mexico. This is due to the decrease in oceanic productivity and flux of biogenic components (Keller and Lidinger, 1989; Arz et al., 1999). However, the rust-red layer sedimentation rate could be greater than that of the boundary clay, because the former includes worldwide dispersed ejecta (iridium-rich dust, shocked minerals, and microspherules). The sedimentation rates in the clastic unit at both Bochil and La Ceiba was evidently much larger. We can only extrapolate the estimated time using the available magnetochronologic data, but the sedimentation rates and absolute ages estimated here must be of the same order of magnitude (see Smit, 1982).

Biomagnetostratigraphic calibration of Agost and Caravaca suggests that the FAD of *Plummerita hantkeninoides* was ~300 k.y. before the K-T boundary (Pardo et al., 1996; Arz, 2000). According to our data, the last pre-K-T extinctions of *Archaeoglobigerina cretacea* and *Gublerina acuta* probably occurred in the last 25 k.y. of the Maastrichtian. Biomagnetostratigraphic calibration of Agost, Zumaya, Caravaca, and Gubbio (Arenillas, 1998, 2000) suggests that the FAD of *P. longiapertura* (top of P0) was ~3.5–5 k.y. after the K-T boundary, and the FADs of *P. eugubina*, *Eoglobigerina simplicissima*, *and P. pseudobulloides* were ~15–17.5 k.y., ~28–31 k.y., and ~45–55 k.y., respectively, after the K-T boundary (Figs. 2 and 3). According to these data, the sedimentation rate in the basal part of Danian at El Kef is ~14.9 cm/k.y. At Bochil, the sedimentation rate could be ~3.4 cm/k.y. from the base of clay topping the clastic and breccia sequence.

DISCUSSION

The K-T stratotype definition of El Kef (Cowie et al., 1989) implies that the K-T boundary is at the base of the clay that includes the red-rust layer containing the Ir anomaly and microspherules. For this reason, the K-T boundary in other sections should also be placed at the base of the layer with the impact evidence, because this K-T horizon is the most isochronous worldwide (Smit et al., 1996). The closer the studied section is to the Chicxulub crater, the clearer is the impact evidence. The energy transmitted by the Chicxulub impact was able to collapse continental margins and generate large tsunami

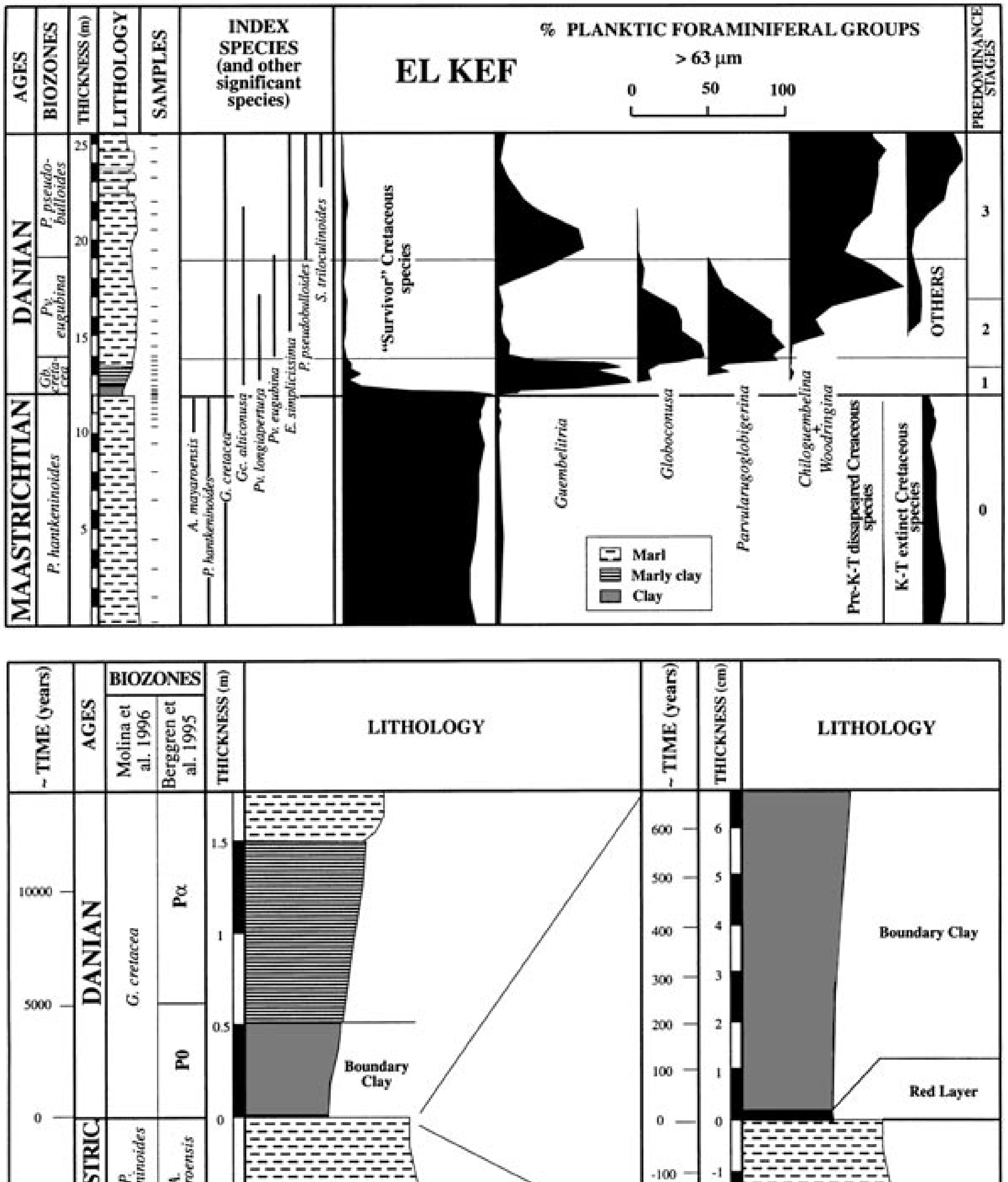

Figure 4. Ranges of planktic foraminifera index species, relative abundance of Danian planktic foraminifera faunal groups, and stages at El Kef section in size fractions larger than 63 µm. Probable duration (in years) of El Kef boundary clay and red layer. K-T is Cretaceous-Tertiary.

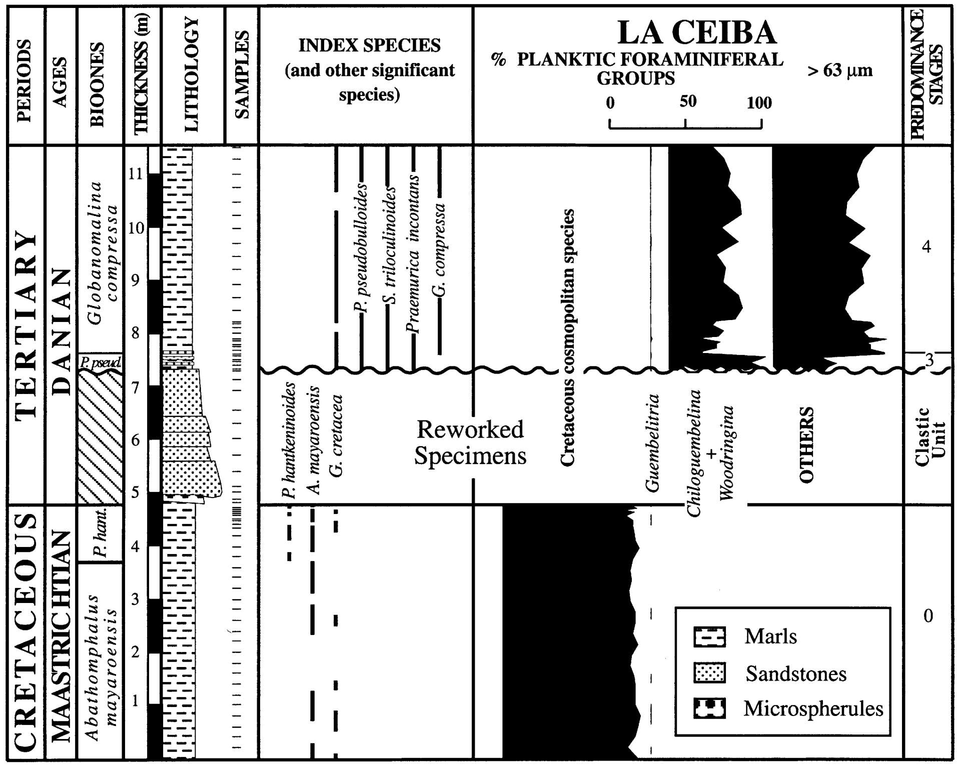

Figure 5. Species ranges of planktic foraminifera index species, relative abundance of Danian planktic foraminifera faunal groups, and stages at La Ceiba section in size fractions larger than 63 µm.

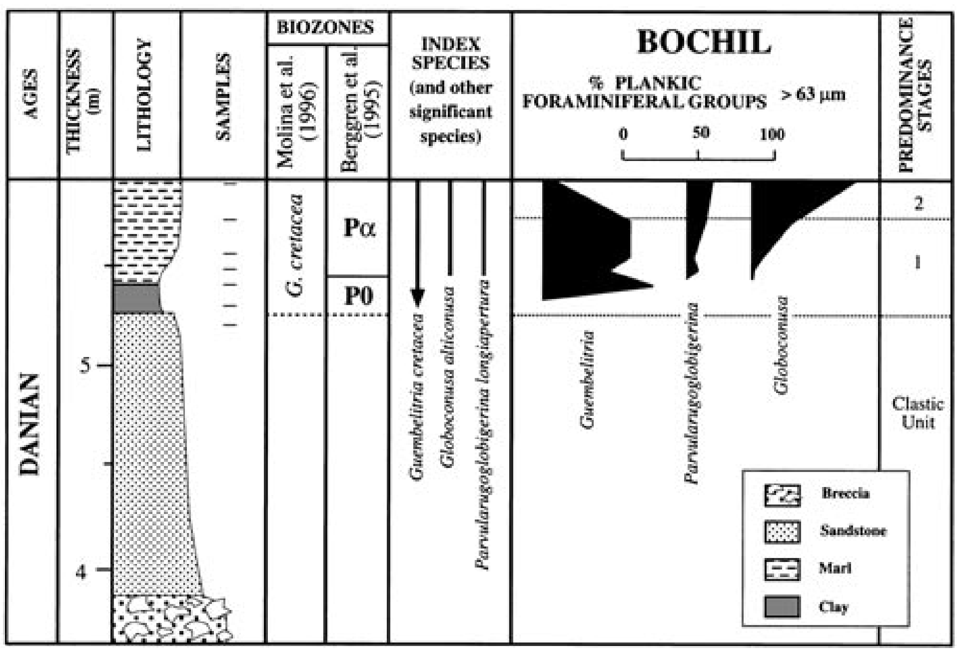

Figure 6. Ranges of planktic foraminifera index species, relative abundance of Danian planktic foraminifera faunal groups, and stages at Bochil section in size fractions larger than 63 µm.

waves that affected Gulf Coast shelf sedimentation (Bourgeois et al., 1988; Bralower et al., 1998). Unstable deposits with microtektites were mobilized from the shelf, forming sediment gravity currents toward the slope and deep basin (Bohor, 1996).

The coarse ejecta (e.g., breccia, microtektites) and the Ir anomaly are separated by a controversial sandstone unit in the Gulf of Mexico. Arz et al. (2001) have suggested that sandstone deposits at La Ceiba were deposited in a single-pulse event as turbidites at lower bathyal depths. This sedimentation model is similar to the one proposed by Bohor (1996) for other Gulf

Coast sections. If all these deposits were directly or indirectly caused by the bolide impact mentioned in Alvarez et al. (1980), then the clastic breccia, microspherules, and tsunami-derived sandstone unit are equivalent to the K-T red-rust layer from the El Kef stratotype. According to the criteria used at El Kef, the K-T boundary at La Ceiba must be placed at the base of the clastic (microspherules) layer because it is equivalent to the base of the boundary clay at El Kef (Arz et al., 2001). Similarly, the K-T boundary at Bochil should be placed at the base of the K-T clastic complex just below the impact-generated polymict debris flow.

The identification of the stages 1 and 2 at Bochil, just above the polymict breccia and sandstone complex, is significant because it supports the following two views.

1. The K-T boundary and mass extinction are just below the clastic unit. According to the sedimentological characteristics of the breccia and sandstone bed, the Maastrichtian specimens in the clastic unit are obviously reworked. Therefore, the last appearance of the mostly indigenous Maastrichtian species coincides with the base of the clastic unit at La Ceiba (and probably at Bochil) and the K-T boundary must be placed at this horizon (Arz et al., 2001).

2. The planktic foraminiferal evolutionary radiation also occurs just above clastic unit in the Gulf of Mexico. At El Kef, stage 1 is located just above the K-T boundary and red-rust layer, which confirms that the Gulf Coast clastic unit is equivalent to the Tethyan and the worldwide red layer. Moreover, the planktic foraminiferal evolution model and the different stages across the basal part of Danian are similar worldwide.

How long did the red layer deposition last? The El Kef red layer is 2–3 mm thick. Assuming a constant sedimentation rate (14.9 cm/k.y.), the red layer deposition would have taken ~13–20 yr. However, $CaCO_3$ in the clay layer and red layer is lower than in the upper Maastrichtian and lower Danian marls, indicating that the sedimentation rate fluctuated across the K-T boundary. At El Kef, the average $CaCO_3$ in the red layer and the clay layer is respectively 3 and 10 wt%, and 35 wt% in the lowermost Danian marl. If the depositional flux of the residual mineral matrix was constant (Kaiho et al., 1999), the sedimentation rate in the El Kef red layer and clay layer would be ~10 and 10.7 cm/k.y., respectively. In this case, the red layer deposition would have taken 20–30 yr. However, this is uncertain because the depositional flux of extraterrestrial and impact-derived material was larger in the red layer than the uppermost Maastrichtian and lowermost Danian. The duration of the red layer deposition at El Kef was probably <20 yr (Fig. 4), i.e., geologically instantaneous.

How long did the clastic unit deposition last? Fine-grained Ir-rich particles settle more slowly through the atmosphere and water column than coarse ejecta (Smit et al., 1996). Ir concentration must have increased after the high-energy episode represented by the coarse ejecta (breccia, microspherules, and shocked minerals) and megatsunami clastic unit. This suggests that the clastic unit, including polymict breccia, microspherules (microtektites), and megatsunami-derived sandstone, was deposited between the K-T boundary and red layer or boundary clay. If the deposition of the red layer occurred during the first years of the Danian, we can assume that the K-T clastic unit formed almost instantaneously.

Stinnesbeck et al. (1993) and Keller et al. (1994b) suggested that the clastic units were deposited over a long period of time. However, this cannot have been the case because they are characterized by a high sedimentation rate in upper flow regimes (Bohor, 1996; Arz et al., 2001), suggesting that K-T sandstones were deposited rapidly over a very short period. According to Bralower et al. (1998), much of the impact-derived material would have accumulated within hours or days after the impact. The gravity-flow deposit throughout the Gulf of Mexico basin was probably the result of destabilization of unconsolidated shelf sediments after the huge accumulation of impact- and tsunami-generated sediments above the Gulf Coast shelf and associated seismic events. Consequently, the main clastic deposition may have lasted only days or weeks. If the last indigenous specimens of most Maastrichtian planktic foraminifera are only found just below the K-T impact-generated bed, we conclude that their mass-extinction model was clearly catastrophic. We suggest that there is a close relation between the K-T planktic foraminiferal mass extinction and the Chicxulub impact.

CONCLUSIONS

A micropaleontological study across the K-T boundary from the El Kef, Tunisia, and La Ceiba and Bochil, Mexico, sections was used to examine K-T planktic foraminiferal biostratigraphy and assemblage turnover in Mexico and calibrate the timing of clastic deposition. The El Kef section is one of the most continuous and expanded marine K-T boundary sections known at the Tethys, because the gradual Tertiary species appear over an extensive stratigraphic interval at the lower part of the Danian. All stages were identified in the El Kef stratotype, including the peak of *Guembelitria* (stage 1). However, stages 1 and 2 were not identified at La Ceiba, indicating a hiatus in the lower Danian. However, the identification of stages 1 and 2 at Bochil support two views: (1) the K-T boundary and mass extinction are placed below the impact-generated polymict debris-flow and sandstone complex, and (2) the planktic foraminiferal evolutionary radiation also occurs just above impact-generated clastic complex in the Gulf of Mexico. Consequently, our micropaleontological and sedimentological evidence is consistent with the K-T impact theory and the impact on the Yucatan Peninsula.

On the basis of calculated average sedimentation rates and estimated age, the duration of the K-T red layer deposition at El Kef is probably <20 yr. The impact-generated clastic unit in the Gulf of Mexico was deposited between the K-T boundary and the red layer or boundary clay. If the red layer deposition occurred during the first years of the Danian, we can assume that the K-T clastic unit was geologically instantaneous. If the last certain indigenous specimens of most of Maastrichtian species are only found just below the K-T impact-generated bed, it appears that the planktic foraminiferal mass extinction was catastrophic.

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