



# Micropaleontology and sedimentology across the Cretaceous/Tertiary boundary at La Ceiba (Mexico): impact-generated sediment gravity flows

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## Abstract

A micropaleontological and sedimentological study across the Cretaceous/Tertiary boundary—officially Cretaceous/Paleogene (K/P) boundary from the La Ceiba section (Mexico) was performed to examine the K/P planktic foraminiferal biostratigraphy, the sedimentology of a controversial K/P clastic unit, and the benthic and planktic foraminiferal assemblages turnover across this boundary. The clastic unit is stratigraphically placed between two pelagic marly units (Méndez and Velasco Formations) and displays a fining-upward gradation similar to a turbidite sequence. This K/P clastic unit contains a basal subunit consisting of calcareous marls rich in millimeter-sized spherules (microtektites) altered to clay minerals, abundant detrital quartz, mica minerals, and shocked quartz. According to the K/P stratotype definition from El Kef (Tunisia), the K/P boundary at La Ceiba must be placed at the base of the clastic (microspherules) unit since it is equivalent to the base of the boundary clay at El Kef. A short hiatus affects the lower part of the Danian, including the *Guembeltria* cretacea and *Parvularugoglobigerina eugubina* biozones and the lower part of the *Parasubbotina pseudobulloides* biozone. Nearly all commonly recorded Maastrichtian planktic foraminiferal species were found in the uppermost Maastrichtian interval, and there was no support for a gradual mass extinction pattern in the terminal Cretaceous. Benthic foraminiferal assemblages suggest that the La Ceiba section was deposited at lower bathyal depths. Oscillating megatsunami waves and/or a sea-level lowstand cannot explain the nature of the clastic deposits because of the observed deposition paleodepth (more than 1000 m). There is also evidence that the clastic unit was deposited under a high-sedimentation rate in upper flow regimes and that was emplaced as a single-pulse event as turbidites. This datum and other sedimentological features support a sediment gravity flow genesis for the clastic unit. All these results are consistent with the K/P impact theory and the asteroid impact on the Yucatan Peninsula. © 2001 Elsevier Science Ltd. All rights reserved.

**Keywords:** Cretaceous/Tertiary boundary; La Ceiba; Impact generated sediment gravity flows

## 1. Introduction

The Cretaceous/Paleogene (K/P) boundary in and around the Gulf of Mexico is marked by an unusual and controversial clastic deposit. In eastern Mexico, this sandstone bed is interbedded in a planktic foraminifera-rich pelagic marl sequence, and its origin is still under debate. Initially, Morgan (1931), Kellum (1937), and Muir (1936) interpreted it as a shallow-water deposit or nonmarine sandstone. It has since been considered as lowstand channel infill (Mancini and Tew, 1993; Savrda, 1991), storm deposits (Hansen et al., 1987), or deltaic deposits (Stinnesbeck et al., 1993, 1994a, 1996). However, the most commonly accepted interpretation is that it corresponds to gravity flow deposits

(turbidite and debris flows) (Bohor and Betterton, 1993; Bohor, 1994, 1996) and impact-megatsunami deposits related to the Yucatan bolide impact (Smit and Romein, 1985; Bourgeois et al., 1988; Maurrasse and Sen, 1991; Smit et al., 1992b, 1996).

The 180 km diameter Chicxulub structure on the north of the Yucatán Peninsula (Mexico) supports the K/P boundary impact and catastrophic mass extinction theory (Alvarez et al., 1980; Smit and Hertogen, 1980). It is commonly interpreted as a bolide impact crater (Hildebrand et al., 1991), whereas the mentioned clastic deposits are considered a consequence of megatsunami waves generated by the impact (Smit et al., 1992b, 1994a). The timing of the clastic bed deposition is controversial because some authors consider that it occurs precisely at the K/P boundary (Smit and Romein, 1985; Bourgeois et al., 1988; Smit et al., 1992b, 1996; Bohor and Betterton, 1993; Bohor, 1996),

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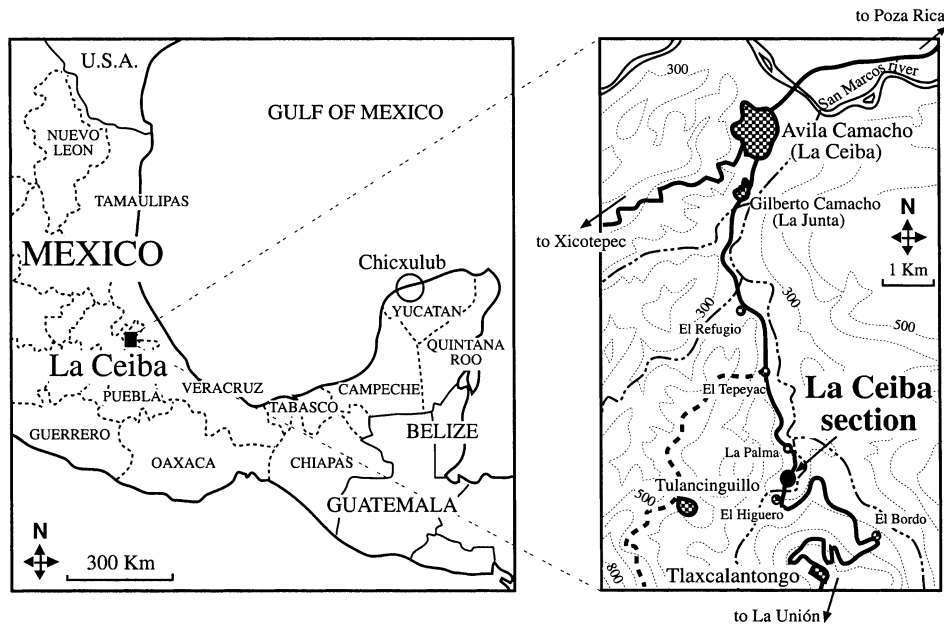


Fig. 1. Geographic location of the La Ceiba section.

whereas others consider that it predates the K/P boundary (Jiang and Gartner, 1986; Keller, 1989; Keller et al., 1993, 1994a; Stinnesbeck et al., 1993, 1994b). It is also unclear whether it was deposited as one event (Smit et al., 1996) or several events (Stinnesbeck et al., 1993; Keller et al., 1994a; Stinnesbeck and Keller, 1996). Stinnesbeck et al. (1994a) suggest that this clastic deposit in northeastern Mexico was formed during successive sea-level lowstands that lasted several thousands of years, and that represents channel fills that formed by erosion from deltaic to inner neritic sediments. A micropaleontological and sedimentological evaluation of the nature and timing of the clastic unit is crucial for either theory.

Recent planktic foraminiferal studies of several continuous sections from Spain and Tunisia (Molina et al., 1996, 1998; Arenillas et al., 1998, 2000; Arz and Arenillas, 1998; Arz et al., 1999a,b) support a main pattern of sudden and catastrophic mass extinction at the K/P boundary (Smit, 1982, 1990). The K/P boundary Global Stratotype Section and Point (GSSP) was officially defined at the El Kef section (Tunisia) at the base of a clay layer anomalously enriched in iridium (Cowie et al., 1989). The placement of the K/P boundary is evident in Tunisia and Spain where the base of the boundary clay coincides with a Maastrichtian planktic foraminiferal mass extinction. However, the K/P boundary placement in the Gulf of Mexico is more controversial than in the Tethys (Smit et al., 1994a; Stinnesbeck et al., 1994b) because some authors place the K/P boundary above the clastic deposits (Beeson et al., 1994; Keller et al., 1993, 1994a; Stinnesbeck et al., 1993, 1994b; Stinnesbeck and Keller, 1996; López-Oliva and Keller, 1996) and others at the base of the clastic bed (Hansen et al., 1987; Bourgeois et al., 1988; Smit et al., 1992b, 1996).

In this paper, we examine the uppermost Maastrichtian

and lowermost Danian strata that are represented in the stratigraphic section of La Ceiba, Mexico, present a detailed sedimentologic study of the clastic unit that is located between those strata, and include a biostratigraphic study of the planktic and benthic foraminiferal assemblages and its turnover across the K/P boundary. This section was previously studied by Smit et al. (1996), but we provide a more detailed micropaleontological study and analyse the nature and stratigraphic position of the clastic deposits.

## 2. Geographical location and micropaleontological methods

The La Ceiba section is located about 7 km south of La Ceiba (Avila Camacho) township ( $20^{\circ}19.8'N$ ,  $97^{\circ}41.0'W$ ), along the road from La Ceiba to Tlaxcalantongo (Fig. 1), in the state of Veracruz (central-east Mexico). The La Ceiba section is located about 900 km west of the Chicxulub impact crater and may correspond to the Tlaxcalantongo section studied by López-Oliva (1996) and quoted by Keller and Stinnesbeck (1996). The K/P sedimentary section at La Ceiba is characterized by a clastic unit sandwiched between two marly units (Fig. 2). The lower unit is the Méndez Formation, and the upper is the Velasco Formation. Both Méndez and Velasco Formations are constituted by gray marls interbedded with scarce sandstone beds.

We collected 61 samples from this section, at decimeter intervals, with closer sampling across the top Maastrichtian and basal Danian strata (Fig. 3). Samples were disaggregated in water with diluted  $H_2O_2$ , washed through a  $63 \mu m$  sieve, and dried at  $50^{\circ}C$ . The planktic foraminiferal species diversity was measured in all samples, whereas we used 16 representative samples for the benthic foraminiferal

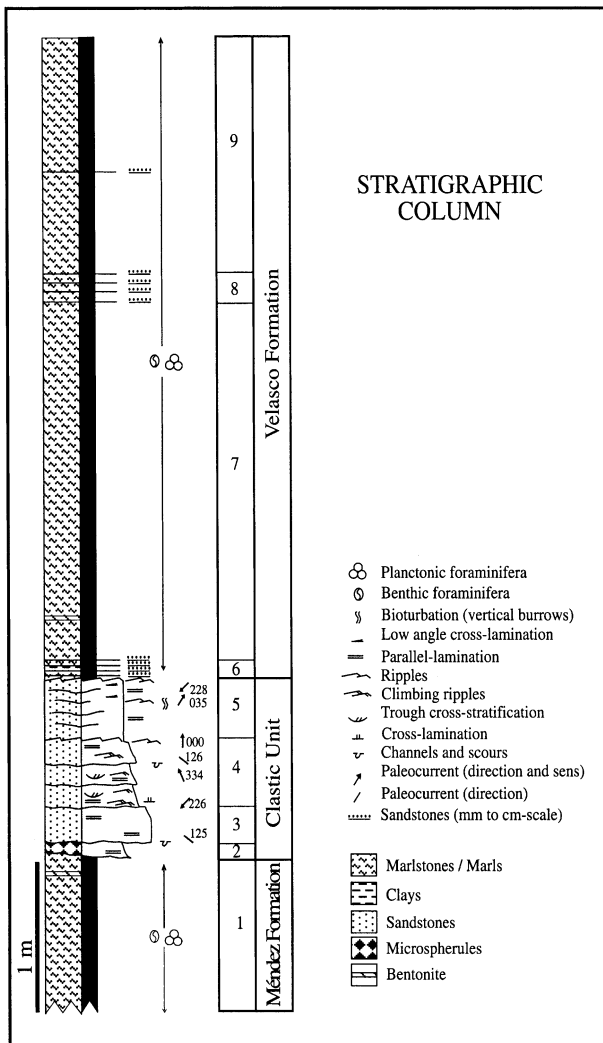


Fig. 2. Stratigraphic column of the La Ceiba section, showing sedimentological features and paleocurrent directions.

quantitative analysis (Figs. 4–7). Species richness measurement and quantitative studies were based on representative splits (using a modified Otto microsplitter) of approximately 300 specimens larger than 63  $\mu\text{m}$ . We intensively scanned the residue in order to find rare species and minimize the Signor and Lipps (1982) effect. All the representative specimens were mounted on microslides for a permanent record and identification. Planktic and benthic foraminiferal preservation is generally good.

The Cretaceous planktic foraminiferal species may be grouped according to their latitudinal trend in cosmopolitan and tropical–subtropical species (López-Oliva, 1996). Carbon and oxygen stable isotope measurements of individual Cretaceous species indicate where they lived in the water column (Boersma and Shackleton, 1981; Barrera and Keller, 1990, 1994; D’Hondt and Lidinger, 1994). These interpretations are the basis for the study of tropical–subtropical and cosmopolitan species turnover, as well as surface, intermediate, and deep dwellers changes at the La Ceiba section (Fig. 5).

The benthic foraminifera can be used to infer seafloor paleoecology on the basis of their morphological similarity with recent benthic foraminifera (Olsson and Wise, 1987; Speijer and Van der Zwaan, 1996; Speijer et al., 1996; Kouwenhoven et al., 1997). Living benthic foraminifera analysed by Corliss (1985), Corliss and Chen (1988), and Jones and Charnock (1985) demonstrate the relationship between morphological features and microhabitat preferences. Benthic foraminifera with rounded planispiral, cylindrical–tapered, spherical, or flattened–tapered tests have an infaunal mode of life, whereas epifaunal species living in the upper 1 cm of sediment have rounded, planoconvex, or biconvex shapes and trochospiral coiling, as well as flattened planispiral, streptospiral, irregular, or tubular morphotypes.

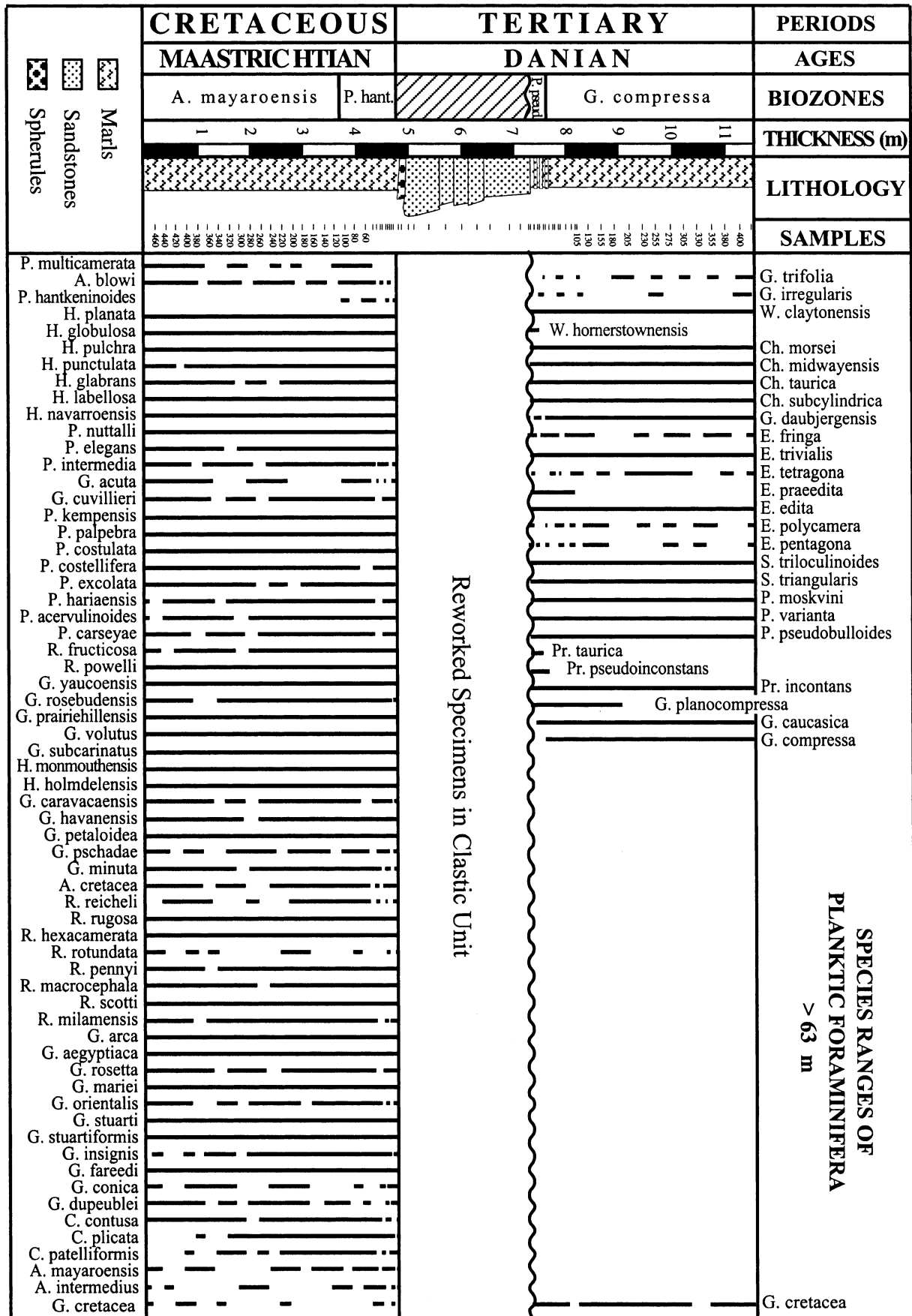
### 3. Stratigraphy




Our study encompasses the uppermost 4.8 m of the Méndez Formation, approximately 1.2 m of the clastic unit, and the lower 4.3 m of the Velasco Formation (Fig. 2). The upper part of the Méndez Formation is Maastrichtian in age, whereas the clastic unit and the lower part of the Velasco Formation are Danian in age. The Méndez Formation is composed of deep-water marine marls interbedded with some sandstone beds. The Velasco Formation has similar sedimentological characteristics but more frequent sandstone layers. Both formations contain abundant microfossils rich in planktic foraminifera, which indicate that they were deposited in an open marine environment and suggest normal hemipelagic sedimentation. Some bentonite layers have been identified in both formations.

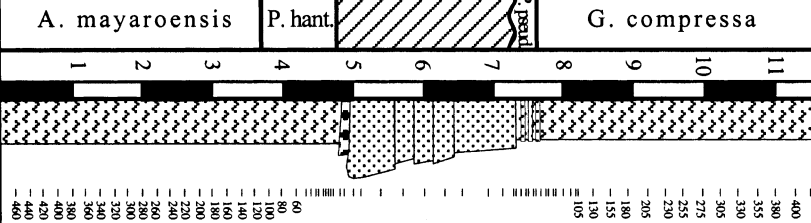
The clastic unit displays a fining-upward sequence and is composed of four different subunits according to their textural and architectural characteristics (subunits 2, 3, 4, and 5 in Fig. 2). Similar clastic units were described by Smit et al. (1992a, 1994b,c 1996), Stinnesbeck et al. (1993), and Keller et al. (1994b) from several outcrops in northeastern Mexico. These authors designated the basal microspherule-bearing bed as Unit 1 and subdivided the overlying sandstone into Units 2 and 3.

Our basal clastic Subunit 2 (Fig. 2) is a parallel-laminated calcareous marl rich in millimeter-sized microspherules, abundant detrital quartz, mica minerals, shocked quartz, and bioclasts (large and small benthonic foraminifera, bryozoans, and echinoderms) of shallow-water origin. The microspherules are usually interpreted as microtektites and microkrystites altered to clay minerals (Smit et al., 1992a,b, 1996). The average thickness of Subunit 2 is 10 cm and corresponds to the clastic Unit I in Smit et al. (1996).

Subunit 3 is a 25 cm thick tabular bed of middle-grained sandstones. Its base is slightly channelized and presents abundant parallel-lamination. Subunit 4 consists of a tabular body of middle- to fine-grained sandstone with internal erosive surfaces that separate tabular strata 15–20 cm



 Spherules  
 Sandstones  
 Marls



- P. multicamerata
- A. blowi
- P. hantkeninoides
- H. planata
- H. globulosa
- H. pulchra
- H. punctulata
- H. glabrans
- H. labellosa
- H. navarroensis
- P. nuttalli
- P. elegans
- P. intermedia
- G. acuta
- G. cuvillieri
- P. kempensis
- P. palpebra
- P. costulata
- P. costellifera
- P. excolata
- P. hariaensis
- P. acervulinoides
- P. carseyae
- R. fructicosa
- R. powelli
- G. yaucoensis
- G. rosebudensis
- G. prairiehillensis
- G. volutus
- G. subcarinatus
- H. monmouthensis
- H. holmdelensis
- G. caravacaensis
- G. havanensis
- G. petaloidea
- G. pschadae
- G. minuta
- A. cretacea
- R. reicheli
- R. rugosa
- R. hexacamerata
- R. rotundata
- R. pennyi
- R. macrocephala
- R. scotti
- R. milamensis
- G. arca
- G. aegyptiaca
- G. rosetta
- G. mariei
- G. orientalis
- G. stuarti
- G. stuartiformis
- G. insignis
- G. fareedi
- G. conica
- G. dupeublei
- C. contusa
- C. plicata
- C. patelliformis
- A. mayaroensis
- A. intermedius
- G. cretacea

- G. trifolia
- G. irregularis
- W. claytonensis
- W. hornerstownensis
- Ch. morsei
- Ch. midwayensis
- Ch. taurica
- Ch. subcylindrica
- G. daubjergensis
- E. fringa
- E. trivialis
- E. tetragona
- E. praeedita
- E. edita
- E. polycamera
- E. pentagona
- S. triloculinoides
- S. triangularis
- P. moskvini
- P. varianta
- P. pseudobulloides
- Pr. incontans
- G. planocompressa
- G. caucasica
- G. compressa
- G. cretacea

thick. In this subunit we found parallel- and cross-lamination, trough cross-stratification, current ripples, and climbing ripples. The upper clastic Subunit 5 is a tabular body of fine-grained sandstone with parallel- and low-angle cross-lamination and asymmetric ripples; its upper plane bed is affected by burrow traces. Subunits 3 and 4 could correspond to Unit II in Smit et al. (1996), and Subunit 5 to Unit III.

We identified a Subunit, 6, that overlies the clastic bed. It is a 20 cm thick bed of marl, clays, and silt with laminations of fine-grained sandstone. This subunit that may correspond to Unit IV in Smit et al. (1996) has Paleocene planktic foraminifera and must be included in the Velasco Formation. Subunits 7, 8, and 9 are composed mostly of marls and belong to the Velasco Formation. Subunit 8 contains frequent interbeds of sandstone layers.

#### 4. Biostratigraphy and stratigraphic position of the K/P boundary

For our biostratigraphic work, we follow the lower latitude biozonation suggested by Molina et al. (1996), who identified the following biozones: *Abathomphalus mayaroensis*, *Plummerita hantkeninoides*, *G. cretacea*, *Pv. eugubina*, *P. pseudobulloides*, and *G. compressa* biozones. The first two biozones belong to the upper part of the Maastrichtian. The *P. hantkeninoides* biozone is defined by the total range of the nominate taxon (Fig. 8), and its top coincides with the K/P boundary. This taxon is scarce at the La Ceiba section, and its first appearance was identified 100 cm below the K/P boundary. This short stratigraphic distribution is similar to that identified at the section in the Tlaxcalantongo area (López-Oliva, 1996), where the upper part of the biozone may be affected by a short hiatus below the clastic deposits (López-Oliva, 1996; Keller and Stinnesbeck, 1996). However, according to Pardo et al. (1996), the *P. hantkeninoides* biozone only spans the uppermost 170–200 ky of the Maastrichtian at Agost (Spain). Thus, if the hiatus exists, it is probably very short.

The other four biozones belong to the lower Danian. According to the biozonation proposed by Berggren et al. (1995), the *G. cretacea* biozone corresponds to P0 zone, the lower part of the P $\alpha$ , the *Pv. eugubina* biozone to the upper part of the P $\alpha$  zone, and the *P. pseudobulloides* and *G. compressa* biozones approximately to the P1a and P1b subzones. Nevertheless, we did not identify the *G. cretacea* nor *Pv. eugubina* biozones at La Ceiba, nor their characteristic assemblages dominated by *Guembelitra*, *Globocornusa*, and *Parvularugoglobigerina* (Arenillas et al., 1998). This is interpreted as a short hiatus affecting the lower part of the Danian above the clastic unit. According to the stratigraphical distribution of the lower Danian species at

temperate and tropical–subtropical sections in Tunisia (Molina et al., 1996, 1998; Arenillas et al., 1998, 2000; Arz and Arenillas, 1998; Arz et al., 1999a,b), this hiatus may affect the *G. cretacea* and *Pv. eugubina* biozones and the lower part of the *P. pseudobulloides* biozone. The lowermost Danian sample at La Ceiba belongs to the upper part of the *P. pseudobulloides* biozone, and includes species with perforate cancellate wall texture (*Eoglobigerina*, *Parasubbotina*, *Subbotina*, and *Praemurica*; Fig. 8). Moreover, *G. compressa* appears nearly just above the clastic unit and, for this reason, the *P. pseudobulloides* biozone is only 25 cm thick. This short hiatus has also been identified at other Gulf Coast sections such as El Mimbrial, El Mulato, and Tlaxcalantongo (López-Oliva, 1996; López-Oliva and Keller, 1996; López-Oliva et al., 1998).

Keller and Stinnesbeck (1996) place the top of the *P. hantkeninoides* biozone and the K/P boundary above the clastic deposits, as also suggested by Jiang and Gartner (1986), Keller (1989), Keller et al. (1993), and Stinnesbeck et al. (1993, 1994b), from other Gulf Coast sections. However, other authors place it at the base of the clastic beds (Smit and Romein, 1985; Hansen et al., 1987; Bourgeois et al., 1988; Smit et al., 1992b, 1994a, 1996; Olsson and Liu, 1993). The basal part of the K/P boundary clay at El Kef stratotype has an Ir anomaly, an increase in total organic carbon (TOC), a decrease in  $^{13}\text{C}$ , as well as crystalline microspherules (altered microtektites according to Smit, 1982, and Smit et al., 1992a), Ni-rich spinels, and shocked minerals. The most useful way to locate the K/P boundary in other sections is to identify this layer with worldwide dispersed impact ejecta, including the Ir anomaly and the microspherules. The K/P boundary should be placed at the base of the layer with these impact evidences, since this K/P horizon is the most isochronous worldwide (Smit et al., 1996).

Smit et al. (1996) suggested that all deposits with K/P impact ejecta are Danian in age. At the El Kef and other Tunisian and Spanish sections, all the impact evidence seems to be concentrated at the same level (often at an iron-rich oxidized red layer) just at the base of the K/P clay boundary. In the Gulf of Mexico, this layer is evidently more complex than in the Tethys. For instance, at El Mimbrial (Smit et al., 1996), the coarse ejecta (altered microtektites level) and the Ir anomaly are separated by the clastic unit. If all the mineralogical and geochemical anomalies were caused by a bolide impact (Alvarez et al., 1980), Ir must obviously increase in concentration in beds deposited after strata formed by the high-energy episode represented by the coarse ejecta (breccia, microspherules, and shocked minerals) beds and the megatsunami clastic unit. This is because the Ir fine grains settled more slowly through the atmosphere and water column than coarse ejecta (Smit et al., 1996). Following the criteria used at the El Kef

Fig. 3. Species ranges of planktic foraminifera at the La Ceiba section in the size fraction bigger than 63  $\mu\text{m}$ .

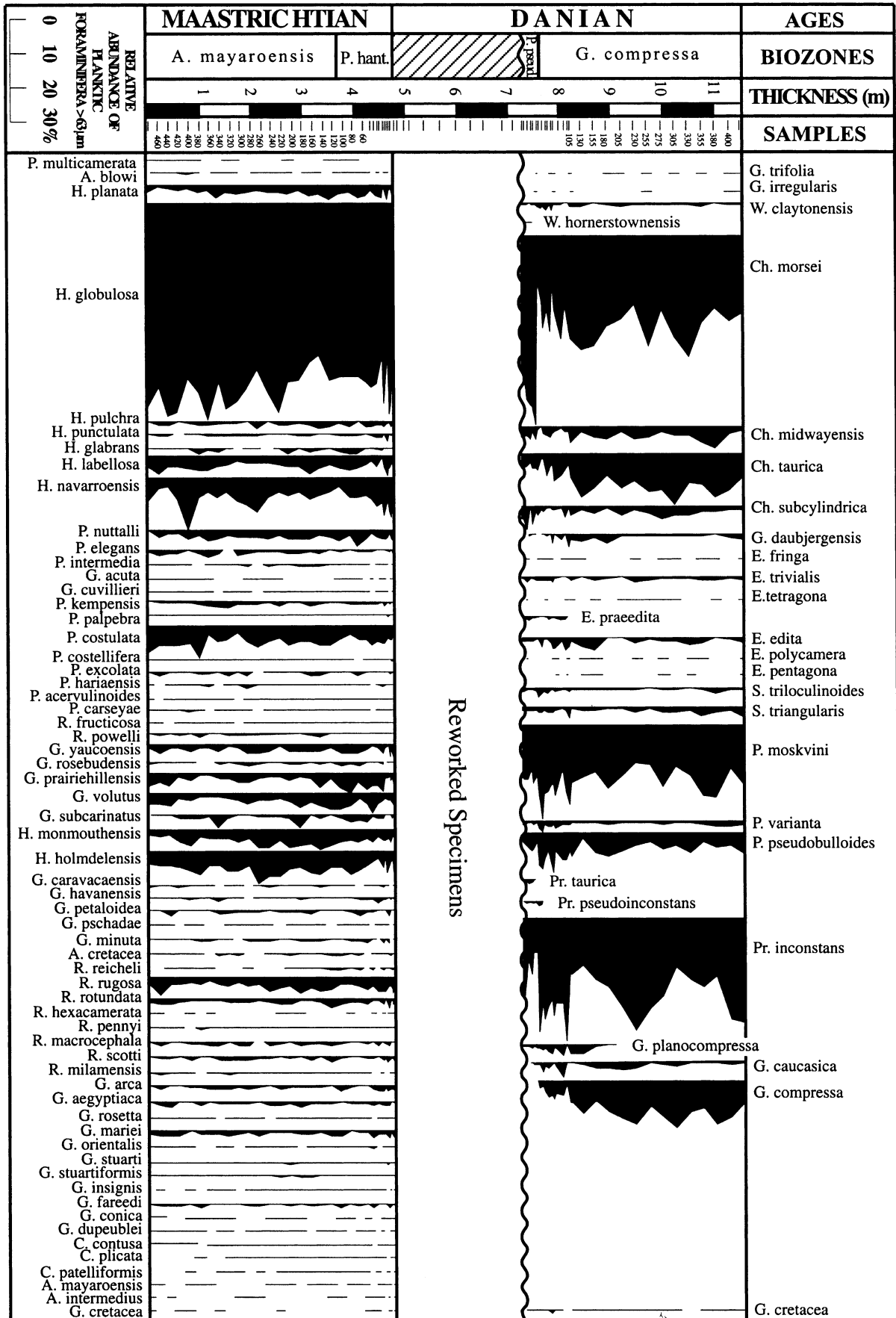


Fig. 4. Relative abundance of planktic foraminifera species across the K/P boundary at the La Ceiba section in the size fraction bigger than 63 µm.

stratotype, the K/P boundary in Gulf Coast sections must be placed at the base of the layer with all the mineralogical and geochemical anomalies. This layer corresponds to the complex clastic unit, and the K/P boundary at La Ceiba should be placed at the base of the microspherules (altered microtektites) layer.

Biostratigraphically, the most coherent placement of the K/P boundary is the planktic foraminiferal mass extinction horizon that coincides with the last appearance of *P. hantkeninoides* and *A. mayaroensis*. However, this horizon is often blurred by reworking. The boundaries between biozones must be placed at the true, last or first appearances of the index-species identified with indigenous specimens, but not with reworked specimens. Species reworking is usually difficult to evaluate or determine. However, according to the sedimentological characteristics of the sandstone bed, the Maastrichtian specimens in the clastic unit are obviously reworked. López-Oliva (1996), López-Oliva and Keller (1996), and López-Oliva et al. (1998) identified Maastrichtian fauna near the top of the clastic bed and in the lowermost Velasco marls in other Mexican sections, such as Tlaxcalantongo or El Mimbral. For this reason, Keller et al. (1993, 1994a), Stinnesbeck et al. (1993, 1994b), Stinnesbeck and Keller (1996), and López-Oliva and Keller (1996) suggested that the K/P boundary is placed above the clastic unit. They considered that the K/P boundary was also marked by the Ir anomaly and the first appearance of Danian species at the base of the Velasco marls. However, although we have also identified Maastrichtian species in the clastic unit, we did not include them in the figures because we have considered them as reworked speci-

mens. Also, Smit et al. (1994b) suggested that they represent part of the reworked suspended sediments that settled down through the water column during the tsunami event that formed the clastic unit. For this reason, we consider that the last-majority indigenous-Maastrichtian planktic foraminiferal assemblage occurs below the clastic unit in the last Maastrichtian strata of the Méndez Formation. At La Ceiba, the last appearance of the Maastrichtian species coincides with the base of the microspherules strata, and the K/P boundary must be placed at this horizon.

The first appearance of the Danian species has also been used to place the K/P boundary, but it is more ambiguous and probably more diachronous. Danian species occur several centimeters above the K/P boundary in most continuous Tethyan outcrops (Smit, 1982; Keller, 1988, 1997; Canudo et al., 1991; Molina et al., 1996, 1998; Smit and Nederbragt, 1997). Between both horizons there is a zone (lowermost part of P0) with only reworked specimens and some indigenous Maastrichtian species (Huber, 1996; Arenillas et al., 1998, 2000; Kaiho and Lamolda, 1999; Arz et al., 1999a,b). No one has placed the K/P boundary at the top of P0, from El Kef or other sections, based on these reworked Maastrichtian assemblages because biozone boundaries cannot be placed on the basis of reworked specimens. Similarly, it would be wrong to place the K/P boundary above the clastic unit using reworked specimens. We consider these sandstones are Danian in age because they clearly postdate the main K/P boundary event characterized by all impact evidence (including the microtektites) and the mass extinction horizon.

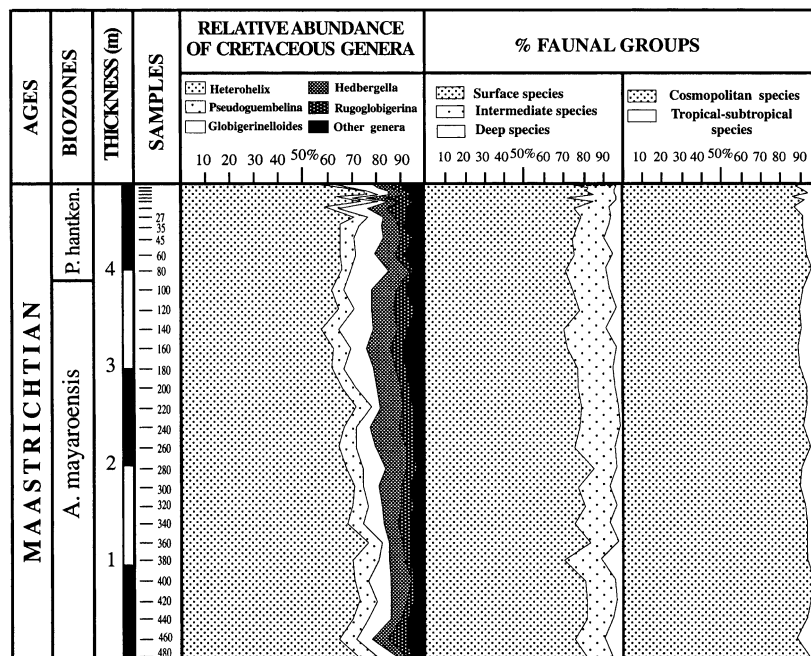


Fig. 5. Relative abundance of Cretaceous planktic foraminiferal fauna and planktic foraminifera faunal groups across the K/P boundary in the size fraction bigger than 63 μm. ('Other genera' include *Guembelitra*, *Pseudotextularia*, *Gublerina*, *Planoglobulina*, *Racemiguembelina*, *Globotruncanella*, *Archaeoblobigerina*, *Plummerita*, *Globotruncana*, *Globotruncanita*, *Contusotruncana*, and *Abathomphalus*).

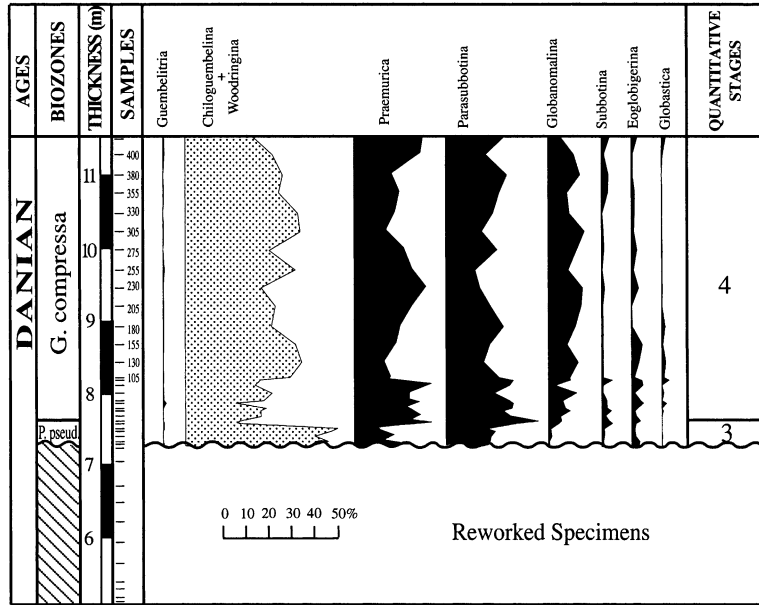


Fig. 6. Relative abundance of Danian planktic foraminifera faunal groups and quantitative stages in the size fractions bigger than 63 μm.

**5. Planktic foraminiferal quantitative analyses**

The upper Maastrichtian planktic foraminiferal assemblages from La Ceiba section are very diverse. We identified 63 Cretaceous species in typical low-latitude assemblages. These assemblages are very similar to other assemblages

that have been reported from Tunisian and Spanish sections (Molina et al., 1996, 1998; Arz et al., 1999a,b; Arenillas et al., 2000). The Maastrichtian assemblages were quantitatively dominated by *Heterohelix* (approximately 65% in abundance), and especially by *Heterohelix globulosa* (54%). Other abundant genera in the upper Maastrichtian

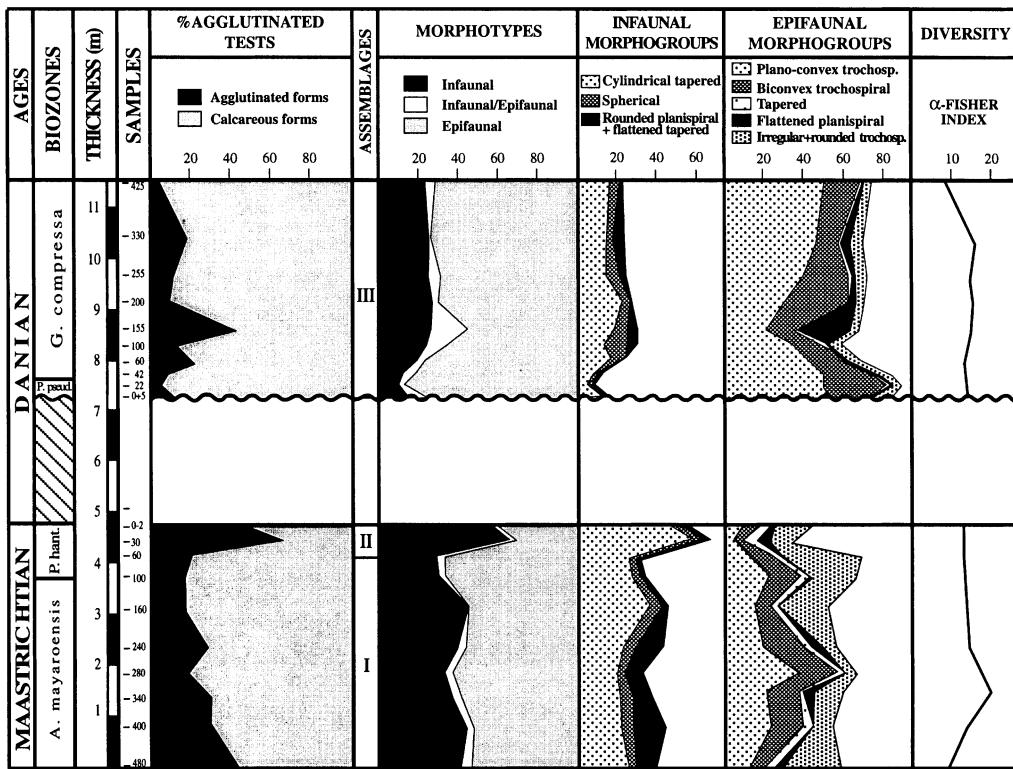


Fig. 7. Relative abundance of benthic foraminifera faunal groups (% agglutinated tests, morphotypes, infaunal morphogroups, epifaunal morphogroups), assemblages and diversity ( $\alpha$ -Fisher index) in the size fractions bigger than 63 μm.



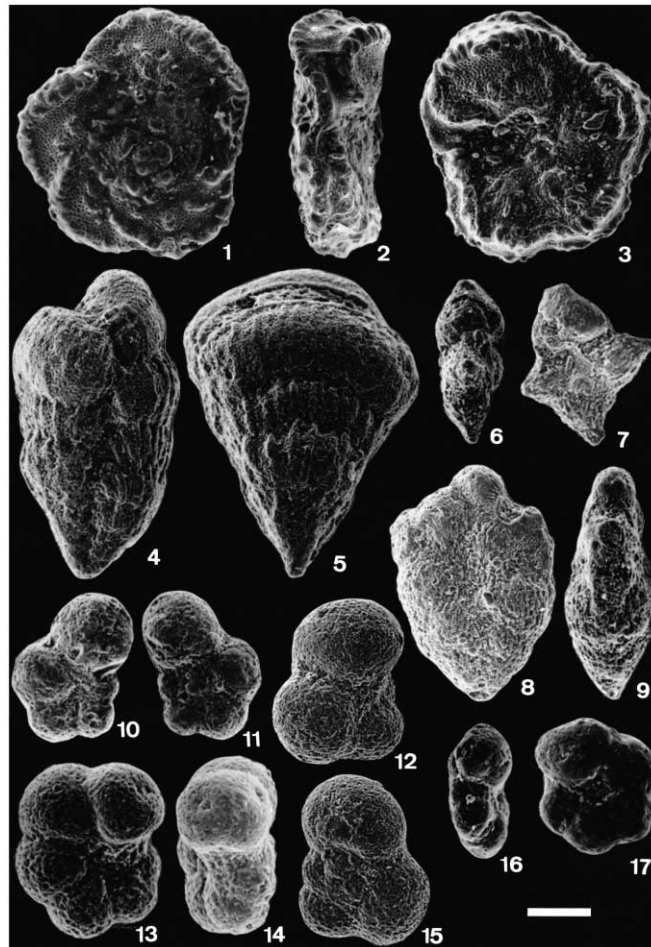


Fig. 8. SEM micrographs of some examined upper Maastrichtian and lower Danian planktic foraminiferal species. Scale bar corresponds to 100  $\mu\text{m}$  (1, 2, 3) *Abathomphalus mayaroensis* (Bolli), sample LC -6 - 8; (4, 5) *Pseudotextularia elegans* (Rzehak), sample LC 0 - 2; (6, 7) *Plummerita hantkeninoides* (Brönnimann), sample LC 0 - 2; (8, 9) *Pseudoguembelina hariaensis* (Nederbragt), sample LC 0 - 2; (10, 11) *Parasubbotina pseudobulloides* (Plummer), sample LC +20 + 25; (12, 15) *Subbotina triloculinoides* (Plummer), sample LC +350 + 355; (13, 14) *Praemurica inconstans* (Subbotina), sample LC +20 + 25; (16, 17) *Globanomalina compressa* (Plummer), LC +50 + 55.

assemblages are *Pseudoguembelina*, *Globigerinelloides*, *Hedbergella*, and *Rugoglobigerina*. Of the scarce genera, complex heterohelicids and globotruncanids are the most abundant. Common species (2% in abundance) included *Heterohelix labellosa*, *H. navarroensis*, *Pseudoguembelina costulata*, *Hedbergella monmouthensis*, *H. holmdelensis*, and *Rugoglobigerina rugosa*. Very scarce species are *G. cretacea*, *Rugoglobigerina reicheli*, *R. rotundata*, *Globotruncana orientalis*, *G. conica*, *G. dupeblei*, and other species belong to *Gublerina*, *Planoglobulina*, *Racemiguembelina*, *Archaeoglobigerina*, *Plummerita*, *Contusotruncana*, and *Abathomphalus*. Most large, complex, tropical–subtropical species are rare (10% in abundance), but high in number. Less than one-third (21 species) is cosmopolitan. However, the cosmopolitan and surface-intermediate dweller species average 90% in abundance. This high proportion of cosmopolitan planktic foraminifera and surface-intermediate dweller species is usual in the fossil record because they have a rapid ontogenetic cycle and short reproduction time.

All species and faunal groups were notably stable in abundance in the terminal Maastrichtian (Fig. 5). The surface/deep and cosmopolitan/tropical–subtropical species ratios do not vary in either *A. mayaroensis* or *P. hantkeninoides* biozones, indicating few changes in sea level, local minimum oxygen zone, or oceanic water circulation across the uppermost part of the Maastrichtian. The cosmopolitan/tropical–subtropical ratio indicates no changes in sea surface temperatures during this time period. It only oscillates about 5% in the Méndez interval, which does not justify changes in the surface temperature or productivity. In the clastic unit, planktic foraminifera are very scarce. We studied several thin sections and found a few Maastrichtian specimens from *H. globulosa*, *Pseudotextularia* sp., *P. nuttalli*, *P. carseyae*, *Hedbergella* sp., *H. holmdelensis*, *G. subcarinatus*, *G. petaloidea*, *G. arca*, and *Globotruncanita* sp. Planktic foraminiferal specimens are only frequent at the base of the clastic unit, but are probably reworked (not included in the figures).

A comparative planktic foraminiferal quantitative study

of the continuous sections in Tunisian and Spanish sections (El Kef, Ain Settara, Elles, Zumaya, Agost, Caravaca, and others) allowed us to establish five quantitative stages in the population larger than 63  $\mu\text{m}$  across the K/P boundary (Arenillas et al., 1998; Arz and Arenillas, 1998; Arz et al., 1999a,b). Stage 0 corresponds to the typical faunal association of the uppermost Maastrichtian described above, which is dominated by biserial species (*Heterohelix*). Stage 1 is the first Danian quantitative stage, dominated by *Guembelitra* and spanning the lower part of the G. cretacea biozone. Stage 2 is dominated by *Parvularugoglobigerina* and *Globoconusa*, and it spans the upper part of the G. cretacea biozone and the lower part of the Pv. eugubina biozone. We did not identify these two last stages in the study section (Fig. 6), confirming the short hiatus in the lowermost part of the Danian. Stage 2 is also characterized by the first appearance of *Parvularugoglobigerina* and *Globoconusa*, but these species were not found. We were very careful to distinguish juvenile globanomalids for parvularugoglobigerinids.

At the La Ceiba section, we only identified Stages 3 and 4 (Fig. 6). The species *Chiloguembelina* and *Woodringina* dominate the planktic foraminiferal assemblage in Stage 3, which spans the upper part of the Pv. eugubina biozone and the P. pseudobulloides biozone. *Eoglobigerina*, *Parasubbotina*, *Subbotina*, *Praemurica*, and *Globanomalina* species first appeared in the lower part of this stage (Fig. 6). Since Danian planktic foraminiferal species evolved sequentially in the K/P boundary continuous sections, their simultaneous first appearances at La Ceiba mark a hiatus that also affects the lower part of the P. pseudobulloides biozone. Finally, Stage 4 is characterized by the predominance of *Eoglobigerina*, *Parasubbotina*, *Subbotina*, *Praemurica*, and *Globanomalina* and begins in the G. compressa biozone. A slight increase of *Globanomalina* coincides with this stage as observed in the Tethyan sections (Arenillas and Molina, 1997).

## 6. Benthic foraminifera

Benthic foraminifera, although scarce, were also found in all the studied samples. The planktic/benthic ratio is higher than 99% in most samples, except for one (sample-340) with 10% benthic foraminifera. The benthic foraminiferal assemblages are composed of mixed calcareous and agglutinated foraminifers (Fig. 7). According to Moullade (1984), the high percentage of agglutinated taxa found at La Ceiba would characterize a lower bathyal depth. The most abundant morphotypes are epifaunal plano-convex and biconvex trochospiral, which are common at oceanic depths from 1600–2700 m (Corliss and Chen, 1988). Several bathyal and abyssal species were also determined, including *Stensiöina beccariiiformis*, *Spiroplectamina spectabilis*, *Osangularia velascoensis*, *Nuttalides trümpyi*, and *Gaugryina pyramidata*. We also found higher percentages of other

species whose upper depth limits are useful in paleobathymetric interpretations: *Cibicoides hyphalus*, *Gyroidinoides globosus*, and *Nuttalinella florealis*. According to Morkhoven et al. (1986), the upper depth limit of these species is at the lower–middle bathyal boundary (1000 m depth). Assemblages described by Thomas (1990) in the lower bathyal depths are similar to ours, including important percentages of *Gyroidinoides nitidus* and *Osangularia* spp. Most of these species belong to the Velasco-type fauna (Berggren and Aubert, 1975).

Three assemblages that were recognised in the study section are related to changes in the relative abundance of epifaunal and infaunal species (Fig. 7):

1. Assemblage I (A. mayaroensis biozone and lower P. hantkeninoides biozone). Assemblage I has mixed epifaunal and infaunal morphogroups. The lower A. mayaroensis biozone has the highest diversity in the whole section (Fig. 7). Infaunal morphogroups are clearly dominated by cylindrical tapered species (*G. pyramidata*, *Clavulinoides trilatera*, and laevidentalinids) and flattened tapered species such as *Spiroplectamina spectabilis* and *S. israelsky*. Epifaunal morphogroups are more abundant (59–61%) with plano-convex trochospiral (*Gyroidinoides nitidus*, *S. beccariiiformis*, *N. trümpyi*) and biconvex trochospiral forms (*Osangularia* sp.).
2. Assemblage II (upper P. hantkeninoides biozone). In Assemblage II, benthic foraminifera are rather scarce. Infaunal morphogroups increase from 28–57% in the uppermost P. hantkeninoides biozone, where they are represented by cylindrical tapered taxa (*G. pyramidata* and *C. trilatera*). Within epifaunal morphogroups, plano-convex trochospiral (*G. depressus*, *G. nitidus*, *Nuttalinella coronula*, and *N. trümpyi*) and biconvex species (*Osangularia* spp.) dominate along with tapered taxa such as *Bathysiphon* and *Rhizammina*.
3. Assemblage III (P. pseudobulloides and G. compressa biozones). In Assemblage III, infaunal morphogroups abundance decreases 40% between the last Cretaceous sample (Assemblage II) and the first Paleocene sample (Assemblage III). There are no relevant changes in diversity in this interval (Fig. 7). Infaunal morphogroups are 10–12% of the benthic foraminiferal assemblages in the lowermost Danian and slightly more in the G. compressa biozone. Epifaunal morphogroups from the lower Paleocene are characterized by plano-convex trochospiral (*N. florealis*, *N. truempyi*, and *C. hyphalus*) and biconvex trochospiral forms (*Osangularia* sp.).

According to Jorissen et al. (1995), deep infaunal foraminifera inhabited sediment under mesotrophic conditions with enough organic matter to sustain infaunal and epifaunal taxa. We consider that this was the most probable paleoenvironmental situation during the late Maastrichtian at La Ceiba, with sufficient supply of food particles for benthic

foraminifera (assemblages I and II). Assemblage I suggests somewhat more oligotrophic conditions than assemblage II. Under real oligotrophic (food-limiting) conditions, the underlying sediment is not provided with metabolizable food particles, which are consumed by the epifaunal taxa at the sediment surface. Epifaunal morphogroups are thought to live in the upper sediment layer, but under food-limiting conditions, they can move to the sediment surface. This situation prevailed at La Ceiba during the lower Danian (Assemblage III). Due to this lack of nutrient supply, infaunal species abundance decreased 40% from the uppermost Maastrichtian (assemblage II) to assemblage III.

## 7. Discussion

According to the benthic foraminiferal assemblages, we interpret that the La Ceiba section was deposited at lower bathyal depths. This finding helps to interpret the nature of the clastic unit in this section. The paleobathymetric datum allows us to reject those interpretations that suggest a sea-level lowstand in the origin of the K/P-La Ceiba sandstone unit. This hypothesis, suggested by Stinnesbeck et al. (1993) and Keller et al. (1994a), was proposed to support a deltaic to inner neritic environment of deposition for the clastic unit in several Mexican sections. We consider that a 1000 m sea-level fall took place at La Ceiba in such a short period.

Stinnesbeck et al. (1993) and Keller et al. (1994b) also considered that the boundaries between the clastic subunits in some sections of northeastern Mexico were unconformities, suggesting that deposition of the clastic unit occurred during a long period. However, we consider that the boundaries among the different subunits of the La Ceiba clastic unit are not unconformities since they are nonerosional. This interpretation was also suggested by Bohor (1996) for other K/P boundary sections in northeastern Mexico. The clastic unit cannot have been deposited over a long period since its architectural characteristics show a high-sedimentation rate in upper flow regimes, and this suggests that the K/P sandstones were deposited rapidly during a very short period.

In their study on cross-laminated layers of the K/P boundary sandstones at La Lajilla, Smit et al. (1994c) noticed paleocurrent directions oriented at almost 180°. Later, Smit et al. (1996) found similar data at the La Ceiba section that were interpreted as the back-and-forth passage of different tsunami megawaves. This may be right for other shallow Gulf Coast sections, but it does not explain the origin of the La Ceiba clastic unit because it represents deeper waters. According to Harvey (1976) and Bohor (1996), waves can only move grains back and forth on the seafloor in shallow water, creating strong return currents only after breaking upon a shoreface.

At the study section, we found dominant paleocurrent directions varying 130° (from SW to N), which can be explained as representing unidirectional flow currents. We

only identified a cross-laminated level with a NE paleocurrent direction near the top of the sandstone unit (Fig. 2), which is more difficult to explain with a unidirectional flow current hypothesis. However, this set of cross-laminations may also be explained as local up-current inclination on antidune ripples from a turbidite upper flow regime (Skipper, 1971; Bohor and Betterton, 1993; Bohor, 1996). All these data support a sediment gravity flow genesis for the K/P clastic deposits at La Ceiba, as suggested by Bohor (1994, 1996). At least at the La Ceiba section, the paleo-depth of depositional environments (more than 1000 m) avoids invoking a series of oscillating megawaves to explain the deposition of the clastic unit.

The possibility of a very short sedimentary hiatus at the top of the *P. hantkeninoides* biozone and the hiatus at the base of the Danian impede us from establishing the true extinction pattern at La Ceiba. However, the biostratigraphic data from Tlaxcalantongo suggests a gradual extinction pattern beginning below the clastic unit and ending above it (López-Oliva, 1996). These data indicate that several species, such as *P. intermedia*, *G. rosebudensis*, *G. stuartiformis*, *P. hariaensis*, *P. carseyae*, or *P. hantkeninoides*, disappeared through the uppermost part of the Maastrichtian Méndez Formation. All these species are rare in the size fraction larger than 63 µm, according to López-Oliva (1996). Similar extinction patterns were suggested at other Mexican sections such as El Mimbral, La Parida, La Sierita, El Mulato, and Los Ramones (Keller et al., 1994a; López-Oliva, 1996; López-Oliva et al., 1998). However, our biostratigraphic data from La Ceiba indicate that nearly all the Maastrichtian planktic foraminiferal species are present in the upper Maastrichtian interval (except for *P. multicamerata* and *A. blowi*; Fig. 4).

Keller (1988, 1989, 1996) and Keller et al. (1993, 1995) also suggested a similar gradual pattern of disappearance in other sections from the Tethys and the Gulf of Mexico. In contrast, our planktic foraminiferal biostratigraphic studies in Tunisian and Spanish sections showed clear catastrophic extinction patterns (Molina et al., 1996, 1998; Arz and Arenillas, 1998, 1999a,b). For this reason, we consider that most of the apparent extinctions just prior to the K/P boundary identified in low-latitude sections may be caused by the Signor–Lipps effect (Molina et al., 1996, 1998; Arenillas et al., 2000). According to Signor and Lipps (1982), sampling could be responsible for some of the observed patterns. Even if the samplings are sufficiently detailed, a similar effect occurs if the sample residue is not intensively scanned (Molina, 1995). In this case, the Signor–Lipps effect may be minimized, and then the end result is a K/P-planktic foraminiferal catastrophic mass extinction.

The few Maastrichtian specimens in the clastic unit are probably reworked, bearing in mind the internal sedimentological features of these deposits. They are more abundant in the lower beds of the clastic unit, precisely where the grain size is similar to planktic specimens. Smit et al. (1996) identified bioclasts of shallow-water origin, such as orbitoid

foraminifers and bryozoans, in these beds, and we have also observed echinoderm spines. Unidirectional currents could transport terrigenous sands and shallow-water bioclasts from nearshore areas into deeper basins, and probably these reworked specimens behaved as the terrigenous grains during the deposition of the clastic unit.

The hiatus at the base of the Danian did not allow us to research into the last and first appearance datum of possible Maastrichtian survivor species and new Danian evolving species. We have found some isolated Maastrichtian specimens, but they were clearly reworked. The first Danian assemblage in the Velasco Formation has species with perforate cancellate and spinose wall texture (*Eoglobigerina*, *Parasubbotina*, and *Subbotina*), perforate cancellate and nonspinose wall texture (*Praemurica*), and perforate smooth wall texture (*Globanomalina*). No *Parvularugoglobigerina* and *Globoconusa* species, typical of G. cretacea and Pv. eugubina biozones, were found in these first Danian samples. With these data truncated by the hiatus, we can only affirm that there is no evidence for Cretaceous survivor species into the Velasco Formation, except for *G. cretacea*. Therefore, the La Ceiba data do not refute the catastrophic mass extinction hypothesis (Smit, 1982, 1990; Smit and Nederbragt, 1997). Moreover, this extinction probably coincides with the base of the microspherules layer.

According to the benthic foraminiferal data, the infaunal morphogroups decreased in earliest Danian from assemblage II to assemblage III. However, the lack of data from the lowermost Danian also prevented us from obtaining detailed information about when and how the decrease of infaunal morphogroups took place (drastic versus gradual decrease). The change in morphotypic composition suggests a collapse of the food supply during the missing interval, related to an important fall in primary productivity in the ocean. The hypothesis of a possible bolide impact during this interval affecting global photosynthesis (Alvarez et al., 1980) and primary productivity is consistent with the changes observed in benthic foraminifera fauna at La Ceiba, and similar to those described by other authors (Thomas, 1990; Peryt et al., 1997; Kuhnt and Kaminski, 1993). The slight increase of infaunal morphogroups in assemblage III suggests a small increase in food supply to the seafloor in the *G. compressa* biozone.

It is known that an early Danian sea-level fall represented in the Gulf Coast sections (Mancini and Tew, 1993) caused an erosional gap in shallow-marine sections such as at Brazos River (Texas) and Moscow Landing (Alabama). However, it is difficult to interpret the basal Danian hiatus at La Ceiba with a similar eustatic cause because it is a deeper section, although eustatic changes could also cause hiatus at deep-marine sections due to depositional cessation. Nevertheless, it is not possible to determine the cause of this hiatus with a single section because we do not know if this hiatus is local or regional. Although we could not accurately establish whether the planktic foraminiferal mass extinction coincides with the base of the microspherules layer due to

this hiatus, the clastic unit was closely related to the K/P impact event. The Chicxulub megatsunami waves were probably unable to transport, deposit, or shape this sandstone due to the deep depositional setting at La Ceiba. However, rapid sedimentation is very probable above the Gulf Coast shelf due to disturbances associated with the K/P impact event. The energy transmitted from the Chicxulub impact could cause the collapse of continental margins and generate large tsunami waves affecting shelf sedimentation (Bourgeois et al., 1988; Bralower et al., 1998; Klaus et al., 2000).

A strong 'shower' of impact microtektites could have fallen on the whole Gulf Coast area. Moreover, the megatsunami-generated backwash could have dragged a large amount of sediment from the coast and inner shelf to the outer shelf. The huge accumulation of impact and tsunami-generated sediments above the Gulf Coast shelf and probable seismic events associated with the impact could destabilize unconsolidated shelf sediments. Unstable deposits with impact microtektites may have been mobilized from the shelf, forming sediment gravity currents toward the slope and deep basin (Bohor, 1996). According to Bralower et al. (1998), the deposition of gravity flow through the Gulf of Mexico basin may have occurred in several phases, although much of the impact-derived material would have accumulated within hours to days of the impact. In summary, we consider that the La Ceiba clastic deposits were emplaced in a single-pulse event (Bohor, 1996) and deposited at lower bathyal depths by turbidite currents. This event agrees with the impact theory of Alvarez et al. (1980), coinciding with the asteroid impact on the Yucatan Peninsula (Smit et al., 1992a,b, 1994a,b,c, 1996; Bohor, 1994, 1996).

## 8. Conclusions

Based on sedimentological and micropaleontological studies, we interpret the clastic unit at the La Ceiba section as formed by sediment gravity flow probably emplaced in a single-pulse event and directly related to the K/P impact event. The clastic unit displays a fining-upward trend similar to a turbidite sequence and contains a basal subunit consisting of calcareous marls rich in microtektites altered to clay minerals, abundant detrital quartz, mica minerals, and shocked quartz. This clastic unit is sandwiched between two pelagic marly units (the Méndez and Velasco Formations), and the benthic foraminiferal assemblages suggest that the La Ceiba section was deposited at lower bathyal depths (more than 1000 m depth). The paleodepth of deposition does not support sea-level lowstand hypotheses to explain the nature of this clastic deposit, as a 1000 m drop in sea-level is not possible at La Ceiba in such a short period of time. For the same reason, it is difficult to explain its deposition as the back-and-forth passage of different tsunami megawaves because this section is too deep. The

evidence suggests that the clastic deposit with impact microtektites may have been mobilized from the shelf, forming sediment gravity flows toward the slope and deep basin.

The K/P boundary at La Ceiba should be placed at the base of the clastic (microspherules) layer since it is equivalent to the base of the boundary clay at El Kef stratotype. According to the criteria used to place the boundary at El Kef, the K/P boundary should be placed at the base of the layer that contains all the K/P mineralogical and geochemical anomalies, including the Ir anomaly, microspherules (altered microtektites), and shocked quartz. We identified a short hiatus affecting the lower part of the Danian, including G. cretacea and Pv. eugubina biozones and the lower part of the P. pseudobulloides biozone. This fact precludes establishing the true planktic foraminiferal extinction pattern at La Ceiba, although we have found nearly all the Maastrichtian planktic foraminiferal species in the upper Maastrichtian sample. Our results do not support a gradual mass extinction pattern at La Ceiba, but all the micropaleontological and sedimentological evidence is consistent with the K/P impact theory and the asteroid impact on the Yucatan Peninsula.

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