Foraminiferal biostratigraphy and paleoenvironmental reconstruction at the Yaxcopoil-1 drill hole, Chicxulub crater, Yucatán Peninsula

José A. ARZ,[1*] Laia ALEGRET,[2] and Ignacio ARENILLAS[1]

[1]Departamento de Ciencias de la Tierra, Universidad de Zaragoza, E-50009 Zaragoza, Spain
[2]Department of Earth Sciences, University College, London, UK
[*]Corresponding author. E-mail: josearz@unizar.es

Abstract–The Yaxcopoil-1 (Yax-1) drill hole comprises Cretaceous limestones and calcarenites, the K/P boundary cocktail unit (including impact breccia), and a Danian marly clay layer overlain by calcareous marls. The biostratigraphy, paleobathymetry, and environmental turnover across the K/P interval were inferred after analyzing the planktic and benthic foraminiferal assemblages. The Cretaceous samples only contain a few poorly preserved planktic foraminifera of a middle Campanian to Maastrichtian age, while low-diversity benthic foraminiferal assemblages suggest a sufficient nutrient supply to the sea floor and a shallow neritic, occasionally stressed environment. The impact breccia and the redeposited suevite are overlain by a 46 cm-thick dolomitic calcareous sandstone unit that contains scarce, reworked planktic foraminiferal specimens. This unit probably represents the uppermost part of the initial infill of the crater. The uppermost centimeters of this unit are bioturbated, and its top represents a hiatus that spans at least the *G. cretacea, Pv. eugubina,* and part of the *P. pseudobulloides* biozones. This unit is overlain by a 3–4 cm-thick marly clay layer that represents a condensed layer. Benthic foraminiferal assemblages suggest a low food supply to the sea floor and environmental instability during the deposition of the marly clay layer. The increase in diversity of the assemblages indicates that the environmental conditions improved and stabilized from the *G. compressa* biozone toward the *A. uncinata* (P2) biozone. The Danian planktic and benthic foraminiferal assemblages indicate a deeper, probably bathyal environment.

INTRODUCTION

It is widely accepted that the 180 km-wide Chicxulub structure in the Yucatán Peninsula (Mexico) is the result of a large asteroid impact (Penfield and Camargo 1981). Hildebrand et al. (1991) suggested that the Chicxulub crater had been formed during the Cretaceous/Paleogene (K/P) boundary, mainly based on the similarity between the geochemical and isotopical composition of andesitic and carbonate rocks from the crater and Haitian K/P tektites. Since then, many studies have been performed to confirm the K/P age for the Chicxulub impact. Several authors (e.g., Sigurdsson et al. 1991; Smit et al. 1992; Blum et al. 1993) have shown that the Chicxulub crater melt rocks have geochemical and isotopic similarities with Beloc (Haiti) tektites, and tektites in the K/P deposits at El Mimbral (Mexico). Finally, $^{40}Ar/^{39}Ar$ dating has shown that the Chicxulub crater melt rock and K/P boundary microtektites in Beloc and El Mimbral sections have the same age and that the

K/P boundary is approximately 65 Myr-old (Sharpton et al. 1992; Swisher et al. 1992).

Nevertheless, the dating of the Gulf Coast and Caribbean K/P sediments usually associated with the Chicxulub impact is a controversial issue. Such an impact would have caused major coastal flooding, megatsunamis, and destabilization of the continental margin of North America (e.g., Norris et al. 2001; Soria et al. 2001), thus triggering the deposition of the so called "K/T boundary cocktail" unit all around the Gulf of Mexico (Bralower et al. 1998). This unit includes a distinctive mixture of reworked microfossils such as foraminifera, impact-derived materials, and lithic fragments. In Haiti, north-eastern Mexico, and the states of Texas and Alabama, the K/P cocktail unit is characterized by a sandstone complex usually called the "Clastic Unit," which contains a basal layer with abundant mm-size spherules that have been interpreted as altered microtektites derived from the Chicxulub impact crater (Bourgeois et al. 1988; Smit et al. 1996). In southern Mexico, Cuba, Guatemala, and Belize, the K/P cocktail unit is

characterized by a chaotic breccia up to several tens of m thick, which is overlain by the K/P ejecta sequence (Iturralde-Vinent 1992; Pope et al. 1999; Grajales-Nishimura et al. 2000; Molina et al. 2002). In the Chicxulub structure, impactite sequences, including different impact breccia deposits (monomict impact breccia and suevite) and redeposited suevites have also been identified (Hildebrand et al. 1991).

Most specialists agree that the K/P cocktail unit was deposited in coincidence with the K/P boundary in one geologically instantaneous event clearly associated with the Chicxulub impact (Smit 1999; Grajales-Nishimura et al. 2000; Arz et al. 2001a, b). Nevertheless, based on planktic foraminiferal biostratigraphical data in sections from the Gulf of Mexico and the Caribbean area, other authors have recently proposed that several impacts occurred across the K/P boundary and that the Chicxulub impact predated the K/P boundary by about 300 Kyr (Stinnesbeck et al. 1999, 2001; Keller et al. 2002). Their main argument is based on several horizons of microspherules found in the La Sierrita area (northeast of Mexico). However, these apparent multiple microspherule horizons can be easily explained by diapir-like structures (Smit et al. 1996) or slumping processes that mostly affect the spherule-bearing level and occasionally the sandy facies (Soria et al. 2001).

The Yaxcopoil-1 core was drilled by the Chicxulub Scientific Drilling Program (CSDP) in 2001 and 2002. One of the main objectives of this program was to determine the role of the Chicxulub impact event in the K/P mass extinction.

Recently, Keller et al. (2004) performed a biostratigraphic, magnetostratigraphic, and geochemical study of the Yaxcopoil-1 core and concluded that the Chicxulub impact predated the K/P boundary by ~300,000 yr, as previously suggested by these same authors in the Gulf Coast and Caribbean sections (Stinnesbeck et al. 1999, 2001; Keller et al. 2002). The study of Yaxcopoil-1, thus, offers a good opportunity to test this controversial hypothesis. The aim of our study was to perform a detailed micropaleontological analysis of the K/P interval at Yaxcopoil-1 and to obtain planktic foraminiferal biostratigraphic data to determine the chronostratigraphic position of the Chicxulub impact crater. Moreover, the environmental evolution around the Yucatán peninsula across the K/P interval is not well-understood, and benthic foraminifera are an important tool to infer the paleobathymetry and the environmental conditions of the sea floor at the time of the impact.

MATERIALS AND METHODS

Yaxcopoil-1 was drilled approximately 60–70 km from the center of the Chicxulub impact crater on its southern flank (Fig.1). The well reached a depth of 1510.6 m, but we analyzed the K/P interval between 917 m and 783 m (Fig. 2). We studied planktic and benthic foraminiferal assemblages from 32 samples recovered by the CSDP to perform biostratigraphic and paleoenvironmental analyses.

Below 894.94 m, the Cretaceous deposits consist of shallow shelf calcarenites and limestones and a suevitic dike
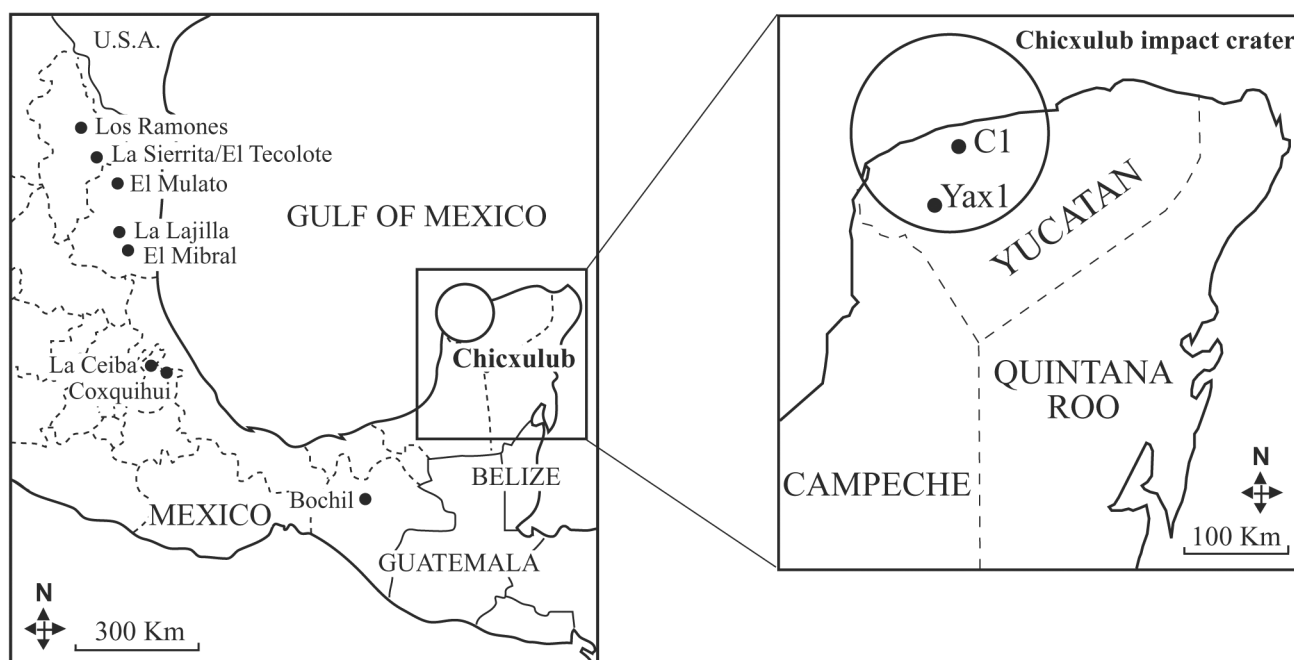

Fig. 1. Geographical location of the Yaxcopoil-1 drill hole and some K/P boundary sections from central and northeastern Mexico (Yax1 = Yaxcopoil-1, C1 = Chicxulub 1).

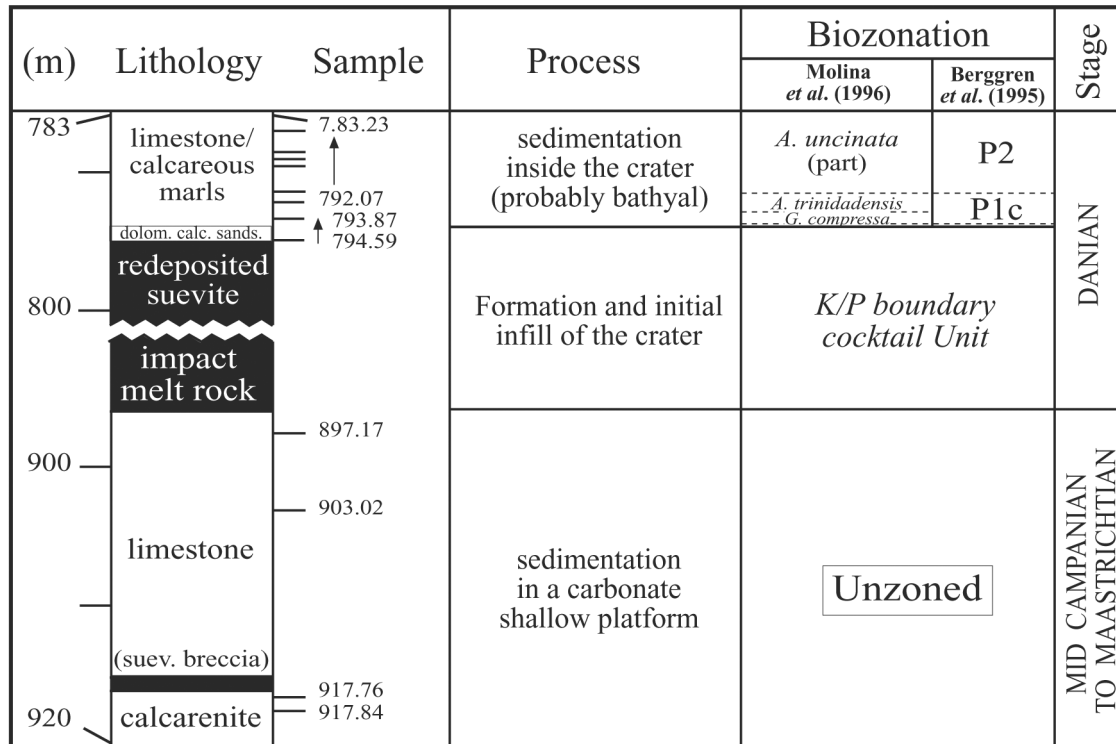| (m)	Lithology	Sample	Process	Biozonation		Stage
				Molina *et al.* (1996)	Berggren *et al.* (1995)	
783	limestone/ calcareous marls	7.83.23	sedimentation inside the crater (probably bathyal)	*A. uncinata* (part)	P2	DANIAN
		792.07 793.87 794.59		*A. trinidadensis G. compressa*	P1c	
	dolom. calc. sands. redeposited suevite		Formation and initial infill of the crater	*K/P boundary cocktail Unit*		
800	impact melt rock					
900	limestone	897.17 903.02	sedimentation in a carbonate shallow platform	Unzoned		MID CAMPANIAN TO MAASTRICHTIAN
920	(suev. breccia) calcarenite	917.76 917.84				

Fig. 2. Schematic diagram of the studied interval, sedimentological processes, and biozonation at the Yaxcopoil-1 drill hole (dolom. calc. sands. = dolomitic calcareous sandstone).

between 915.99 m and 916.79 m. We studied four samples in this interval (897.17 m–917.84 m), where foraminiferal tests are poorly preserved. Since planktic foraminifera are almost absent in this interval, no unequivocal age attributions were obtained. Benthic foraminiferal assemblages were analyzed in these four Cretaceous samples, although the last three contained scarce specimens.

The K/P cocktail unit, which includes the 100 m-thick impactite sequence, was recovered from 894.94 m to 794.14 m. The impact sequence consists of polymict and monomict impact breccia and suevite, with a 13 m-thick redeposited suevite unit toward its top. Higher up in the K/P cocktail unit, and overlaying the redeposited suevite, there is a 46 cm-thick dolomitic calcareous sandstone unit with common amalgamated dolomite crystals. We studied 13 samples from this unit (794.60 m to 794.14 m), where three subunits can be recognized. The lower subunit consists of a 24 cm-thick (794.60 m–794.36 m) crossbedded body of very dolomitized, calcareous sandstones with some microconglomerate layers intercalated. The cross-lamination and the microconglomeratic layers indicate high current activity during its deposition. The middle subunit consists of a 17 cm-thick (794.36 m–794.19 m), predominantly laminated, dolomitic calcareous sandstone layer. The upper subunit consists of a 5 cm-thick (794.19 m–794.14 m) bioturbated, dolomitic calcareous sandstone bed, the top of which represents an omission surface. In spite of the fact that

we intensively scanned the sediment in this interval, foraminifera are practically absent in the 13 samples recovered from the dolomitic calcareous sandstone unit, though some reworked specimens were found (Figs. 3 and 4). The dolomitization processes affecting these rocks might be one of the reasons for the scarcity of foraminifera in this unit.

A 3–4 cm-thick (794.14 m–794.11 m) laminated marly clay layer with ichthyoliths overlies the dolomitic calcareous sandstone unit. Sample 794.11 m is barren of planktic foraminifera, and it yields only few benthic specimens. Higher up in the core (794.10 m), Danian laminated and occasionally bioturbated calcareous marls overlie the K/P cocktail deposits and the marly clay layer. The interval between 794.10 m to 793.99 m contains scarce and poorly preserved foraminifera, which become more abundant and better preserved higher up in the studied section (up to 783 m).

One of the main problems found when analyzing the foraminifera was to obtain clean and undamaged specimens from the Yaxcopoil-1 deposits, which mainly consist of limestones, calcareous marls, calcarenites, and dolomitic calcareous sandstones. Following standard procedures, we disaggregated part of each sample in water with diluted H_2O_2 and Calgon and sieved them into 38 μm–63 μm, 63 μm–106 μm, and ≥106 μm size fractions. Since the sieves were reused to wash each sample, it was necessary to clean them thoroughly with water jets, submerge them in a dye (i.e., methylene blue), and dry them. After this procedure, the

Lithology	(m)	Sample	Biozonation			Stage
Foraminifera-rich calcareous marls	793.85	— 793.87				
		— 793.91				
	793.96 —		*G. compressa*	P1c		
Laminated/bioturbated calcareous marls		— 793.99				
		— 794.03				
		— 794.06				
		— 794.08				
		— 794.10	*P. pseudob.* ?	P1b		
Laminated dark marly clay layer	794.11 —	— 794.11	Condensed layer			
Bioturbated dolomitic calcareous sandstone		— 794.14				
		— 794.16				
		— 794.18				
	794.19 —	— 794.23				
Predominantly laminated dolomitic calcareous sandstone		— 794.26	Reworked foraminifera		*K/P boundary cocktail Unit (upper part)*	DANIAN
		— 794.29				
	794.31 —	— 794.31				
		— 794.33				
		— 794.37				
	794.41 —	— 794.44				
Crossbedded dolomitic calcareous sandstone with occasional microconglomerates		— 794.49	No preserved foraminifera			
	794.54 —	— 794.55				
	794.60	— 794.59				

Fig. 3. Detail of the upper part of the K/P boundary cocktail unit and lower Danian marly clay layer and calcareous marls at the Yaxcopoil-1 drill hole.
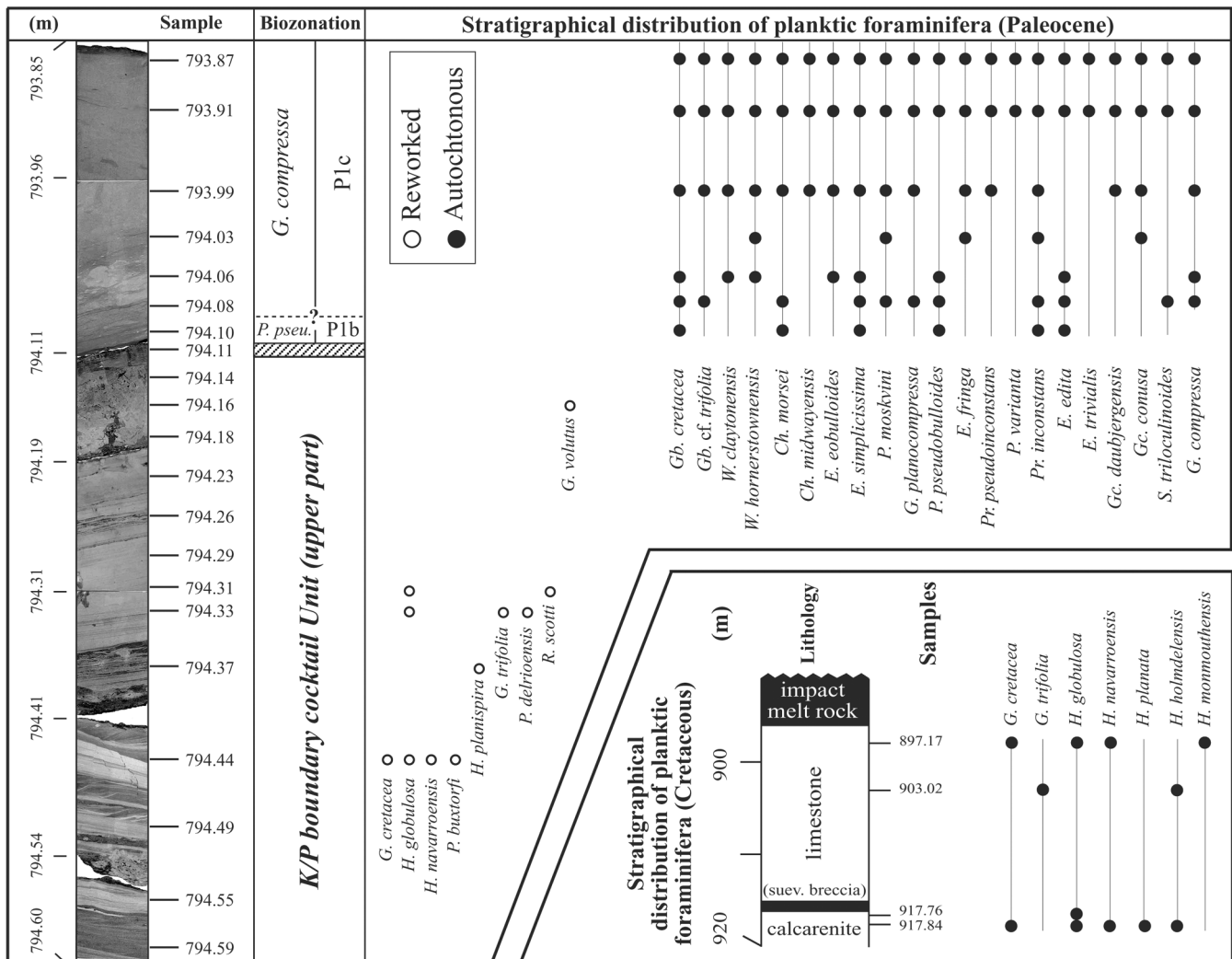
Fig. 4. Stratigraphical distribution of Cretaceous and Paleocene planktic foraminiferal species at the Yaxcopoil-1 drill hole.

possible contaminated specimens were dyed blue and, thus, were easily recognizable. The washed residue was soaked in water and sonically agitated (for 5–10 sec) to remove the sediment infilling from the foraminiferal tests. To obtain more and better preserved specimens, we also used a different preparation method to extract foraminifera from carbonate rocks with dilute acids. According to Moura et al. (1999), the best results are obtained when soaking in 0.1 M HCl for 60–120 min. We kept the samples in 0.1 M HCl for an average of 90 min. Finally, the residue was intensively scanned in size fractions larger than 38, 63, and 106 μm. All the picked specimens were identified, sorted, and fixed to a standard 60-square micropaleontological slide.

Benthic foraminiferal microhabitat preferences, mainly based on morphological features, can be explained in terms of nutrient supply to the sea floor and sea water oxygenation (e.g., Bernhard 1986; Jorissen et al. 1995). According to these authors and to Alegret et al. (2001), all benthic foraminiferal taxa were allocated into morphogroups with an inferred

infaunal or epifaunal mode of life. These data allowed us to infer the paleoenvironmental turnover across the K/P boundary.

STRATIGRAPHIC POSITION OF THE K/P BOUNDARY

The K/P boundary was formally defined at the base of a dark clay layer ("boundary clay") in the El Kef stratotype section (Tunisia), while other horizons such as the base of the tsunamite, the planktic foraminiferal mass extinction horizon, the lowest stratigraphic datum of the dinoflagellate *Danea california,* or the Ir-maximum in the boundary clay were rejected (Cowie et al. 1989). The use of the boundary clay at El Kef as the main K/P marker bed is attractive because this layer contains impact evidence, and its base coincides with the K/P planktic foraminiferal mass extinction (Arenillas et al. 2000). Since the lowest stratigraphic datum of the first Paleogene planktic foraminiferal species almost coincides with the top of the boundary clay (Arenillas et al. 2002), this

level corresponds approximately to the P0 zone of Berggren et al. (1995).

In the Tethyan sections such as El Kef, the impact ejecta are concentrated in a mm-thin, rust-red layer at the basal part of this boundary clay (Smit and Klaver 1981; Robin and Rocchia 1998). The impact evidence include an Ir-anomaly, microspherules (interpreted as altered microkrystites), Ni-rich spinels, and shocked minerals. Many authors have attempted to look for these impact indicators to locate the K/P boundary in other sections, and the Ir-anomaly has been the most commonly used criterion. However, the criteria used to recognize a chronostratigraphic boundary must not be confused with the boundary itself. A chronostratigraphic boundary is a stratigraphic horizon that is theoretically isochronous, having the same age everywhere and no thickness. In the case of the K/P boundary, this horizon corresponds to the base of the boundary clay at El Kef, so all impact evidence overlies the K/P boundary and are consequently Paleogene in age.

The most useful way to locate the K/P boundary in other sections is to identify the lithostratigraphic unit with the impact ejecta and to place the boundary at the base of this unit (Smit and Romein 1985; Smit et al. 1996; Smit 1999; Arenillas et al. 2002). Since the K/P cocktail units in the Gulf of Mexico and Caribbean contain impact evidence, the K/P boundary in these areas must be placed at the base of these units: 1) in sections from Haiti, northeastern Mexico, Alabama, and Texas, the K/P boundary must be placed at the base of the complex Clastic Unit because it contains altered microtektites in its basal part. This Clastic Unit corresponds to the deposits generated directly by the passages of the post-impact megatsunami waves (Bourgeois et al. 1988; Smit et al. 1992) and/or impact-originated gravity flow deposits and slumps (Bohor 1996; Bralower et al. 1998; Soria et al. 2001); 2) in southern Mexican and Cuban sections, the K/P boundary must be placed at the base of the Breccia Unit, because this K/P breccia corresponds to the platform margin collapse and debris-flow deposits that occurred around the Chicxulub impact crater (Iturralde-Vinent 1992; Grajales-Nishimura et al. 2000); 3) at Yaxcopoil-1, which is located inside the Chicxulub impact crater, the K/P boundary must be placed at the base of the impact sequence (894.94 m).

BIOSTRATIGRAPHY

The precise age of the Chicxulub impact must be determined by analyzing the micropaleontological record of the materials directly underlying and overlying the K/P cocktail unit, as well as the suevitic breccia matrix and the dolomitic calcareous sandstone that overlie the impactite sequence. We obtained the following results after a detailed study of planktic foraminiferal assemblages at Yaxcopoil-1.

Uppermost Cretaceous

The uppermost Cretaceous samples that were studied at Yaxcopoil-1 (917.84 m–897.17 m) contained only a few poorly preserved planktic foraminifera, so it was not possible to obtain precise age attributions. We identified scarce specimens of *Guembelitria cretacea, G. trifolia, Heterohelix globulosa, H. navarroensis, H. planata, Hedbergella holmdelensis,* and *H. monmouthensis* (Figs. 4 and 5).

The occurrence of *H. navarroensis, H. planata,* and *H. monmouthensis* suggests that the age of the interval just under the impact sequence is middle Campanian to Maastrichtian. Due to the lack of complex heterohelicids, globotruncanids, and rugoglobigerinids, specific age inferences were not obtained. The scarcity of planktic foraminifera in the K/P interval makes it difficult to establish the pattern of extinction at Yaxcopoil-1. Among all the species identified in the Cretaceous sediments, only *G. cretacea* and *G. trifolia* were recorded in the Danian, i.e., above 794.11 m. Most micropaleontologists consider that both species are survivors of the K/P mass extinction (see Arenillas et al. 2000).

K/P Cocktail Unit

One way to determine the age of the K/P cocktail unit is to analyze the micropaleontological record in the impact breccia matrix, as well as that of the underlying and overlying sediments. Although, unfortunately, we did not study samples from the impact breccia at Yaxcopoil-1, Ward et al. (1995) reported upper Maastrichtian planktic foraminifera (including *Abathomphalus mayaroensis*) from the breccia matrix in several wells located in and around the Chicxulub structure. According to the nature of the impact breccia, which is composed of a mixture of fragments from the target lithologies, these planktic foraminiferal specimens are clearly reworked. Their presence, together with the lack of Paleogene species, is compatible with the inferred K/P age of the base of the impactite sequences.

In the 46 cm-thick dolomitic calcareous sandstone unit overlaying the redeposited suevite (794.60–794.14 m) at Yaxcopoil-1, we found only 11 planktic foraminiferal specimens that belong to the species *Guembelitria cretacea, G. trifolia, Heterohelix globulosa, H. navarroensis, Praeglobotruncana delrioensis, Hedbergella planispira, Planomalina buxtorfi, Rugoglobigerina scotti,* and *Globigerinelloides volutus* (Figs. 4 and 5). They represent reworked, mixed assemblages containing species from the Albian-Turonian (*P. delrioensis, H. planispira, P. buxtorfi*) and Campanian-Maastrichtian (*H. navarroensis, R. scotti*). All the foraminifera were found in the size fractions larger than 63 μm and 106 μm. Similar reworked Cretaceous assemblages have been found in the K/P cocktail unit from northeastern Mexico (Smit et al. 1996; Smit 1999; Arz et al. 2001a, b; Soria et al. 2001; Alegret et al. 2002a) and Cuba (Molina et al. 2002).

The redeposited suevite and dolomitic calcareous sandstone unit probably represent the infill of the crater due to the marine invasion into the cavity just after the K/P boundary impact. Von Dalwigk and Ormö (2001) and Dypvik et al. (2003) have demonstrated that marine craters are commonly invaded by gushing waters immediately after the crater formation. According to von Dalwigk and Ormö (2001), the surging waters not only contain impact ejecta but also fractured lithologies from the target rocks.

Keller et al. (2004) propose a different sedimentological and biostratigraphic interpretation of the dolomitic calcareous sandstone unit. These authors describe this unit as laminated dolomitic and micritic limestones containing burrows and glauconitic layers and suggest that it was deposited in a low-energy hemipelagic environment ($\approx$100 m deep). According to Keller et al. (2004), the micritic limestones are rich in recrystallized and poorly preserved late Maastrichtian planktic foraminifera, suggesting that the Chicxulub impact predated the K/P boundary by $\approx$300,000 yr.

We do not agree with Keller et al. (2004) due to several reasons: 1) after analyzing 13 samples in the dolomitic calcareous sandstone unit, which are stratigraphically equivalent to those studied by Keller et al. (2004), we did not identify any foraminiferal-rich micritic limestones. On the contrary, we found scarce reworked planktic foraminifera (and no molds) from older rocks; 2) most of the thin section micrographs of "late Maastrichtian" foraminifera illustrated by Keller et al. (2004) seem to be amalgamated dolomite crystals, which are very abundant in the residue of all the studied samples; 3) the paleoecological conditions inside the crater would not allow the development of the planktic foraminiferal assemblages identified by Keller et al. (2004) because they include typically thermocline and deep, open ocean dweller species such as *A. mayaroensis, G. stuarti, G. arca,* or *G. insignis* (Abramovich et al. 2003); 4) in case the glauconitic layers had been deposited in a normal sedimentary environment under a low sedimentation rate, they should contain frequent glauconitic internal molds of the foraminiferal tests, which have not been observed at Yaxcopoil-1; 5) only one horizon of bioturbation was identified in the studied part of the K/P cocktail unit, corresponding with its uppermost centimeters. This finding agrees with a period of low sedimentation rate that followed the rapid deposition of the K/P cocktail unit, and indicates bioturbation of these sediments by Paleogene organisms. This horizon may be correlated to the one on top of the K/P Clastic Unit in some sections from northeastern Mexico (e.g., Smit et al. 1996).

The dolomitic calcareous sandstone unit at Yaxcopoil-1 is, thus, a key interval to infer the age of the Chicxulub crater. López-Ramos (1973) and Ward et al. (1995) reported a similar, 18 m-thick interval consisting of "Maastrichtian" marls overlying the impact breccia at the Chicxulub-1 well (Fig. 1). They identified the planktic foraminiferal species *Globotruncana rosetta, G. ventricosa, G. lapparenti, G. fornicata, Pseudoguembelina excolata, Heterohelix globocarinata, Pseudotextularia elegans, Planoglobulina carseyae,* and *Globigerinelloides volutus* in this interval and conclude that the Chicxulub impact occurred before the K/P boundary. Nevertheless, if these planktic foraminiferal assemblages were autochthonous, the Chicxulub impact would have occurred at least 2 to 3 Myr before the K/P boundary (Arz and Molina 2002). Therefore, it is more probable that this Chicxulub-1 interval also contains reworked Cretaceous specimens similar to those found in the Yaxcopoil-1 dolomitic calcareous sandstone unit.

Danian

A tentative planktic foraminiferal zonation of the Danian at Yaxcopoil-1 is shown in Fig. 3. We adopted the middle and lower latitude biozonations proposed by Berggren et al. (1995), Molina et al. (1996), Arenillas and Molina (1997), and Olsson et al. (1999). The precise age of the marly clay layer at Yaxcopoil-1 is not clarified because no planktic foraminifera were found at level 794.11 m. We suggest that the marly clay layer might represent an extremely condensed layer deposited above a hiatus related with the omission surface. Caution should be taken when interpreting this marly clay layer since it might not be related to the K/P boundary clay.

We did not identify the *Guembelitria cretacea, Parvularugoglobigerina eugubina,* and probably *Parasubbotina pseudobulloides* biozones (P0, Pα, P1a, and P1b of Berggren et al. [1995]). They may be absent due to the aforementioned hiatus, or they might be condensed in the marly clay layer. The *P. pseudobulloides* biozone has been provisionally included in Fig. 3 because we identified *P. pseudobulloides* in sample 794.10 m, while no specimens of *Globanomalina compressa* were found in this level.

The planktic foraminiferal assemblages identified between 794.09 m and 793.85 m include the following species (Figs. 4 and 5): *Globanomalina compressa, G. planocompressa, Parasubbotina pseudobulloides, P. moskvini, P. varianta, Praemurica inconstans, Pr. pseudoinconstans, Pr. taurica, Eoglobigerina simplicissima, E. eobulloides, E. edita, E. pentagona, E. trivalis, E. tetragona, Subbotina triloculinoides, Globoconusa daubjergensis, Gc. conusa, Woodringina claytonensis, W. hornerstownensis, Chiloguembelina morsei, Ch. midwayensis, Guembelitria cretacea, Gb. trifolia,* and *Gb. irregularis.* These assemblages clearly belong to the *G. compressa* biozone (P1c of Berggren et al. [1995]).

The *Acarinina trinidadensis* biozone (or upper part of P1c of Berggren et al. [1995]) was not recognized at Yaxcopoil-1 probably due to the lack of samples received from this interval. Planktic foraminiferal assemblages identified between 792 m and 783 m belong to the *Acarinina uncinata* biozone (or P2 of Berggren et al. [1995]). These assemblages include *Acarinina*
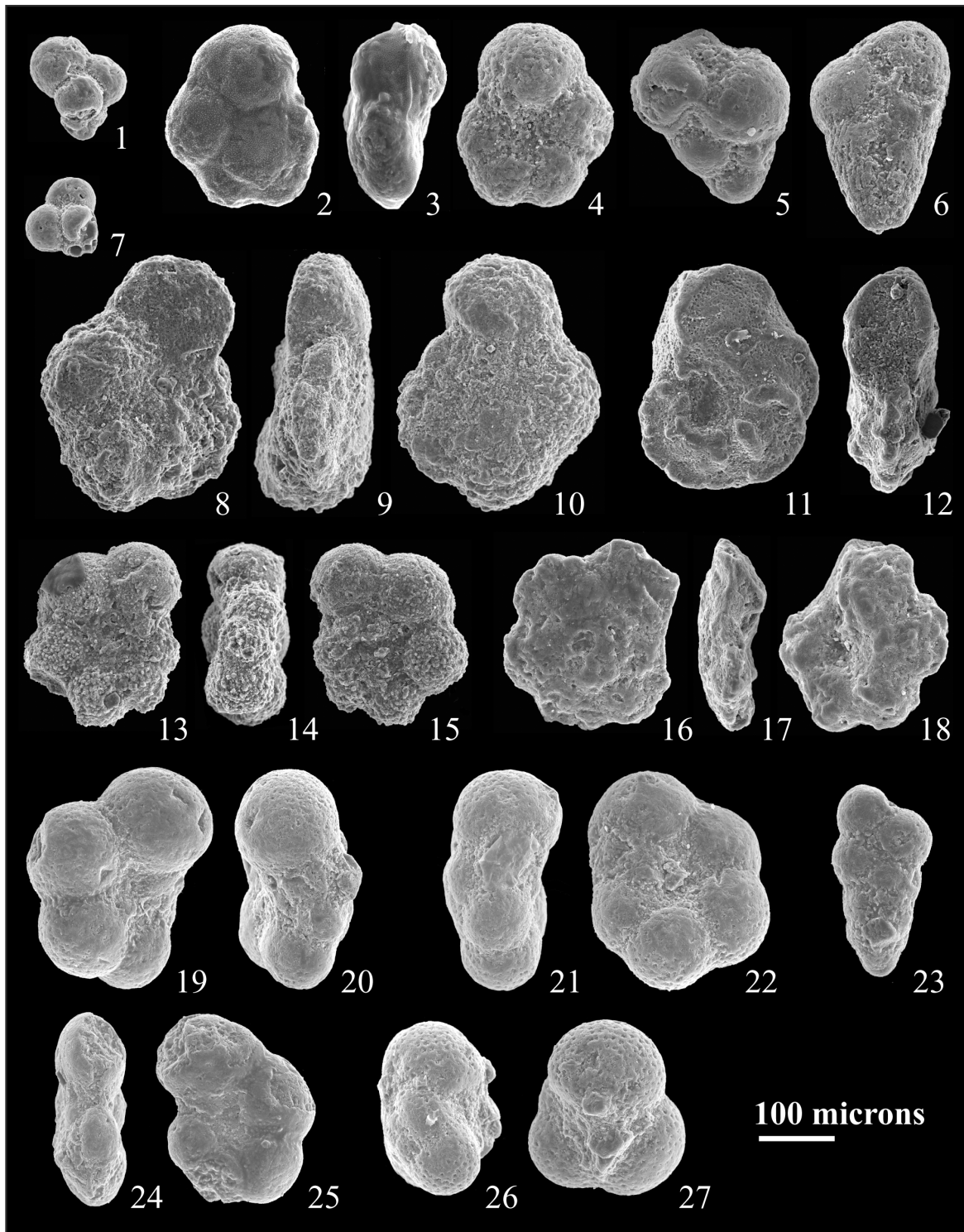
Fig. 5. SEM micrographs of some examined planktic foraminiferal species. Upper Cretaceous: 1) *Guembelitria cretacea* (Cushman), sample 917.84; 2–4) *Hedbergella holmdelensis* (Olsson), sample 903.02; 5) *Heterohelix globulosa* (Ehrenberg), sample 897.17. K/P boundary cocktail unit: 6) *Heterohelix globulosa* (Ehrenberg), sample 794.44; 7) *Guembelitria trifolia* (Morozova), sample 794.33; 8–10) *Rugoglobigerina scotti* (Brönnimann), sample 794.31; 11–12) *Planomalina buxtorfi* (Gandolfi), sample 794.44; 13–15) *Hedbergella planispira* (Tappan), sample 794.37; 16–18) *Praeglobotruncana delrioensis* (Plummer), sample 794.33. Lower Paleogene: 19–20) *Parasubbotina pseudobulloides* (Plummer), sample 793.87; 21–22) *Praemurica inconstans* (Subbotina), sample 793.87; 23) *Woodringina hornerstownensis Olsson,* sample 793.87; 24–25) *Globalomalina compressa* (Plummer), sample 793.87; 26–27) *Subbotina triloculinoides* (Plummer), sample 793.87.
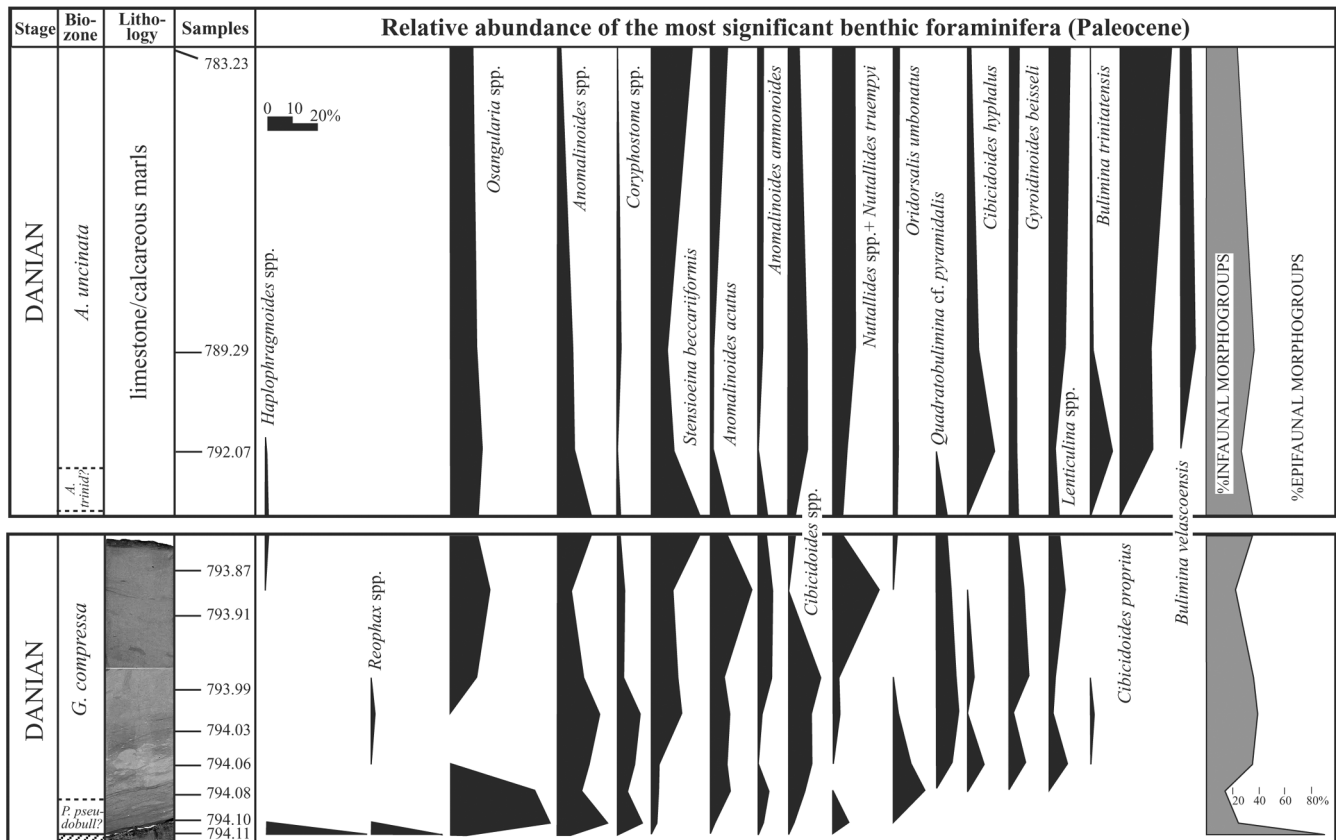
Fig. 6. Relative abundance and distribution of the most abundant benthic foraminiferal taxa across the Danian at the Yaxcopoil-1 drill hole and the percentage of inferred infaunal and epifaunal morphogroups.

uncinata, A. trinidadensis, A. arabica, A. praepentacamerata, Praemurica inconstans, Parasubbotina pseudobulloides, P. varianta, Eoglobigerina edita, E. spiralis, E. trivialis, Subbotina triloculinoides, S. triangularis, Globanomalina compressa, and *G. haunsbergensis* (Figs. 4 and 5).

PALEOENVIRONMENTAL RECONSTRUCTION

The study of benthic foraminiferal assemblages, which strongly depend on environmental parameters, such as nutrient supply or oxygenation of the sea-bottom water, allowed us to infer the paleoenvironmental conditions in the upper Cretaceous and lower Paleogene at Yaxcopoil-1. These results are of special interest because the quantitative changes of benthic foraminifera across the K/P boundary may be correlated with the faunal turnover in the nearby Gulf of Mexico and thus provide a complementary tool for biostratigraphic inferences.

Upper Cretaceous

Benthic foraminifera from sample 917.84 m belong to poorly diversified assemblages (α-Fisher index = 2). They mainly consist of calcareous trochospiral plano-convex

species (*Alabamina*? sp., *Anomalinoides* spp., *Gyroidinoides beisseli, Gyroidinoides* spp.) and the fusiform, subcircular in section *Praebulimina* cf. *carseyae*. The quantitative analysis indicates that the uppermost Cretaceous assemblages at Yaxcopoil-1 consist of a mixture of both infaunal and epifaunal morphogroups, suggesting a sufficient nutrient supply to the sea floor. Nevertheless, the low diversity assemblages indicate a stressed environment, possibly exposed to temporal changes in environmental parameters such as salinity or oxygenation of the bottom water. The composition of the assemblages, their low diversity (α = 2), and the heterogeneity Shannon-Weaver index H (S) = 1.59 suggest that the uppermost Cretaceous sediments were deposited in a shallow, occasionally stressed environment (e.g., Murray 1991).

Few planktic foraminiferal specimens were found in the Cretaceous samples at Yaxcopoil-1. Nevertheless, these assemblages seem to be characterized by low species richness and small planktic foraminiferal test size. They consist of ecological opportunist (*Guembelitria*) and generalist (*Heterohelix* and *Hedbergella*) species similar to those described from central Argentina by Concheiro et al. (2002) and Náñez and Casadío (2002) and from central Egypt by Keller (2002). These planktic foraminiferal assemblages

indicate a very shallow, inner neritic environment probably close to the nearshore zone.

Danian

The lowermost Danian benthic foraminiferal assemblages were found just above the K/P cocktail unit, in the marly clay layer (794.11 m), where planktic foraminifera are absent. Since there is a hiatus comprising the lowermost part of the Danian (*G. cretacea, Pv. eugubina,* and probably, *P. pseudobulloides* biozones), the benthic foraminiferal turnover just after the K/P boundary at Yaxcopoil-1 could not be observed. Changes in benthic foraminiferal assemblages across the K/P boundary were recently documented by Alegret et al. (2001, 2002a, b) in the nearby central and northeastern Mexican sections. According to these authors, the benthic foraminiferal fauna indicate a drastic decrease in the food supply just after the K/P boundary, which is related to the collapse of surface productivity suggested by Zachos et al. (1989), and a staggered pattern of faunal recovery in the lowermost Paleogene. Due to the hiatus at Yaxcopoil-1, the faunal turnover during the lowermost Paleogene cannot be compared with the Mexican sections.

Benthic foraminiferal assemblages found in the marly clay layer at Yaxcopoil-1 are drastically different from those of the uppermost Cretaceous. Only 25 benthic specimens were found in this level, mainly *Haplophragmoides, Clavulinoides,* and *Reophax* (Fig. 6). Alegret (2003) documented an interval comprising the upper part of the *P. pseudobulloides* biozone and the lowermost part of *G. compressa* biozone where the abundance of *Haplophragmoides* increased in sections from northeastern Mexico. We speculate that the high percentage of *Haplophragmoides* at Yaxcopoil-1 might be correlated to the increase in the abundance of this genus documented by Alegret (2003) in the Mexican sections. The low abundance of specimens found in this sample, as well as the high percentage of agglutinated taxa, suggest that dissolution may have played a major role in the marly clay layer deposit.

The genus *Haplophragmoides* may be considered as an opportunistic, shallow infaunal taxon that can move vertically through the sediment depending on food levels and which is tolerant to low oxygen conditions as well as low food conditions (Kuhnt et al. 1996; Kaminski et al. 1999). Similar *Haplophragmoides* acmes have been reported from paleoenvironmental instability events (Alegret et al. 2003). Furthermore, the deep infaunal genus *Reophax* has been reported to be opportunistic and to react rapidly to environmental changes (Kuhnt and Kaminski 1996; Hess and Kuhnt 1996). The occurrence of a peak in the relative abundance of *Haplophragmoides* and *Reophax* at Yaxcopoil-1 suggests environmental instability during the deposition of the marly clay layer. It is broadly accepted that there was a general decrease in food supply to the sea floor just after the K/P

boundary in Mexico and in sections from all over the world (see review by Culver [2003]). If we consider that this decrease also affected benthic faunas from the Yucatán area, the interval with abundant *Haplophragmoides* and *Reophax* might indicate that primary productivity and environmental conditions had not completely recovered at Yaxcopoil-1.

The percentage of calcareous foraminifera increases just above the marly clay layer at Yaxcopoil-1. Planktic foraminiferal assemblages suggest a probably bathyal environment for the *G. compressa, A. trinidadensis,* and *A. uncinata* biozones. The size of the planktic foraminiferal tests remains very small in the basal part of the *G. compressa* biozone. Benthic foraminiferal assemblages from the basal *G. compressa* biozone are dominated by trochospiral biconvex (*Osangularia* spp., *Nuttallides* spp.) and planoconvex (*Anomalinoides acutus, Anomalinoides ammonoides, Anomalinoides* spp.) taxa; the flattened tapered genus *Coryphostoma* is also common (Fig. 6). Diversity and heterogeneity of the assemblages are low during this interval, and epifaunal morphogroups dominate (76–86%), suggesting that primary productivity was still low.

Benthic foraminiferal assemblages in the upper part of the *G. compressa* biozone are dominated by trochospiral planoconvex and biconvex taxa. In addition to *Anomalinoides* spp. (*A. acutus, A. ammonoides*) and *Osangularia* spp., other taxa become common to abundant such as *Cibicidoides* spp., *Gyroidinoides beisseli,* laevidentalinids, lenticulinids, and some deeper-water species such as *Cibicidoides hyphalus, Marssonella oxycona, Quadratobulimina* cf. *pyramidalis*, and *Stensioeina beccariiformis* (Fig. 6). Higher up in the section, the bathyal species *Bulimina trinitatensis, Bulimina velascoensis, Cibicidoides hyphalus, Gyroidinoides globosus,* and *Nuttallides truempyi,* among others, are common to abundant and suggest a deeper, bathyal depth of deposition during the *G. compressa-A. trinidadensis* (P1c) and *A. uncinata* (P2) biochrons. Although the percentage of infaunal morphogroups remains low (24–36%) through the studied part of the Paleocene, the diversity and heterogeneity of the assemblages increase and suggest an improvement and stabilization of the environmental conditions toward the *A. uncinata* (P2) biozone. These results could reflect that the recovery of the open-ocean ecosystem occurred more than 3 Myr after the K/P boundary, although primary productivity might have recovered several hundred thousand years after the impact (e.g., D'Hondt et al. 1998; Alegret et al. 2001; Adams et al. 2004).

CONCLUSIONS

We studied the foraminiferal biostratigraphy and assemblage turnover across the K/P boundary at the Yaxcopoil-1 well, drilled by the Chicxulub Scientific Drilling Program. A section comprising Paleogene sediments, the K/P cocktail unit (including impact breccia), and Cretaceous

deposits beneath the impactites was recovered at the Yaxcopoil-1 drill hole. The Cretaceous samples contain only a few and poorly preserved planktic foraminifera, defying unequivocal age attributions, though the occurrence of *H. navarroensis, H. planata,* and *H. monmouthensis* suggests a middle Campanian to Maastrichtian age for the materials below the impact sequence. The planktic and benthic foraminiferal assemblages indicate a shallow neritic, occasionally stressed environment, probably close to the nearshore zone during the late Cretaceous.

The impact breccia and the redeposited suevite are overlain by a 46 cm-thick dolomitic calcareous sandstone unit that contains scarce, reworked (Albian to Maastrichtian) planktic foraminiferal specimens. This unit probably represents the uppermost part of the initial infill of the crater, before the "normal" Danian sedimentation started. There is no evidence at Yaxcopoil-1 to support that the Chicxulub impact predates the K/P boundary.

The upper part of the dolomitic calcareous sandstone unit is intensively bioturbated, and its top represents an omission surface, suggesting the presence of a hiatus that spans, at least, the *G. cretacea, Pv. eugubina,* and part of the *P. pseudobulloides* biozones (P0, Pα, P1a, and P1b). This unit is overlain by a 3–4 cm-thick marly clay layer with ichthyoliths, which may represent a condensed layer.

A tentative Danian planktic foraminiferal zonation has been proposed. The planktic and benthic foraminiferal assemblages are drastically different from those of the upper Cretaceous and indicate a deeper, probably bathyal environment. Benthic foraminiferal assemblages suggest a low food supply to the sea floor and environmental instability during the deposition of the marly clay layer. The increase in diversity of the assemblages indicates an improvement and stabilization of the environmental conditions from the *G. compressa* biozone (P1c) toward the *A. uncinata* biozone (P2).

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