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The Cretaceous/Paleogene boundary at the Agost section revisited: paleoenvironmental reconstruction and mass extinction pattern

El límite Cretácico/Paleógeno del corte de Agost revisado: reconstrucción paleoambiental y patrón de extinción en masa

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Abstract

The Cretaceous/Paleogene (K/Pg) boundary event has been extensively studied in the Spanish Agost section, which contains one of the most continuous and expanded Cretaceous-Paleogene transitions in the Tethys area. For that reason, it is considered as a classical K/Pg boundary section, and numerous researchers have carefully analysed it from different points of view, such as micropaleontology, paleoichnology, magnetostratigraphy, mineralogy and geochemistry. Sediments from the Upper Cretaceous (*Abathomphalus mayaroensis* and *Plummerita hantkeninoides* planktic foraminiferal Biozones), and from the lower Paleogene (*Guembelitria cretacea*, *Parvularugoglobigerina eugubina*, *Parasubbotina pseudobulloides* and *Globanomalina compressa* Biozones), correspond to a marly, microfossil-rich sequence that was deposited in the upper and middle part of the slope, as indicated by the benthic foraminiferal assemblages. A dark clay layer containing impact evidence is identified at the base of the Danian. Planktic foraminifera show a catastrophic mass extinction pattern in coincidence with the K/Pg, just at the base of the dark clay layer. Approximately 70% of the species clearly became extinct at the K/Pg boundary. Very few species seem to disappear in the uppermost Maastrichtian, although these disappearances might result from the background extinction pattern or the remaining Signor-Lipps effect. Some Cretaceous species seem to have survived, and gradually disappear during the Danian, although this might be due to the long-term effect of the asteroid impact; their presence in Danian sediments can be also interpreted as the result of reworking processes. If we take this into account, the percentage of planktic foraminifera that became extinct at the K/Pg boundary makes up to 90% of the species. In contrast to planktic foraminifera, benthic foraminifera did not suffer any mass extinction, although the drastic reorganization of their assemblages in coincidence with the boundary reflects important environmental changes. These changes are compatible with the castastrophic effects of a large asteroid impact that occurred just at the Cretaceous/Paleogene boundary.

Keywords: Foraminifera, extinction, paleoenvironment, Cretaceous, Paleogene, Spain.

Resumen

El evento del límite Cretácico/Paleógeno (K/Pg) ha sido intensamente estudiado en el corte español de Agost, que contiene uno de los tránsitos Cretácico-Paleógeno más continuos y expandidos en el área del Tetis. Por este motivo, se considera como una sección clásica del límite K/Pg, y ha sido detalladamente analizada por numerosos especialistas desde el punto de vista micropaleontológico, paleoicnológico, magnetoestratigráfico, mineralógico y geoquímico. Los sedimentos del Cretácico Superior (Biozonas de *Abathomphalus mayaroensis* y de *Plummerita hantkeninoides*) y del Paleógeno inferior (Biozonas de *Guembelitria cretacea*, de *Parvularugoglobigerina eugubina* y de *Parasubbotina pseudobulloides*) corresponden a una secuencia principalmente margosa rica en microfósiles, depositada en la parte superior y media del talud, tal y como indican las asociaciones de foraminíferos bentónicos. En el Daniense basal se identifica una capa arcillosa oscura que contiene evidencias de impacto. Los foraminíferos planctónicos muestran un patrón de extinción en masa catastrófico en coincidencia con el límite K/Pg, situado en la base de esta capa arcillosa. El 70% de las especies se extinguieron claramente en coincidencia con en el límite K/Pg. Muy pocas especies parecen extinguirse en el Maastrichtiense final y podrían interpretarse como parte del patrón de extinción de fondo o el remanente efecto Signor-Lipps. Algunas especies cretácicas parecen sobrevivir el evento y desaparecer gradualmente en el Daniense, tal vez como resultado de los efectos a más largo plazo del impacto meteorítico. Sin embargo, su presencia en el Daniense también podría ser interpretada como resultado de la reelaboración. Teniendo en cuenta estas consideraciones, el porcentaje de especies de foraminíferos planctónicos que se extinguieron en el evento del límite K/Pg alcanzaría el 90%. A pesar de que los foraminíferos bentónicos, al contrario que los foraminíferos planctónicos, no sufrieron una extinción en masa, la drástica reorganización de sus asociaciones en coincidencia con el límite refleja importantes cambios paleoambientales, compatibles con los efectos catastróficos causados por el impacto de un asteroide justo en el límite Cretácico/Paleógeno.

Palabras clave: Foraminíferos, extinción, paleambiente, Cretácico, Paleógeno, España

1. Introduction

The Cretaceous/Paleogene boundary event has been the object of multidisciplinary studies in the Agost section, which is one of the most relevant and best-known Spanish Cretaceous/Paleogene (K/Pg) boundary sections. Since the proposal of the impact theory (Alvarez *et al.*, 1980; Smit and Hertogen, 1980), the Spanish sections of Caravaca and Agost became classical localities to test the impact evidence and the mass extinction pattern. The Agost section was first described by Leclerc (1971), who investigated the planktic foraminiferal faunas and argued that the sedimentation in this section was essentially continuous from Santonian to Eocene. Since then, the Agost section has been studied by numerous authors (e.g., von Hillebrandt, 1974; Groot *et al.,* 1989; Smit, 1990; Canudo *et al*., 1991; Martínez-Ruiz *et al*., 1992, 1997; Ortega-Huertas *et al*., 1995, 1998; Molina *et al*., 1996, 2001; Pardo *et al*., 1996; Arenillas, 2000; Arz, 2000; Alegret, 2003; Alegret *et al*., 2003), who analysed the micropaleontology, paleoichnology, biostratigraphy, magnetostratigraphy, mineralogy and geochemistry. Finally, a field trip was organized (Molina et al., 2003) during the meeting *Bioevents: their stratigraphical records, patterns and causes*, organized in Caravaca de la Cruz, June 3rd-8th, 2003.

The aim of this paper is to update and integrate the data that have been published on the Upper Cretaceous and lower Paleogene from Agost, especially those related to foraminifera, in order to reconstruct the paleoenvironment and to evaluate the magnitude of the catastrophic mass extinction.

2. Location and Stratigraphy

The Agost section is located in the Betic Cordillera of southeastern Spain and the outcrop occurs about 1 km north of the village of Agost, in Alicante province (Fig. 1). Agost is located ~100 km to the east of the well-known Caravaca section; both sections have a similar lithology and have been considered as some of the most continuous land-based K/Pg sections. The Cretaceous/Paleogene transition is well exposed, and can be easily sampled along a road cut near the 13 km-marker post of the Agost-Castalla road (Fig. 2).

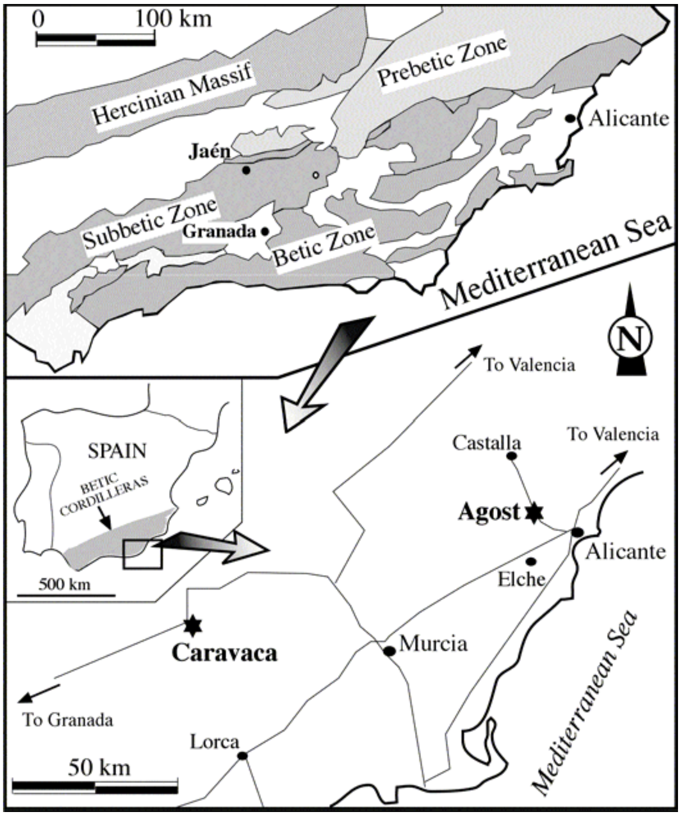

Fig. 1.- Geologic setting, and geographic location of the Agost section.
Fig. 1.- Localización geológica y geográfica del corte de Agost.

Upper Cretaceous and lower Paleogene sediments at Agost include the upper part of the Cenomanian to the Eocene Quipar-Jorquera Formation (Vera, 1983), which was originally described by Van Veen (1969). Maastrichtian sediments consist of gray pelagic, massive marls, interbedded with marly limestones; the latter are very scarce in the uppermost Maastrichtian. These

Fig. 2.- General view of the uppermost Cretaceous and lower Paleogene at the Agost section (above); detail of the lower Danian dark clay layer (left); and detail of the red rusty layer at the K/Pg boundary (right).

Fig. 2.- Vista general del Cretácico terminal y del Paleógeno inferior en el corte de Agost (arriba); detalle de la arcilla oscura del Daniense inferior (izquierda); detalle del nivel rojizo del límite K/Pg (derecha).

marly sediments are rich in foraminifera, ostracods and other microfossils (see field trip guides by Usera *et al*. 2000; Molina *et al*. 2001; 2003). The K/Pg boundary is marked by a sharp contact between the Maastrichtian marly sediments and a 12 cm-thick layer of black clays, with a 2-3 mm thick, red ferruginous level at its base. The ferruginous level contains goethite, hematite, glauconitic clasts, scarce foraminifers, and is enriched in Ir, Ni-rich spinels, Co, Cr as well as sanidine spherules that Smit (1982, 1990) interpreted to be altered microtektites. This oxidized level has been called the “fall-out layer”, which marks the K/Pg boundary (Smit, 1982, 1990; Canudo *et* *al*., 1991; Arz *et al*., 1992; Martínez Ruiz *et al*., 1992, 1999; Molina *et al*., 1996; Alegret *et al*., 2003). A detailed magnetostratigraphic analysis of the Agost section across the K/Pg boundary was performed by Groot *et al.* (1989). They identified the polarity zones C30n, C29r and C29n. The K/Pg boundary is placed at two-thirds from the base of chron C29r. The correlation between this magnetostratigraphy and the planktic foraminiferal biostratigraphy was commented by Berggren (1989) and analysed by Arenillas *et al.* (1993). Figure 3 shows a correlation of planktic foraminiferal biozonations and the magnetostratigraphy at Agost.

The lowermost Danian dark clay level is overlain by a 10 cm-thick layer of massive gray clays. Higher in the section, we recognised two decimeter-thick tabular bodies of marly limestones, with a decimeter-thick intercalated layer of marls. The upper part of the section consists mainly of massive gray marls, with a 10 cm-thick body of marly limestones intercalated 230 cm above the K/Pg boundary. Trace fossils are frequent across the K/Pg boundary. Paleoichnological approach has been performed by analysing ichnotaxa, relative abundance, horizontal and vertical distribution of trace fossils, and cross-cutting relantionship (Rodríguez-Tovar in Molina *et al*., 2001; Rodríguez-Tovar *et al.,* 2004).

3. Mineralogy and Geochemistry

The K/Pg boundary layer at Agost is characterized by a sharp decrease in carbonate content and a subsequent increase in the proportion of clays. Smectite and diagenetically altered spherules made up of either potassium feldspar or iron oxides are the main components of the boundary layer (Smit, 1990; Martínez-Ruiz *et al*., 1992, 1997; Ortega-Huertas *et al*., 1995, 1998). Other trace minerals such as celestite, barite, rutile, Cr oxides, chlorite and palygorskite are also observed in the boundary layer, and in the dark marly clays deposited above this layer.

As in other K/Pg boundary sections worldwide, the K/Pg boundary at Agost is marked by significant geochemical anomalies characterized by a large increase of Ir and other platinum group elements. The boundary is also marked by high contents of different chemical elements such as Fe, Cr, Co, Ni, Cu, Zn, As or Sb and significant changes in δ^{13}C and δ^{18}O (Smit, 1990, Martínez-Ruiz *et al*., 1992, 1994, 1999). The geochemical composition of the boundary layer at Agost and the enrichment in typical extraterrestrial elements thus support the impact scenario at the end of the Cretaceous. In addition, trace element data from the dark clay layer at the base of the Danian indicate that anoxic to hypoxic conditions occurred either at the botton or in the pore waters. Hypoxic conditions appear to have been somewhat more extreme at Agost than at Caravaca (Martínez-Ruiz *et al*., 1992; 1999; Kaiho and Lamolda, 1999).

4. Planktic foraminifera

4.1. Biostratigraphy

The planktic foraminiferal biostratigraphy of the Upper Cretaceous and lower Paleogene transition from Agost was studied by Molina *et al.* (1996; 1998), who suggested that the stratigraphic ranges are very similar to those of the Caravaca section in Spain, and the El Kef section in Tunisia. These authors used the classical system of biozonation to identify six biozones across the K/Pg interval at Agost, namely *Abathomphalus mayaroensis* Biozone, *Plummerita hantkeninoides* Biozone, *Guembelitria cretacea* Biozone, *Parvularugoglobigerina eugubina* Biozone, *Parasubbotina pseudobulloides* Biozone and *Globanomalina compressa* Biozone. Recently, a new high-resolution planktic foraminiferal zonation and subzonation for the lower Danian has been established based on some of the most expanded and continuous pelagic sections including Agost (Arenillas et al., 2004). The zones and subzones (Fig. 3) are defined as follows:

-*Abathomphalus mayaroensis* Zone: Biostratigraphical interval between the lowest record datum (LRD) of the nominal taxon and the HRD of *Plummerita hantkeninoides*. This biozone was divided in three subzones by Arz and Molina (2002), but at the Agost section only the uppermost one has been studied: *Plummerita hantkeninoides* Subzone, which is the biostratigraphical interval characterized by the total range of the nominal taxon. At the Agost section, the total range of *P. hantkeninoides* spans the top 3.45 m of the Maastrichtian.

-*Guembelitria cretacea* Zone: Biostratigraphical interval between the highest record datum (HRD) of *Plummerita hantkeninoides*, precisely at the K/Pg boundary, and the LRD of *Parvularugoglobigerina eugubina*. In the Agost section the *G. cretacea* Biozone spans 14 cm within the level that is mainly characterised by black clays containing a well-preserved autochthonous fauna. The first Tertiary planktic foraminiferal species are found in the lower part of this biozone, which is the stratigraphical interval equivalent to the Zone P0 of Berggren *et al.* (1995). This biozone was divided in two by Arenillas *et al.* (2004): *Hedbergella holmdelensis* Subzone, which is the biostratigraphical interval between the HRD of *Plummerita hantkeninoides* to the LRD of *Parvularugoglobigerina longiapertura*; and Parvularugoglobigerina longiapertura Subzone, which is the biostratigraphical

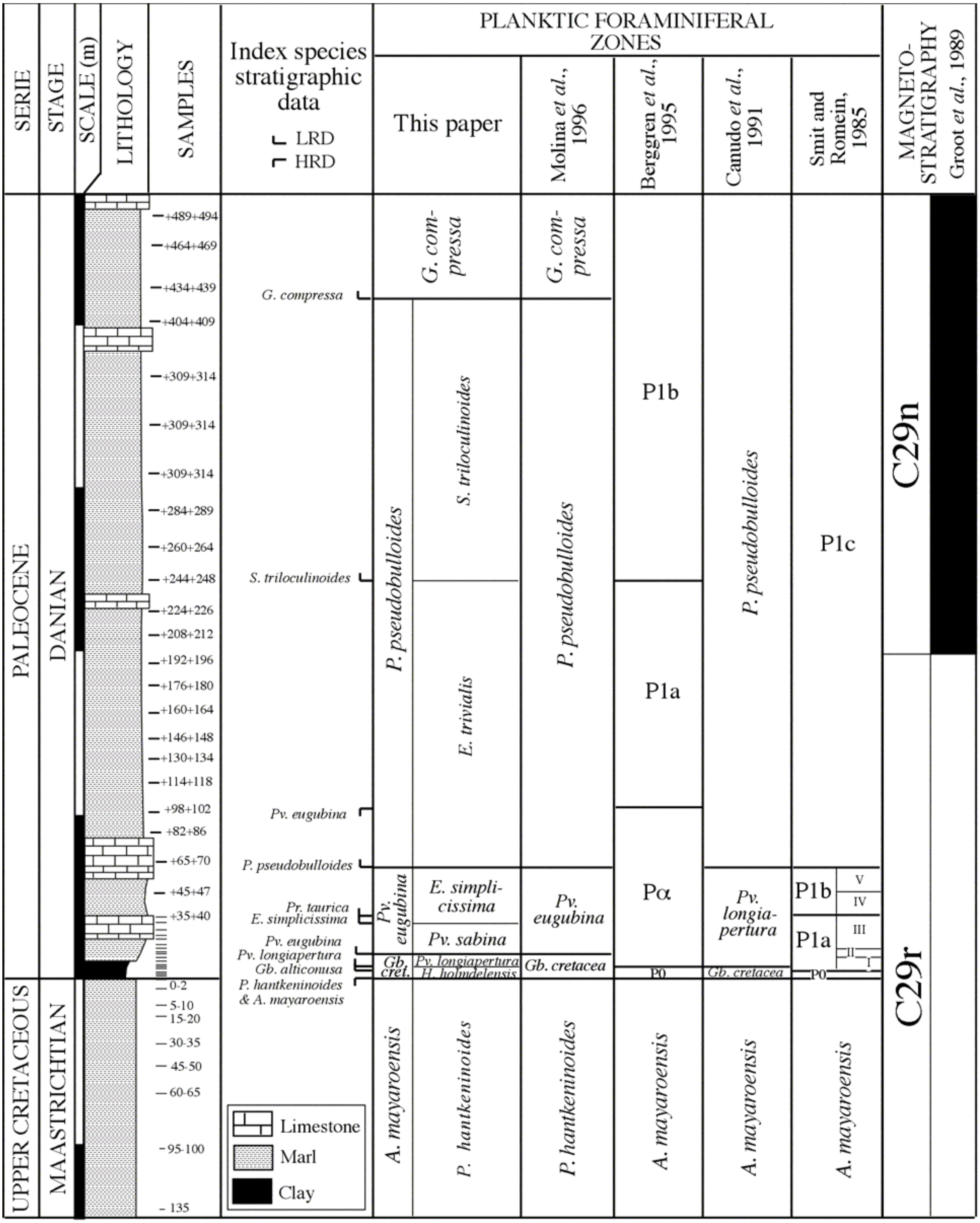

Fig. 3.- Magnetostratigraphy, and planktic foraminiferal biostratigraphy at Agost. The biozonation used in this paper is based on Arz and Molina (2002) for the Upper Cretaceous, and Arenillas *et al.* (2004) for the Paleocene.

Fig. 3.- Magnetoestratigrafía y bioestratigrafía con foraminíferos planctónicos en Agost. La biozonación utilizada en este trabajo está basada en Arz y Molina (2002) para el Cretácico Superior y en Arenillas et al. (2004) para el Paleoceno.

interval from the LRD of the nominal taxon and the LRD of *Parvularugoglobigerina eugubina*.

- *Parvularugoglobigerina eugubina* Zone: Biostratigraphical interval between the LRD of the nominate taxon and the LRD of *Parasubbotina pseudobulloides*. The *Pv. eugubina* Biozone is 45 cm thick at Agost. This biozone was divided in two by Arenillas *et al*. (2004): *Parvularugoglobigerina sabina* Subzone, which is the interval ranging from the LRD of *Parvularugoglobigerina eugubina* to the LRD of *Eoglobigerina simplicissima*; and *Eoglobigerina simplicissima* Subzone, which is the interval between the LRD of the nominal taxon and the LRD of *Parasubbotina pseudobulloides.*

- *Parasubbotina pseudobulloides* Zone: Biostratigraphical interval between the LRD of the nominal taxon and LRD of *Globanomalina compressa*. This biozone spans 3.70 m at Agost. This biozone was divided in two by Arenillas *et al*. (2004): *Eoglobigerina trivialis* Subzone, which is the biostratigraphical interval from the LRD of *Parasubbotina pseudobulloides* to the LRD of *Subbotina triloculinoides*; and *Subbotina triloculinoides* Subzone, which is the interval from the LRD of the nominal taxon to the LRD of *Globanomalina compressa*.

- *Globanomalina compressa* Biozone: Biostratigraphical interval between the LRD of the nominal taxon and the LRD of *Acarinina trinidadensis*. At Agost, this biozone spans 6 m.

4.2. Planktic foraminiferal turnover

The Agost section has been very relevant to solve the controversy generated since the proposal of a model explaining the planktic foraminiferal mass extinction at the K/Pg boundary. Such a controversy originated in 1981, at the Snowbird I Conference, where Jan Smit presented his data showing that all but one Cretaceous species suddenly became extinct at the K/Pg boundary. He interpreted this dramatic faunal turnover as the result of a large asteroid impact (Smit and Hertogen, 1980; Smit, 1982). Afterwards, these data were questioned by Gerta Keller, who argued that species extinctions extended across the K/Pg boundary with about 1/3 of the species surviving well into the Tertiary (Keller, 1988, 1989a,b). Nevertheless, most recent studies (Molina *et al*., 1998; Arz *et al*., 1999; Arenillas *et al*., 2000 a,b, among others) showed a sudden and catastrophic pattern of extinction that they also believed is compatible with a large asteroid impact, as initially proposed by Smit and Hertogen (1980) and Alvarez *et al.* (1980).

In order to elucidate this controversy, Molina *et al.* (1996) studied the Agost section, which is very expanded and continuous, and well exposed across the K/Pg boundary. A total of 68 samples were collected at cm-intervals across the critical K/Pg boundary interval and at m-intervals well below and above the boundary. Planktic foraminifera are well preserved, the assemblages are rich and diverse and there is almost no evidence of reworking. Thus, this excellent K/Pg boundary section provided a good opportunity to test the extinction model of Cretaceous species and the evolution of Tertiary species.

Upper Maastrichtian assemblages from the Agost section are largely dominated by short life-cycle biserial species such as heterohelicids. Planispiral (globigerinelloids) and trochospiral (hedbergellids, rugoglobigerinids and globotruncanids) species are frequent, and triserial species (guembelitriids) and tubulospinose species (schackoinids) are rare. The stratigraphic ranges of these taxa during the late Maastrichtian indicate very few changes in the faunal assemblages, and most of the species are present in the *A. mayaroensis* Zone. The HRDs of some species, such as *Gansserina wiedenmayeri*, *Gansserina gansseri* and *Contusotruncana plicata,* are placed in the upper Maastrichtian *A. mayaroensis* Biozone between 6 and 11 m below the K/Pg boundary. The HRDs of the rest of the species (*Rugoglobigerina milamensis, Archaeoglobigerina cretacea, Gublerina acuta* and *Rugoglobigerina pennyi*) are placed in the upper part of the *P. hantkeninoides* Subzone (Fig. 4). Only one species, namely *P. hantkeninoides*, has its LRD in this interval at 3.45 m below the K/Pg boundary. Quantitative planktic foraminiferal analysis of the uppermost 2.25 m of the Cretaceous shows little variation among the relative abundances of the different species (Fig. 3 in Molina *et al*., 1996).

A total of 46 species have their highest record in coincidence with the red rusty layer that marks the K/Pg boundary. We double-checked this coincidence by scanning the residue of the uppermost Cretaceous samples twice, in order to minimize the Signor-Lipps effect (Signor and Lipps, 1982), because certain rare species might seem to go extinct before their real moment of extinction (Canudo *et al*. 1991). About 72% of the planktic foraminiferal species became extinct in coincidence with the K/Pg boundary, which constitutes the most important extinction event in the history of planktic foraminifera. Most of the extinct taxa, as for instance *Contusotruncana contusa, Globotruncana arca, Abathomphalus mayaroensis*, are large, complex forms adapted to deep environments.

In order to eliminate the potential problem of reworking in a high-resolution sampling, Molina *et al.* (1996, 1998, 2001, 2003) ignored either the presence of isolated specimens in a sample, or specimens with a different preservation. Such specimens were assumed to have been reworked, and hence were not listed in their data tables or figures. In the lowermost Paleogene (*G. cretacea*, *Pv. eu-*

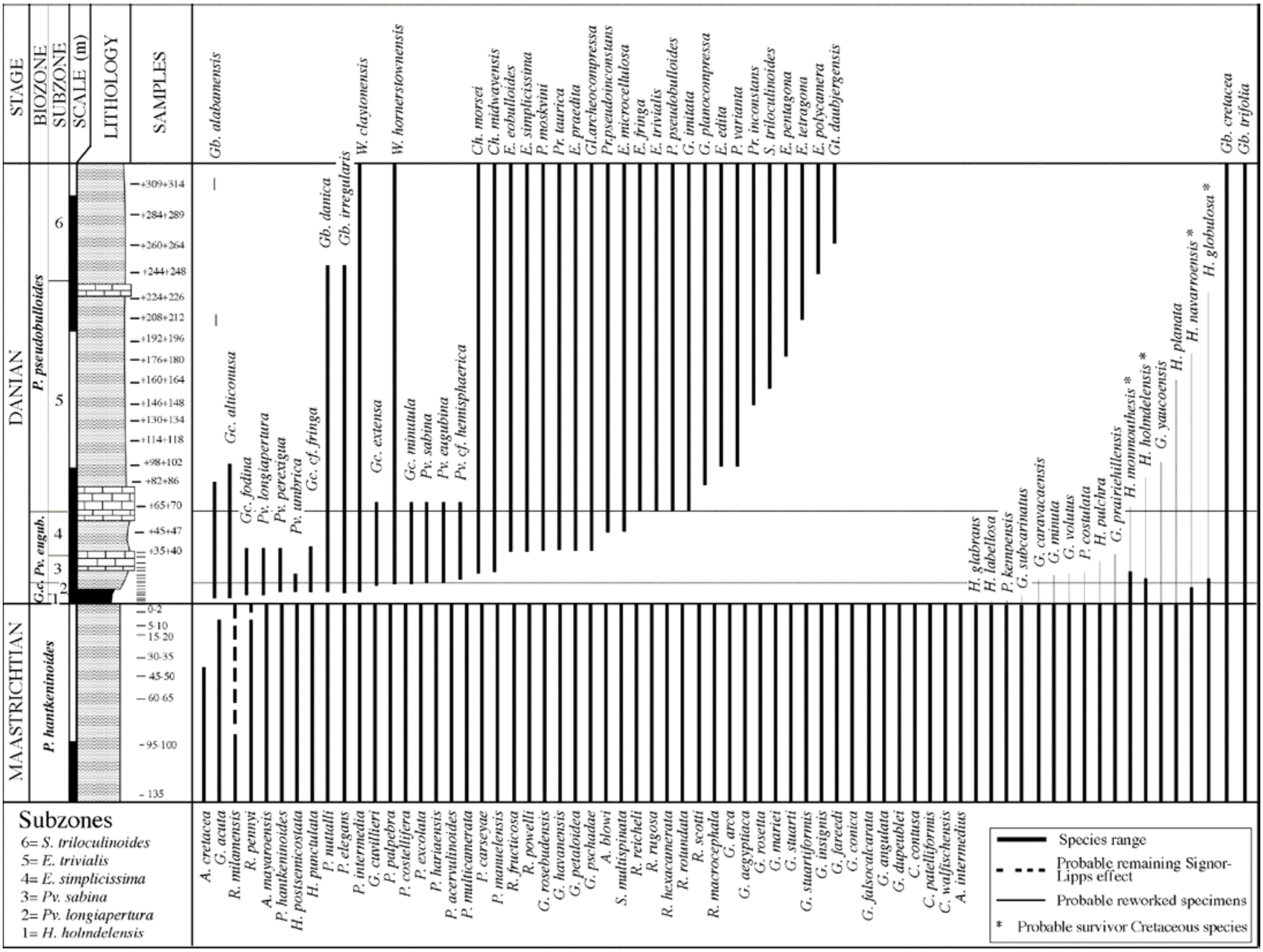

Fig. 4.- Planktic foraminiferal ranges across the Cretaceous-Paleogene transition at Agost.
Fig. 4.- Distribución de los foraminíferos planctónicos a través del tránsito Cretácico-Paleógeno en Agost.

gubina, *Ps. pseudobulloides* Biozones and the lower part of *G. compressa* Biozone), a total of 14 Cretaceous species were identified that may be considered as possible Cretaceous survivors, or as reworked specimens (Kaiho and Lamolda, 1999). These species are cosmopolitan, small and simple surface dwellers that apparently disappeared during the lowermost Danian (Fig. 4). Guembelitriids (*Guembelitria trifolia* and *G. cretacea*) are rare in the Upper Cretaceous, but these opportunistic species are abundant in the lowermost Paleogene, just after the main planktic foraminiferal extinction event. The rest of the small Cretaceous possible survivors are less abundant in the Danian than in the Maastrichtian, thus indicating the possibility of reworking.

The biostratigraphical data at Agost indicate that new opportunistic cosmopolitan species evolved in the earliest Danian and two main Danian assemblages are recognised. The earliest assemblage consists of small cosmopolitan surface dwellers, which originated in the *G. cretacea* Biochron, and became extinct in the early part of the *Ps. pseudobulloides* Biochron. The second assemblage originated in the *Pv. eugubina* Biochron, and diversified within the early part of the *Ps. pseudobulloides* Biochron, where these taxa reached a normal size (200-300 µm).

Species that dominated the lower Danian assemblages are those which evolved after the K/Pg boundary, and most of them became extinct near the base of the *Ps. pseudobulloides* Biochron (e.g., *Parvularugoglobigerina longiapertura, Pv. eugubina, Pv. sabina, Globoconusa fodina* and *G. alticonusa*). Subsequent to their disappearance, *Woodringina claytonensis, Woodringina hornerstownensis, Chiloguembelina morsei* and *Chiloguembelina midwayensis* dominated the assemblages (Fig. 4).

In conclusion, the Agost section shows evidence for a catastrophic mass extinction of about 72% of the Cretaceous species of planktic foraminifera that exactly coincides with the base of the red rusty layer containing clues of an impact event. This is similar to what is found in Tunisia and other K/Pg sections (Molina *et al.*, 1996; 1998; Arz and Arenillas, 1998; Arenillas *et al.*, 2000b). The few species that seem to disappear in the uppermost Maastrichtian can be interpreted to constitute background extinction pattern, or can also be interpreted as the remaining Signor-Lipps effect. Species that seem to disappear in the lowermost Danian may either be the result of the long-term effect of the asteroid impact, or may be reworked (Kaiho and Lamolda, 1999). Only few species such as *Guembelitria cretacea, Guembelitria trifolia*, probably *Hedbergella monmouthensis, Hedbergella holmdelensi,s* and possibly *Heterohelix globulosa* and *Heterohelix navarroensis,* should be considered as survivors. We suggest that the pattern of extinction and origination is very compatible with the impact theory, which caused the extinction of about 90% of the species of planktic foraminifera across the K-Pg transition.

5. Benthic foraminifera

Benthic foraminifera are an important source of information about paleoenvironmental conditions at the sea floor, such as ocean productivity and oxygenation. In addition to being excellent paleobathymetric markers, the abundance of some depth-related species, as well as the upper depth-limits of others, allow us to infer possible changes in paleodepth.

So far, studies of the upper Maastrichtian through lower Danian benthic foraminifera from Southeastern Spain are scarce, and they consist only of brief descriptions of the benthic foraminiferal faunas from Caravaca (Smit, 1990; Keller, 1992; Coccioni *et al*., 1993; Coccioni and Galeotti, 1994; Widmark and Speijer, 1997a, b), and Agost (Pardo *et al*., 1996). More recently, Alegret *et al.* (2003) performed a detailed quantitative analysis of the Upper Cretaceous and lower Paleogene benthic foraminiferal assemblages from Agost, and inferred paleoenvironmental and paleobathymetrical changes across the K-Pg transition; their main results are discussed in the following paragraphs.

5.1. Paleobathymetry

The distribution of benthic foraminifera is related to several depth-related parameters, therefore this group can be used as an excellent tool to infer paleobathymetry. Paleodepths indicated by the benthic foraminiferal faunas are clearly of great importance to interpret the environment of deposition of the K/Pg sediments.

Pardo *et al*. (1996) interpreted the faunal turnover of Upper Cretaceous and lower Paleogene benthic foraminifera at Agost in terms of climatic changes and variations in sea level. They also concluded that paleodepths fluctuated between upper bathyal and outer neritic. In contrast, Alegret *et al*. (2003) recently developed a detailed paleobathymetric reconstruction of the Upper Cretaceous and Lower Paleogene sediments at Agost and concluded that benthic foraminiferal assemblages from the *A. mayaroensis* and lower part of the *P. hantkeninoides* Biozones, which contain abundant *Loxostomum eleyi*, *Eouvigerina subsculptura,* laevidentalinids, *Sitella cushmani, Spiroplectammina spectabilis*, and *Stensioeina beccariiformis* forma *parvula*, indicate an uppermost bathyal depth of deposition (Fig. 5). They further observed a decrease in the percentage of *Loxostomum eleyi* in the middle part of the *P. hantkeninoides* Subzone, as well as an increase in the relative abundance of species typical of middle bathyal environments in the Tethys area, such as *Bolivinoides draco, Bolivinoides delicatulus, Cibicidoides hyphalus, Cibicidoides velascoensis, Eouvigerina subsculptura, Gaudryina pyramidata, Praebulimina reussi*, *Pseudouvigerina plummerae, Pyramidina rudita.* There is also simultaneous increase in the percentage of bathyal and abyssal species, namely *Bulimina trinitatensis, Clavulinoides trilatera, Nuttallinella florealis, Paralabamina lunata* and *Stensioeina beccariiformis* s.s. The composition of the assemblages thus allowed Alegret *et al.* (2003) to conclude that paleodepths increased to middle bathyal during the middle part of the *P. hantkeninoides* Biochron, and remained unchanged through the rest of the section (through the *Ps. pseudobulloides* Biochron; Fig. 5). These authors did not report any perceivable bathymetrical changes at the K/Pg boundary.

A comparison between paleodepth interpretations proposed by Pardo *et al.* (1996) and Alegret *et al*. (2003) is shown in Figure 5. According to the later authors, differences between these paleodepth curves may be due to misidentification of several benthic foraminiferal species by Pardo *et al.* (1996), as well as to their confusing usage of the upper depth limits of certain taxa whose bathymetric distribution is well-known and broadly documented.

5.2. Benthic foraminiferal turnover and paleoenvironmental inferences

Benthic foraminifera from the Upper Cretaceous and lower Paleogene at Agost were included in the study by Pardo *et al.* (1996), who observed a lack of severe extinctions and suggested that climatic changes and variations in sea level can explain the observed faunal changes.

The K/Pg boundary marks one of the largest mass extinctions of the Phanerozoic, but survival rates of different groups of marine organisms varied with habitat

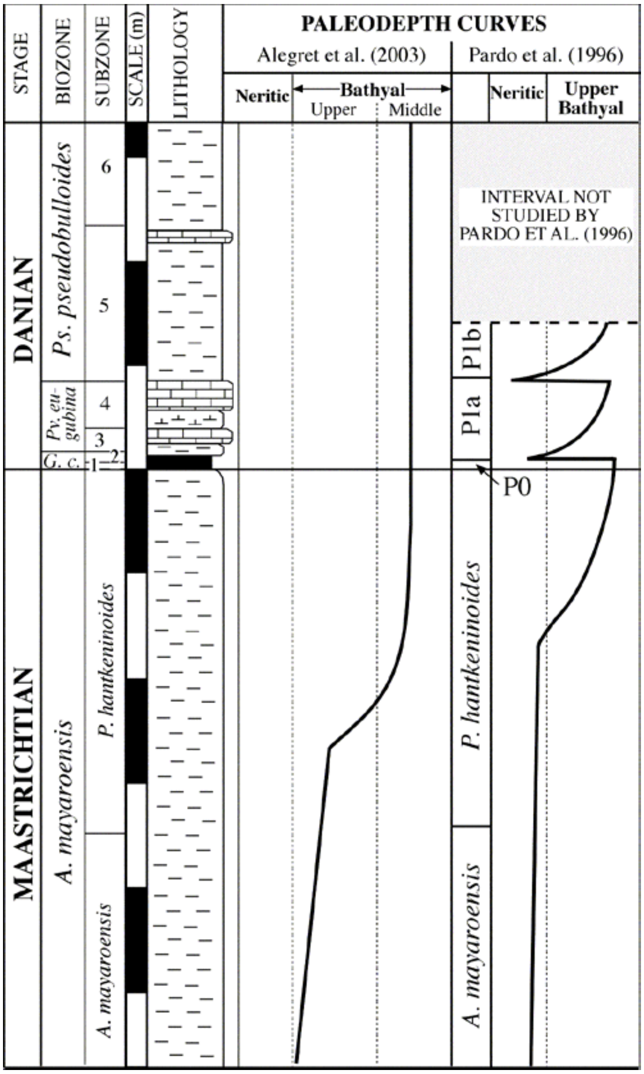

Fig. 5.- Comparison between paleodepth curves inferred by Alegret *et al.* (2003) and Pardo *et al.* (1996). Modified from Alegret *et al.* (2003).

Fig. 5.- Comparación entre curvas de paleoprofundidad inferidas por Alegret *et al.* (2003) y Pardo *et al.* (1996). Modificado de Alegret *et al.* (2003).

(Peryt *et al*., 2002). Planktic foraminifera suffered a catastrophic mass extinction (e.g., Arenillas *et al*., 2000 a,b), whereas benthic foraminiferal assemblages exhibit various degrees of faunal restructuring even in the absence of major extinction (e.g., Alegret *et al*., 2003).

Upper Maastrichtian benthic foraminiferal assemblages from Agost are dominated by calcareous foraminifera (~80%) with tapered tests, such as *Loxostomum eleyi*, laevidentalinids and *Eouvigerina subsculptura*. The upper half of the *P. hantkeninoides* Biozone is dominated by different tapered species such as *Praebulimina reussi*, *Spiroplectammina spectabilis* and laevidentalinids (Fig. 6). According to the model proposed by Jorissen *et al.* (1995), which explains benthic foraminiferal microhabitat preferences in terms of nutrient supply to the sea floor, Alegret *et al.* (2003) interpreted these infaunal-dominated Upper Cretaceous faunas as indicating a moderately eutrophic environment, with a food flux to the sea floor sufficient to sustain infaunal taxa.

Only 5% of the benthic foraminiferal species became extinct at the K/Pg boundary at Agost, although the benthic assemblages underwent a temporary faunal turnover that started just at the boundary. The abundance of benthic foraminifera is low in the lowermost part of the black-clay layer at Agost (46 specimens in the first sample of the Danian, in contrast to 268 specimens found in the uppermost Maastrichtian), and dissolution may have affected the faunas -probably due to a temporal rise of the lysocline-, leading to relatively high abundances (up to 48%) of agglutinated taxa.

Several peaks in relative abundance of *Ammodiscus*, *Glomospirella grzybowski, Repmanina charoides* or *Haplophragmoides,* were identified in the lowermost Danian black clay interval; these taxa have been documented to be opportunistic species that tolerate environmental instability and/or low oxygenation, blooming whenever other taxa cannot compete (e.g., Kaminski *et al*., 1996; Kuhnt *et al*., 1996; Alegret *et al*., 2003).

The percentage of infaunal morphogroups decreased in coincidence with the K/Pg boundary, and Danian assemblages were dominated by epifaunal (*Stensioeina beccariiformis*, *Globorotalites* spp., *Cibicidoides hyphalus, Cibicidoides ekblomi*) or mixed epifaunal-infaunal morphogroups. Such a decrease in the percentage of infaunal morphogroups suggests that the food supply to the benthos drastically decreased in coincidence with the K/Pg boundary, and that the scarce organic matter was consumed at or close to the sediment surface before it could be buried in the sediment, so that no food remained for deep-infaunal taxa (e.g., Peryt *et al*., 2002).

Alegret *et al.* (2003) argued that the strong variability in the fauna, as well as the low diversity and abundance of benthic foraminifera during the first 10-15 kyr (lower ~10 cm) of the Danian reflects not just a collapse of the food supply, but also a major change in the composition of the food supply as a result of the mass extinction of phytoplankton, as well as a rapidly changing food supply driven by blooms of such taxa as *Thoracosphaera*, *Braarudosphaera* or *Biscutum* (e.g., Thierstein, 1981; Perch-Nielsen *et al.*, 1982).

Increase in genus richness and in diversity of the assemblages (Alegret, 2003), and decrease in the percentage of opportunistic taxa at the end of the *G. cretacea* Biochron, indicate a slight stabilization of the ecosystems. Nevertheless, the high percentage of epifaunal morphogroups (e.g., *Cibicidoides ekblomi, Cibicidoides hyphalus, Globorotalites* sp., *Stensioeina beccariiformis*) towards the

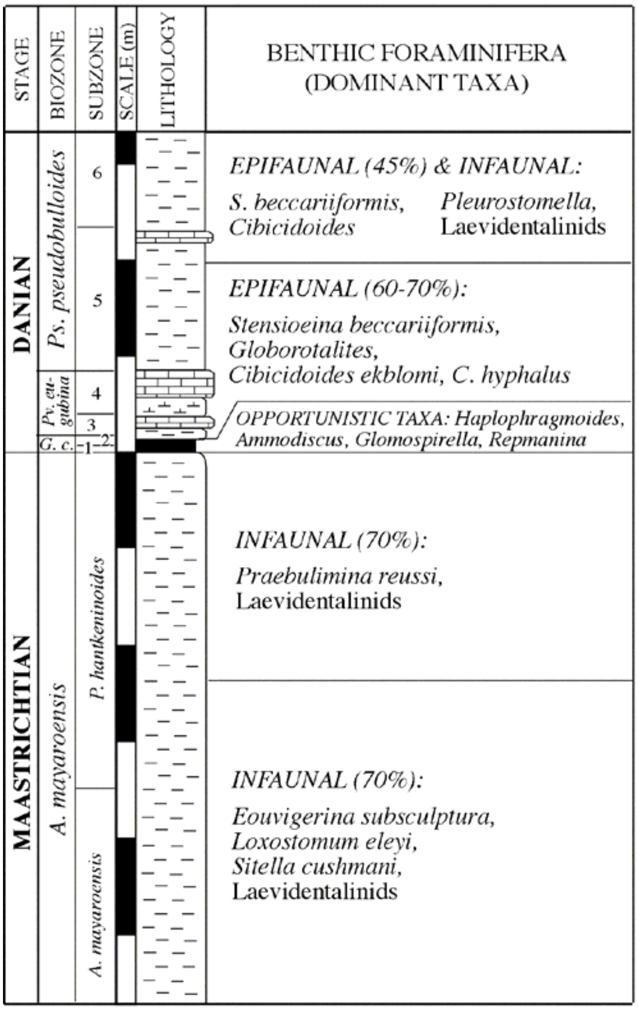

Fig. 6.- Dominant upper Maastrichtian to lower Danian benthic foraminiferal taxa at Agost.

Fig. 6.- Taxones de foraminíferos bentónicos dominantes durante el Maastrichtiense superior y Daniense inferior en Agost.

top of the interval studied suggests that productivity did not recover to pre-extinction levels at Agost, at least in the interval of the *Ps. pseudobulloides* Biozone that has been investigated.

6. Conclusions

The classical K/Pg boundary Agost section has been revisited and analysed mainly from the micropaleontological point of view. The expanded and well-exposed Upper Cretaceous to lower Paleogene sequence contains well preserved benthic and planktic foraminiferal assemblages, which allowed us to perform very detailed biostratigraphical, paleobathymetrical and paleoenvironmental analyses.

Benthic foraminifera at Agost indicate deposition at uppermost bathyal depths during the *A. mayaroensis* Biozone through the early *P. hantkeninoides* Biozone. Paleodepths increased to middle bathyal for the remainder of the time interval studied in the section, and no paleobathymetrical changes have been observed in coincidence with the K/Pg boundary.

Planktic foraminifera show a catastrophic mass extinction pattern in coincidence with the layer containing evidence for an asteroid impact, and about 70% of the species clearly became extinct at the K/Pg boundary. The few species that seem to disappear in the uppermost Maastrichtian may constitute background extinction pattern, or they could also be interpreted as the remaining Signor-Lipps effect. Species that seem to disappear in the lowermost Danian could be the result of the long-term effect of the asteroid impact. On the other hand, these delayed extinctions could also be interpreted as due to reworking, and only few species such as *Guembelitria cretacea, Guembelitria trifolia*, probably *Hedbergella monmouthensis, Hedbergella holmdelensis* and possibly *Heterohelix globulosa* and *Heterohelix navarroensis* should be considered as survivors.

On the whole, the magnitude of the catastrophic mass extinction pattern in planktic foraminifera could be as high as about 90%. In contrast, benthic foraminifera did not suffer mass extinction, indicating that the benthic environment was less affected than the planktic one. However, benthic assemblages indicate a drastic decrease in nutrient supply to the sea floor in coincidence with the K/Pg boundary, followed by environmental instability and/or low oxygenation during the lowermost Danian and a slow recovery through the lower Danian. The benthic foraminiferal changes and the inferred paleoenvironmental turnover are also very compatible with the castastrophic effect caused by a large asteroid that impacted at Chicxulub (Yucatan Peninsula) at the K/Pg boundary.

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APENDIX
List of planktic and benthic foraminiferal species cited in the text and figures.

Cretaceous planktic foraminifera:

Abathomphalus intermedius (Bolli, 1951)
Abathomphalus mayaroensis (Bolli, 1951)
Archaeoglobigerina blowi Pessagno, 1967
Archaeoglobigerina cretacea (d'Orbigny, 1840)
Contusotruncana contusa (Cushman, 1926)
Contusotruncana patelliformis (Gandolfi, 1955)
Contusotruncana walfischensis (Todd, 1970)
Globigerinelloides praeriehillensis Pessagno, 1967
Globigerinelloides rosebudensis Smith y Pessagno, 1973
Globigerinelloides subcarinatus (Brönnimann, 1952)
Globigerinelloides volutus (White, 1928)
Globigerinelloides yaucoensis (Pessagno, 1967)
Globotruncana aegyptiaca Nakkady, 1950
Globotruncana arca (Cushman, 1926)
Globotruncana mariei Banner y Blow, 1960
Globotruncana rosetta (Carsey, 1926)
Globotruncanita angulata (Tiev, 1951)
Globotruncanita conica (White, 1928)
Globotruncanita dupeublei (Caron, González Donoso, Robaszynski, Wonders, 1984)
Globotruncanita falsocalcarata (Kerdany y Abdelsalam, 1969)
Globotruncanita fareedi (El Naggar, 1966)
Globotruncanita insignis (Gandolfi, 1955)
Globotruncanita stuarti (de Lapparent, 1918)
Globotruncanita stuartiformis (Dalbiez, 1955)
Globotruncanella caravacaensis Smit, 1982
Globotruncanella havanensis (Voorwijk, 1937)
Globotruncanella minuta Caron y González Donoso, 1984
Globotruncanella petaloidea (Gandolfi, 1955)
Globotruncanella pschadae (Keller, 1946)
Gublerina acuta de Klasz, 1953
Gublerina cuvillieri Kikoine, 1948
Guembelitria cretacea Cushman, 1933
Guembelitria trifolia (Morozova, 1961)
Hedbergella holmdelensis Olsson, 1964
Hedbergella monmouthensis (Olsson, 1960)
Heterohelix glabrans (Cushman, 1938)
Heterohelix globulosa (Ehrenberg, 1840)
Heterohelix labellosa Nederbragt, 1991
Heterohelix navarroensis (Loeblich, 1951)
Heterohelix planata (Cushman, 1938)
Heterohelix pulchra (Brotzen, 1936)
Heterohelix punctulata (Cushman, 1938)
Heterohelix postsemicostata (Vasilenko, 1961)
Planoglobulina acervulinoides (Egger, 1899)
Planoglobulina carseyae (Plummer, 1931)
Planoglobulina manuelensis (Martin, 1972)
Planoglobulina multicamerata (de Klasz, 1953)
Plummerita hantkeninoides (Brönnimann, 1952)
Pseudoguembelina costellifera Masters, 1976
Pseudoguembelina costulata (Cushman, 1938)
Pseudoguembelina excolata (Cushman, 1926)
Pseudoguembelina hariaensis Nederbragt, 1991
Pseudoguembelina kempensis Esker, 1968
Pseudoguembelina palpebra Brönnimann y Brown, 1953
Pseudotextularia elegans (Rzehak, 1891)
Pseudotextularia nuttali (Voorwijk, 1937)
Pseudotextularia intermedia de Klasz, 1953
Racemiguembelina fructicosa (Egger, 1899)
Racemiguembelina powelli Smith y Pessagno, 1973
Rugoglobigerina hexacamerata Brönnimann, 1952
Rugoglobigerina macrocephala Brönnimann, 1952
Rugoglobigerina milamensis Smith y Pessagno, 1973
Rugoglobigerina pennyi Brönnimann, 1952
Rugoglobigerina reicheli Brönnimann, 1952
Rugoglobigerina rotundata Brönnimann, 1952
Rugoglobigerina rugosa (Plummer, 1926)
Rugoglobigerina scotii (Brönnimann, 1952)
Schackoina multispinata (Cushman y Wickenden, 1930)

Paleogene planktic foraminifera:

Chiloguembelina morsei Kline (1943)
Chiloguembelina midwayensis (Cushman, 1940)
Eoglobigerina edita (Subbotina, 1953)
Eoglobigerina eobulloides (Morozova, 1959)
Eoglobigerina fringa (Subbotina, 1950)
Eoglobigerina microcellulosa (Morozova, 1961)
Eoglobigerina pentagona (Morozova, 1961)
Eoglobigerina polycamera (Khalilov, 1956)
Eoglobigerina praeedita Blow, 1979
Eoglobigerina simplicissima Blow (1979)
Eoglobigerina spiralis (Bolli, 1957)
Eoglobigerina tetragona Morozova (1961)
Eoglobigerina trivialis (Subbotina, 1953)
Globanomalina archeocompressa (Blow, 1979)
Globanomalina compressa (Plummer, 1926)
Globanomalina imitata (Subbotina, 1953)
Globanomalina planocompressa (Shutskaya, 1965)
Globoconusa alticonusa (Li, McGowran and Boersma, 1995)
Globoconusa daubjergensis (Brönnimann, 1953)
Globoconusa fodina (Blow, 1979)
Globoconusa cf. *fringa* (in Luterbacher and Premoli Silva, 1964)
Globoconusa minutula (Luterbacher and Premoli Silva, 1964)
Guembelitria alabamensis Liu y Olsson (1992)
Guembelitria irregularis Morozova (1961)
Parasubbotina moskvini (Shutskaya, 1953)
Parasubbotina pseudobulloides (Plummer, 1926)
Parasubbotina varianta (Subbotina, 1953)
Parvularugoglobigerina cf. *hemisphaerica* (in Blow, 1979)
Parvularugoglobigerina eugubina (Luterbacher and Premoli Silva, 1964)
Parvularugoglobigerina longiapertura (Blow, 1979)
Parvularugoglobigerina perexigua (Li, McGowran and Boersma, 1995)

Parvularugoglobigerina sabina (Luterbacher and Premoli Silva, 1964)
Parvularugoglobigerina umbrica (Luterbacher and Premoli Silva, 1964)
Praemurica inconstans (Subbotina, 1953)
Praemurica pseudoinconstans (Blow, 1979)
Praemurica taurica (Morozova, 1961)
Subbotina triloculinoides (Plummer, 1926)
Woodringina claytonensis Loeblich and Tappan, 1957
Woodringina hornerstownensis Olsson, 1960

Cretaceous/Paleogene small benthic forminifera:

Bolivinoides delicatulus Cushman, 1927
Bolivinoides draco (Marsson, 1878)
Bulimina trinitatensis Cushman and Jarvis 1928
Cibicidoides ekblomi Brotzen 1948
Cibicidoides hyphalus (Fisher, 1969)
Cibicidoides velascoensis (Cushman, 1925)
Clavulinoides trilatera (Cushman, 1926)
Eouvigerina subsculptura McNeil and Caldwell, 1981
Gaudryina pyramidata Cushman, 1926
Glomospirella grzybowski Jurkiewicz, 1960
Loxostomum eleyi (Cushman, 1927)
Nuttallinella florealis (White, 1928)
Paralabamina lunata (Brotzen, 1948)
Praebulimina reussi (Morrow, 1934)
Pseudouvigerina plummerae Cushman, 1927
Pyramidina rudita (Cushman and Parker, 1936)
Repmanina charoides (Jones and Parker, 1860)
Sitella cushmani (Sandidge, 1932)
Spiroplectammina spectabilis (Grzybowski, 1898)
Stensioeina beccariiformis (White, 1928)