FIELD-TRIP GUIDE TO THE AGOST AND CARAVACA SECTIONS (BETIC CORDILLERA, SPAIN)

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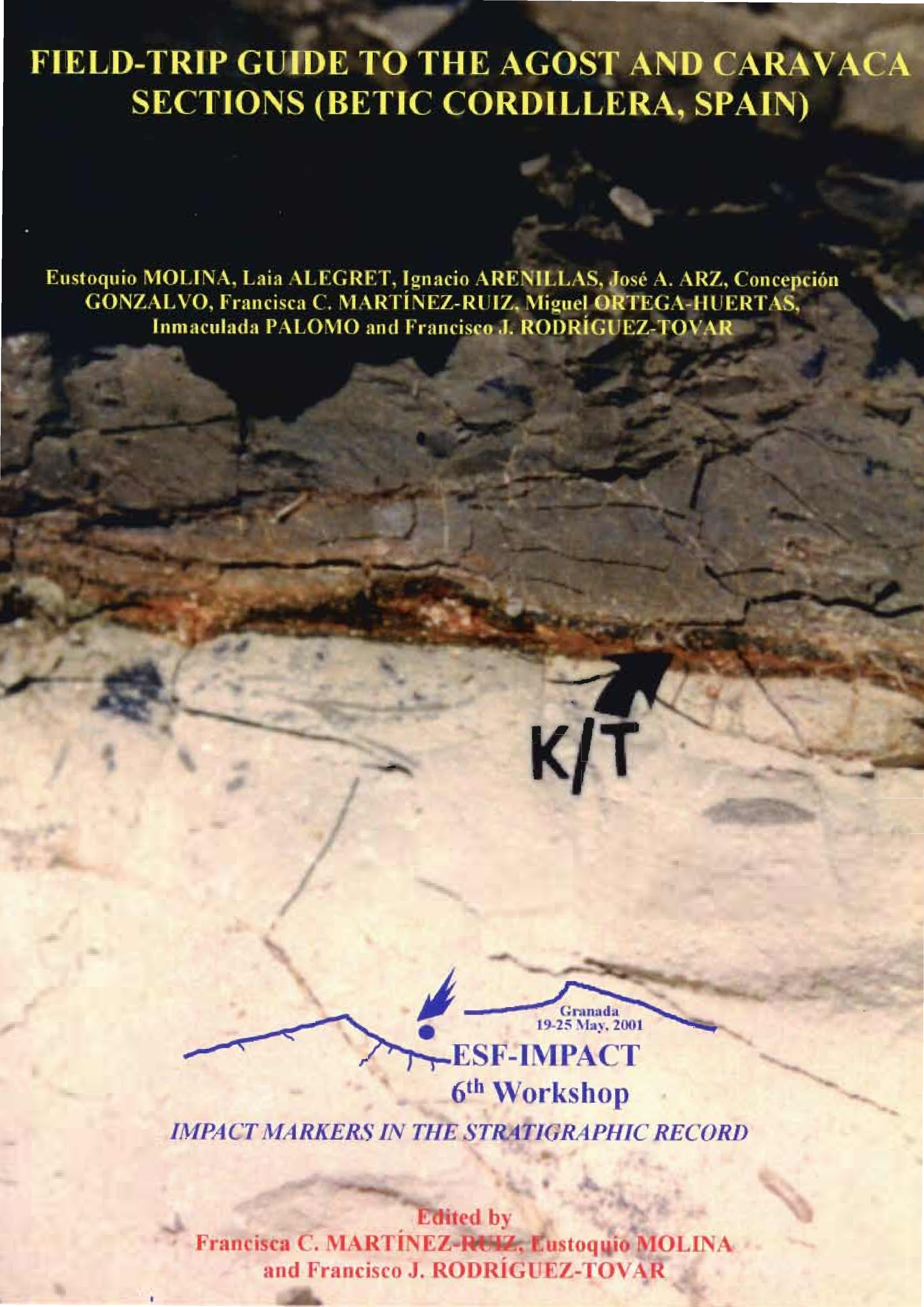

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IMPACT MARKERS IN THE STRATIGRAPHIC RECORD

Edited by
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and Francisco J. RODRÍGUEZ-TOVAR

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The Cretaceous/Tertiary and Ypresian/Lutetian boundaries of the Agost section (Alicante Province, Betic Cordillera)

STOP 1: THE CRETACEOUS/TERTIARY BOUNDARY

LOCATION

The town of Agost is located in the Betic Cordillera of Southeast Spain and the section is placed about 1 km North of the town (Fig. 1).

The K/T boundary transition can be sampled in a roadcut near the 13 km marker post and the Maastrichtian sequence closer to the town in a small gully opposite to the cemetery. Maastrichtian sediments consist of intercalated grey marls and marly limestone beds. The K/T boundary is marked by a 10 cm thick dark clay layer with a basal 2 mm thick rust-red layer, which contains the impact evidence. The Tertiary sediments above the 10 cm black clay layer consist of marls and marly limestones that are of gray colour in the basal Paleocene and red at the top of the section. All the samples can be taken in a well exposed outcrop, but the outcrop must be trenched across the K/T boundary to remove surface contamination and obtain fresh unweathered bedrock.

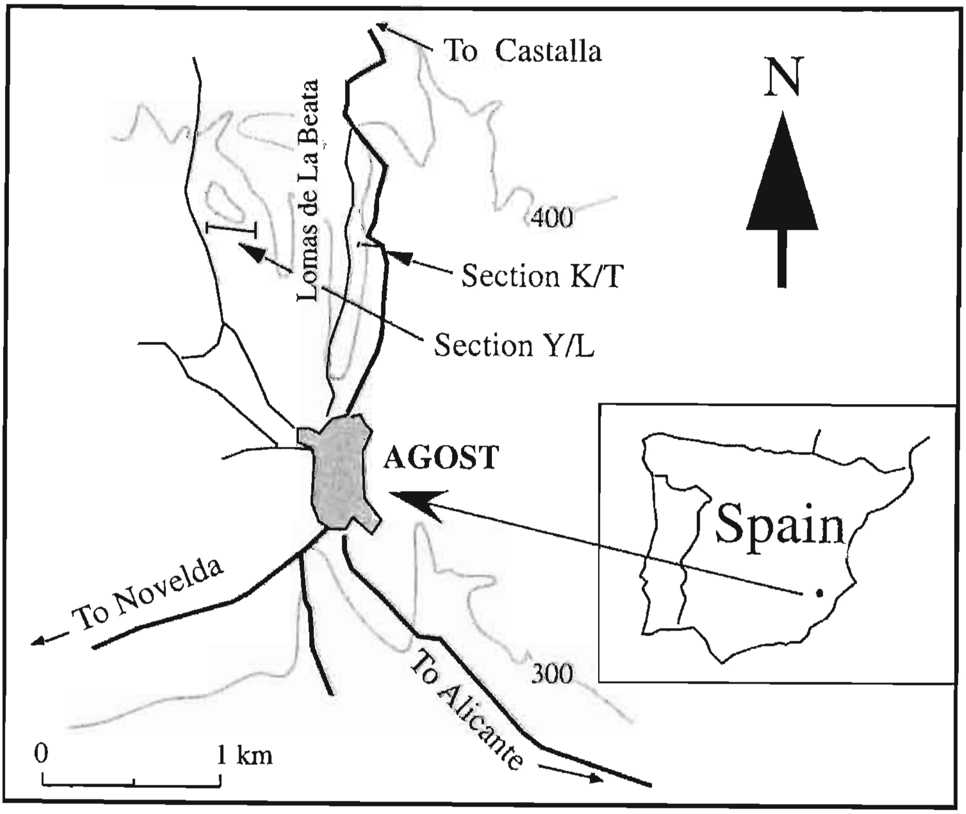

Fig. 1.- Geographical location of the Agost K/T and Y/L sections.

MICROPALEONTOLOGY (E. Molina, J. Arenillas and J. A. Arz)

According to Molina *et al.* (1996) the Cretaceous/Tertiary boundary (K/T) mass extinction model in planktic foraminifera and its interpretation has been a very controversial topic. The origin of this controversy can be found in the data that Smit presented at the Snowbird I Conference in 1980, showing that all but one Cretaceous species suddenly became extinct at the K/T boundary, which he interpreted as the result of a large meteorite impact (Smit and Hertogen, 1980; Smit, 1982). These data were questioned by Keller (1988) who apparently provided evidence that species extinctions extended across the K/T boundary with about 1/3 of the species surviving well into the Tertiary (Keller, 1988, 1989a,b). Our most recent studies (Molina *et al.*, 1998; Arz et *al.*, 1999; Arenillas *et al.*, 2000 a,b, among others) demonstrated that the pattern of extinction is very sudden and catastrophic, being very probably the result of a large meteorite impact as was first proposed by Alvarez *et al.* (1980) and Smit and Hertogen (1980).

The oldest detailed studies were published by Luterbacher and Premoli-Silva (1964), who established the *Globigerina eugubina* Biozone at the K/T boundary in Italy. The assemblage of this biozone was later recorded from the South Atlantic, Northwest Pacific, Gulf of Mexico and Caribbean deep-sea cores, which led Premoli-Silva (1977) to conclude that the *G. eugubina* Biozone fauna is cosmopolitan, and represents the earliest Tertiary assemblage from which all Paleogene genera could be derived either directly or by inference. Subsequently, high resolution sampling of the K/T boundary at Caravaca (Spain) by Smit (1977, 1979) let to the discovery of a still earlier Tertiary planktic foraminiferal association below the *G. eugubina* Biozone. By this time Alvarez *et al.* (1980) proposed the now popular hypothesis that an extraterrestrial bolide caused the Cretaceous-Tertiary mass extinction. This has led to a tremendous interest in the K/T mass extinction across disciplines ranging from paleontology to chemistry and astrophysics. Many authors have since tried to elucidate the model of extinction and their causes but few have studied continuous sections or at the necessary high sample resolution. Consequently, as a result of large sample spacing or hiatuses, mainly based on the Italian sections, it was assumed that Cretaceous planktic foraminifera suffered near total extinction precisely at the K/T boundary.

During the late 1980's, however, some workers studied more complete sections and sampled the critical intervals at the centimetre scale. As a result, they discovered a more gradual mass extinction pattern in planktic foraminifera (Keller, 1988, 1989a,b, 1993; Canudo *et al.*, 1991). Nevertheless, studying the same sections Smit (1990) has maintained his interpretation of a catastrophic pattern with all but one Cretaceous species (*Guembelitria cretacea*) extinct precisely at the K/T boundary. To resolve this catastrophic versus gradual mass extinction controversy, a group of scientists re-sampled the El Kef section in Tunisia and samples were distributed for a "blind sample text". For this blind test six unlabeled samples were studied by four investigators, the result was exhibited at the Snowbird III Conference and both Keller and Smit claimed that the data support their interpretations (Smit, 1994; Keller *et al.*, 1995).

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

Planktic Foraminiferal Biostratigraphy

The Agost planktic foraminiferal biostratigraphy is very similar to the Spanish section at Caravaca and quite similar to the very well known El Kef section in Tunisia. We have used the classical system of biozonation, indicating the sequence of planktic foraminiferal datum events used to establish our biozones at Agost. Following the lower latitude biozonation used by Molina *et al.* (1996), we have identified six biozones across the K/P boundary at Agost: *Abathomphalus mayaroensis* Biozone, *Plummerita hantkeninoides* Biozone, *Guembelitria cretacea* Biozone, *Parvularugoglobigerina eugubina* Biozone, *Parasubbotina pseudobulloides* Biozone and *Globanomalina compressa* Biozone. Figure 2 (Molina *et al.*, 1996) shows the datum events at the Agost section along with our biozonation and the comparison with other related biozonations.

Abathomphalus mayaroensis Biozone

This biozone was originally defined by the total range of *A. mayaroensis*, but in this study following the zonation proposed by Ion (1993) is restricted to the first appearance datum (FAD) of *Plummerita hantkeninoides*. The *A. mayaroensis* Biozone characterize the late Maastrichtian in low latitude and high latitude deep sea sequences such as the Tethyan palaeogeographic realm (Robaszynski *et al.*, 1983-1984), including the Alamedilla (Linares, 1977) and Caravaca sections (Canudo *et al.*, 1991) and the southern Indian Ocean Sites 690 and 738 (Huber, 1991; Keller, 1993). However, *A. mayaroensis* is very rare or absent in shallow sections such as El Kef (Keller, 1988), Brazos River (Keller, 1989a,b) and Stevns Klint and Nye Klov in Denmark (Schmitz *et al.*, 1992; Keller *et al.*, 1993). This biozone is thus restricted mainly because *A. mayaroensis* is a deep water dweller. Therefore, alternative biozones have been proposed to characterise the terminal Maastrichtian. The *Globutruncana falsocalcarata* Biozone was originally proposed by Kassab (1976) based on sections in northern Iraq and applied by Solakius *et al.* (1984) in the Ain Mdeker section in Tunisia. However, few workers have observed the first appearance of the index species prior to the FAD of *A. mayaroensis*. The *Pseudotextularia deformis* Biozone was proposed by Keller (1988) but this index species has taxonomical problems.

Plummerita hantkeninoides Biozone

This biozone is defined by the total range of *Plummerita hantkeninoides* and was recognised by Pardo *et al.* (1996) at the Agost section. Nevertheless, Masters (1993) had previously suggested that *P. hantkeninoides* is a junior synonym of *Rugoglobigerina reicheli,* but we think that both morphotypes belong to different species. It is used in this paper due to the scarcity of *A. mayaroensis* in the terminal Maastrichtian mainly in shallow sections as indicated above. Nevertheless, in the two uppermost Cretaceous samples *A. mayaroensis* is more frequent that *P. hantkeninoides*. The abundance of *A. mayaroensis* just below the layer with the iridium anomaly has also been observed in some continuous sections in the Basque Country in Northern Spain (Orúe-Etxebarría *et al.*, 1991; Arz *et al.*, 1992). The presence of *A. mayaroensis* just below the K/T boundary in these sections could be associated with a sea-level rise during the last 50 kyr of the Maastrichtian (Li and Keller, 1999). All large tropical Cretaceous taxa suddenly disappear at the top of this biozone. At the Agost section, the total range of *P. hantkeninoides* spans the top 3.45 m of the Maastrichtian, whereas at the El Kef stratotype it corresponds to the top 6 m. This suggest that the El Kef section has a higher rate of sedimentation than the Agost section.

Guembelitria cretacea Biozone

This biozone spans the interval between the last appearance datum (LAD) of *Plummerita hantkeninoides* precisely at the K/T boundary and the first appearance datum of *G. eugubina*. The *G. cretacea* Biozone is the equivalent to Zone P0 of Smit (1982), Keller (1988) and Pardo *et al.* (1996). The K/T boundary was defined at the base of a clay layer at the El Kef boundary stratotype section, where the K/T boundary is recognised by a thin red oxidized layer, an Ir anomaly, an increase in Ni-rich spinels, an increase in total organic carbon (TOC), a decrease in $\partial^{13}C$, and the first appearance of the Tertiary planktic foraminifera. This boundary clay and its basal red layer is easily correlated with the basal yellow-red layer of Jarosite and FeO, which is just below an interval of 10 centimetres thick dark clay at the Agost section. This yellow-red layer contains geochemical evidence that is related to the effect of a large meteorite impact (Smit and ten Kate; 1982, Smit, 1990). Most of the *G. cretacea* Biozone is characterised by black clay which contains a well preserved autochthonous fauna and the Tertiary planktic foraminifera first appeared in the lower part of this biozone.

Parvularugoglobigerina eugubina Biozone

This biozone defines the interval between the *P. eugubina* FAD and the *P. pseudobulloides* LAD. Keller (1993) defines the *P. eugubina* Biozone as the total range of this species and uses the *P. pseudobulloides* FAD to subdivide this biozone into P1a(1) and P1a(2). Canudo *et al.* (1991) follow Blow (1979) and used *P. longiapertura* to characterise this biozone because this species has a very distinct and stable morphology with its compressed test and high slit-like aperture and thus may be a more suitable index taxon. Nevertheless, to date this alternative biozone has been less accepted and most workers have included *P. longiapertura* within the *P. eugubina* group. For this reason we decided to continue the use of the classical *P. eugubina* Biozone.

Parasubbotina pseudobulloides Biozone

This biozone defines the interval between the *P. pseudobulloides* FAD and *Globanomalina compressa* FAD. *Parasubbotina pseudobulloides* is an index taxon that has been used in most of the classical biozonations. Nevertheless, the FAD of *S. pseudobulloides* appears to be very diachronous and Canudo *et al.* (1991) suggested the *P. longiapertura* LAD as alternate datum event. However, this proposal also has taxonomic and biostratigraphic problems and we decided to follow the standard biozonation of Bolli (1966). In the lower part of this zone, planktic foraminifera reach normal size and can be found in the fraction larger than 150 microns, as also observed by Keller (1988) for the El Kef section.

Globanomalina compressa Biozone

This biozone defines the interval between the *G. compressa* FAD and the top of the section studied. This event was used by Blow (1979) to define the base of the *G.(T.) compressa/G(T.) eobulloides simplicissima* (P1b) Biozone. This interval is well above the K/T boundary and not relevant for the K/T boundary event, since all but one Cretaceous taxa (*G. cretacea*) became extinct earlier, and the adaptive radiation of early Tertiary taxa is well established.

Planktic Foraminiferal Faunal Turnover

Late Maastrichtian assemblages from the Agost section are largely dominated by biserial species (heterohelicids). Planispiral (globigerinelloids) and trochospiral (hedbergellids, rugoglobigerinids and globotruncanids) species are frequent, triserial species (guembelitriids) are common and tubulospinose (schackoinids) species are rare. The stratigraphic ranges of these taxa during the late Maastrichtian indicate very few changes in the faunal assemblages and most of species are present in the *A. mayaroensis* and *P. hantkeninoides* Biozones. Some species seem extinct at the base of the upper Maastrichtian (in the *A. mayaroensis* Biozone), such as *Gansserina wiedenmayeri*, *Gansserina gansseri* and *Contusotruncana plicata*. The rest of the species (*Racemiguembelina milamensis, Archaeoglobigerina cretacea, Gublerina acuta* and

Rugoglobigerina pennyi) disappear in the upper part of the *P. hantkeninoides* Biozone (Fig. 2). Only one species has its first appearance in this interval: *P. hantkeninoides*. Therefore, more species disappear than appear in the late Maastrichtian and this tendency could suggest adverse environmental conditions during the latest Maastrichtian. However, 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 47 species disappear in coincidence with the yellow-red layer that marks the K/T boundary. We double checked this coincidence by scanning the residue of the uppermost Cretaceous samples. This methodology is necessary in order to minimize the Signor-Lipps (1982) effect, because certain rare species could appear to become extinct before their real moment of extinction. The total percentage of the species that became extinct at or below the K/T boundary is about 20 % in the size fraction larger than 63 microns. However, they represent about 68% of the species, which clearly implies the most important extinction event in the history of planktic foraminifera. All of these taxa are large, complex forms adapted to deep environments. In contrast, the small, cosmopolitan forms which were largely surface dwellers were most abundant (e.g., *Heterohelix globulosa* and *Heterohelix navarroensis*).

In the Agost section there is almost no evidence of reworking, the sedimentology shows no evidence of currents. To eliminate the potential problem of reworking, that could interfere in high resolution sampling, we ignored the presence of isolated specimens in a sample or with a different preservation, assuming them to be reworked and hence did not list them in our data tables or figures. In the lowermost Tertiary (*G. cretacea*, *P. eugubina*, *P. pseudobulloides* and the lower part of *G. compressa* Biozones) a total of 16 Cretaceous species are present that can be considered possible Cretaceous survivors. These 16 species are cosmopolitan, small and simple surface dwellers that disappeared gradually during the early Danian (Fig. 2). Survivorship of cosmopolitan Cretaceous species was first noted by Keller (1988, 1989a,b) and later documented in numerous sections worldwide (Canudo *et al.*, 1991; Keller *et al.*, 1993, 1995; MacLeod and Keller, 1994). The guembelitriids (*Guembelitria trifolia* and *G. cretacea*) are rare in the upper Cretaceous, but these opportunistic species are very abundant in the lowermost Tertiary, just after the main planktic foraminiferal extinction event. The rest of the Cretaceous surface dwellers are less abundant in the Danian than in the Maastrichtian (Fig. 2).

In the same Danian levels in which the surviving Cretaceous species are disappearing, new Tertiary species are evolving. These new species are also opportunistic cosmopolitan taxa, which can be divided into two main assemblages. The first assemblage to appear consists of the small cosmopolitan surface dwellers, which originate in the *G. cretacea* Biozone and become extinct in the lower part of the *P. pseudobulloides* Biozone. The second assemblage originates in the *P. eugubina* Biozone and diversifies during the lower part of the *P. pseudobulloides* Biozone where these taxa reach normal size. This assemblage colonises the intermediate and deeper water environments in the upper part of this biozone and they continue to be abundant at least to the top of the interval studied (Fig. 2).

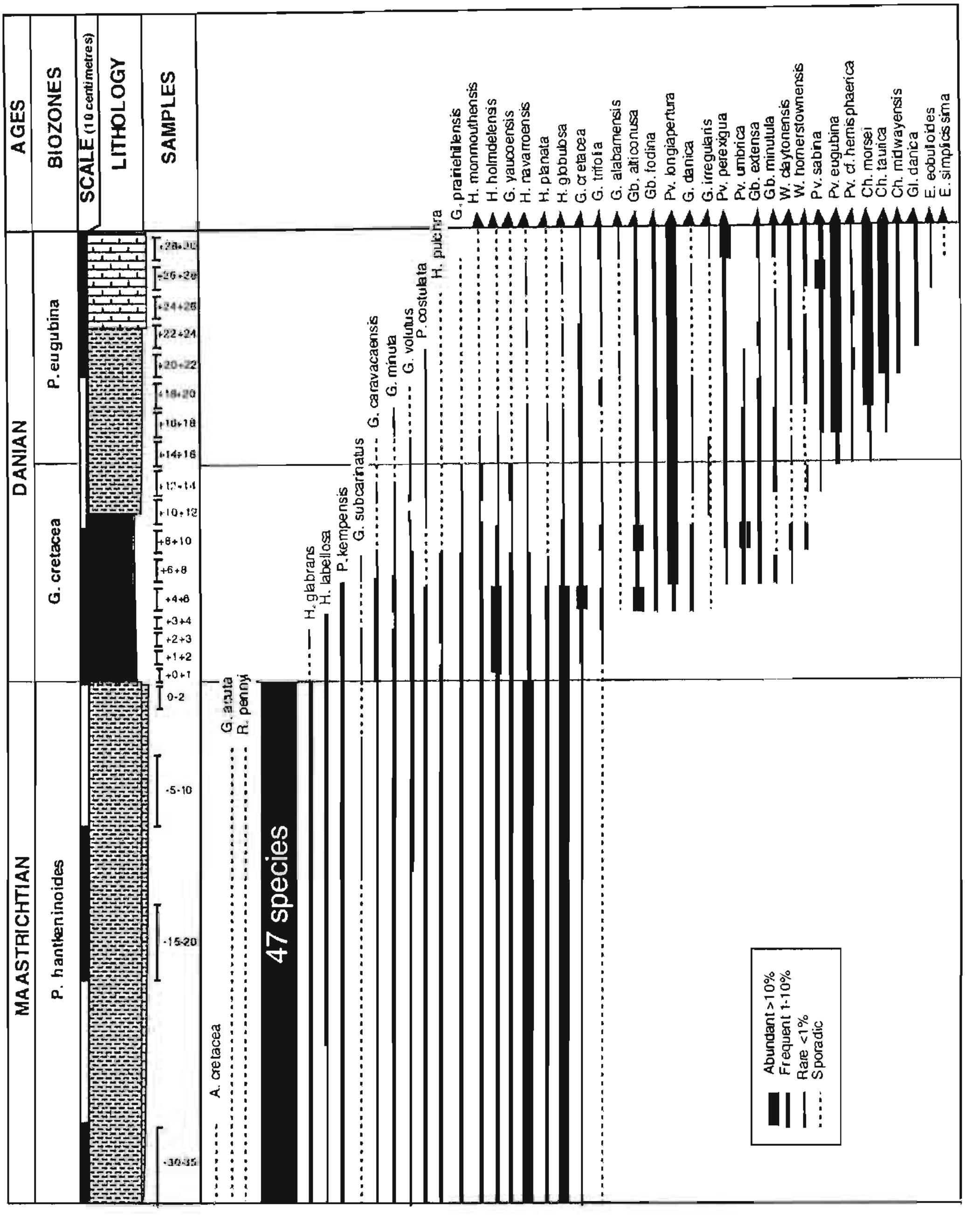

Fig. 2.- Planktic foraminiferal ranges across the Cretaceous/Tertiary boundary at the Agost section (modified from Molina *et al.*,1996).

The relative abundance of species that evolved in the lower Danian are dominant during the early Danian and most of them became extinct near the base of the *P. pseudobulloides* Biozone (e.g., *Parvularugoglobigerina longiapertura, P. eugubina, P. sabina, Globoconusa fodina* and *G. alticonusa*). After the disappearance of these species, the dominant species are *Woodringina claytonensis, Woodringina* *hornerstownensis* (=*Chiloguembelina morsei*), *Chiloguembelina taurica* and *Chiloguembelina midwayensis* (Fig. 2).

Patterns and causes of extinction

The planktic foraminiferal extinction pattern for the K/T boundary is a controversial topic because it depends on different interpretations of the data and on the methodology used to obtain these data (Molina, 1994, 1995). The continuity of the Agost section, the abundance of planktic foraminifera, the high resolution sampling and the quantitative study provide an excellent opportunity to evaluate the K/T boundary mass extinction and elucidate the real nature of this controversy.

The oldest and least detailed studies of the K/T transition were performed on widely spaced samples (Bolli, 1966) or on sections which contained hiatuses (Linares and Martínez-Gallego, 1971). At present it is quite obvious that such methodology, or discontinuous sections are unsuitable to establish the pattern of extinction in planktic foraminifera, and that by default such studies will show a catastrophic extinction pattern. An additional constraint in evaluating this mass extinction is the thickness of the K/T transition, or the rate of sediment deposition. Luterbacher and Premoli-Silva (1964) sampled and studied Gubbio section in great detail. They defined several new species and named a new biozone (*G. eugubina* Biozone). However, this Italian section is very condensed (Arenillas and Arz, 2000) and thus can not be used as the real model of extinction. Alvarez *et al.* (1980) proposed the bolide impact hypothesis for the Cretaceous-Tertiary mass extinction based on these Italian sections, and hence assumed the nearly total extinction of the planktic foraminifera. This concept of near total extinction was the prevailing view among micropaleontologists at that time.

Nevertheless, more expanded sections were studied by Smit (1977, 1979), assuming the total extinction of all the planktic foraminifera, except *G. cretacea* and probably *H. monmouthensis* and *G. messinae*. Although Smit studied closely spaced samples across the K/T boundary, he concluded that the extinction of planktic foraminifera was abrupt and without any previous warning in the sedimentary record (Smit and Hertogen, 1980). Smit also studied the Agost section (Groot *et al.*, 1989) and the Tunisian section at El Kef, and maintained and even further developed the idea that the impact event at the K/T boundary suddenly exterminated all but one species (Smit, 1982, 1990). He considered all Cretaceous specimens present above the K/T boundary as reworked. However, Keller (1988), studying the El Kef section, suggests that species extinction extended across the K/T boundary with 10 of the species surviving well into the Tertiary. She also apparently found 14 species disappearing below the boundary and concluded that these extinctions appear unrelated to an impact event. These ideas were apparently documented studying other sections distributed all over the world (Keller, 1989a,b, 1994). Nevertheless, some authors critically commented those ideas (Huber *et al.*, 1994), which were well defended and largely replied (Keller and MacLeod, 1994).

One of the most controversial aspect in the K/T extinction pattern is the decline of the fauna prior to the K/T boundary. Our data from Agost indicate that in the terminal Maastrichtian (uppermost meter) 4 species disappeared, but no species appeared (Fig. 2). Changes prior to the K/T boundary were also noted in the Spanish sections of Zumaya (Herm, 1965; Lamolda, 1983, 1990), Sopelana (Lamolda *et al.*, 1983; Orúe-Etxebarría *et al.*, 1984), Caravaca (Canudo *et al.*, 1991; Canudo, 1994; Pardo *et al.*, 1996) and in the Tunisian section of El Kef (Brinkhuis and Zachariasse, 1988). However, the magnitude of the decline shown by the former authors is less notable than the one found at El Kef (Keller, 1988; Keller *et al.*, 1995), at Brazos River (Keller, 1989a,b) and in the Antarctic Ocean (Keller, 1993).

This decline prior to the K/T boundary could be due to a gradual decrease in temperature (Schmitz *et al.*, 1992; Keller *et al.*, 1993; Barrera, 1994; D'Hondt and Lindinger, 1994), which produced the retreat to low latitudes of certain species.

However, the discrepancies in interpretations in low latitudes and even in the same sections, are due to the Signor-Lipps effect. According to our data from Agost, the species extinctions prior to the K/T boundary are not significant and could be considered as the result of background extinction or even the remaining Signor-Lipps effect.

The Agost section is very continuous since all the planktic biozones have been found and Danian planktic foraminiferal species appear sequentially in basal part of the Danian. This section is similar to El Kef and Caravaca, which are some of the most complete sections known world wide. The paleoenvironment at Agost was a subtropical upper slope, based on small benthic foraminifera (Pardo *et al.*, 1996), with a very diversified planktic foraminifera fauna. The high resolution methodology and the intensive search in every terminal Cretaceous sample (to minimize the Signor-Lipps effect) indicate that 47 species suddenly disappeared at the K/T boundary at Agost section (Fig. 2). This is the major extinction event in the history of planktic foraminifera, and it exactly coincides with the layer containing the impact evidence. Regarding the causes of this major extinction, now it is generally accepted that a meteorite impacted at the K/T boundary (D'Hontd, 1994; Schmitz, 1994). The species that suddenly became extinct were mainly the tropical-subtropical and intermediate and deep dwellers, whereas the cosmopolitan surface dwellers suffered less.

How many species survived the K/T boundary event? This question constitutes one of the most controversial aspects of this topic. According to Smit (1982, 1990) only *Guembelitria cretacea* survived. In contrast, Keller (1988, 1989a,b, 1993, 1994), Keller *et al.* (1993, 1995) and MacLeod and Keller (1994) reported that about 1/3 of the species survived. Historically it was assumed by most of the micropaleontologists that almost all planktic foraminifera became extinct at the K/T boundary; consequently, all Cretaceous specimens found in the basal Danian were considered as reworked. However, isotopic analyses of some Cretaceous species present in earliest Tertiary sediments allowed Barrera and Keller (1990) and Keller *et al.* (1993) to conclude that some of the abundant Cretaceous species present in Tertiary sediments have Tertiary signals and are, therefore, Cretaceous survivors (Keller, 1988, 1989a,b, 1993; Canudo *et al.*, 1991; Keller *et al.*, 1993; MacLeod and Keller, 1994). The 16 species found in the basal Tertiary of the Agost section can be considered possible survivors. Other specialists have accepted that some species, such as *Hedbergella holmdelensis* and *Hedbergella monmouthensis*, survived apart from *G. cretacea* (Liu and Olsson, 1994), at the same time that the Cretaceous survivors are gradually disappearing in the basal.

Perhaps, the few pre-K/T extinctions are only local disappearances and are the product of a Lazarus effect in the Tethyan region caused by global geological changes, such as a decrease in temperature that began in the latest Maastrichtian (Schmitz *et al.*, 1992; Barrera, 1994; D'Hondt and Lindinger, 1994) which may have been associated with a sea level fall (Ginsburg, 1964, 1984; Brinkhuis and Zachariasse, 1988; Keller, 1988). The biological constraints that affected the post-K/T assemblages could have been controlled by both terrestrial geological causes and the long term disruptive effect of the extraterrestrial bolide impact. However, we consider that the terrestrial causes do adequately not explain the catastrophic mass extinction at the K/T boundary nor the model of "explosive" adaptative radiation just after the K/T boundary event. It is quite generally accepted that an asteroid impacted the Earth at the K/T boundary time and that the layer is a record of short and long term sedimentologic processes, which differ depending on the proximity to impact site (Maurrasse and Sen, 1991; D´Hondt, 1994; Schmitz, 1994). Furthermore, the catastrophic mass extinction exactly coincides with the base of the yellow-red layer containing the impact evidence at Aïn Settara (Arenillas *et al.*, 2000b) and other sections (Molina *et al.*, 1998). For these reasons, we suggest that the pattern of extinction and origination across the K/P boundary is more compatible with the impact hypothesis than other geological causes.

TRACE FOSSILS (F. J. Rodríguez-Tovar)

In the last years, a general consensus appears to exist in the relationship between the bolide impact registered in the Earth at the end of the Cretaceous, and the mass extinction affecting several species at or near the Cretaceous/Tertiary boundary. The impact of an extraterrestrial bolide is interpreted as the origin of relatively rapid and dramatic environmental changes, affecting, at different order, species belonging to the marine and terrestrial communities. Numerous papers, focusing on the environmental consequences of the impact in the marine ecosystem and the Global Bio-Event registered, mainly documented in planktonic microfossil biota.

In relation to the environmental changes occurred during the boundary event in the benthic marine ecosystem and the recovery of the ecosystem after the impact, trace-fossils record reveals extremely interesting, specially when shelly benthic fauna is scarce. However, little attention has been paid to the ichnological record of the K/T boundary sediments, and only in some marine sections from Denmark (Ekdale and Bromley, 1984), Alabama (Savrda, 1993), and northeastern Mexico (Stinnesbeck *et al.*, 1993, 1996; Keller *et al.*, 1994, 1997; Ekdale and Stinnesbeck, 1998) trace-fossil analyses have been performed. In most of these papers, ichnologic approach allow the authors to interpret a non catastrophic origin of these sediments. Thus, trace-fossil record indicate sea-level changes near the K-T transition (Savrda, 1993), or a general upward shoaling that, accompanied by an abrupt shift in deposition, created unstable substrates for benthic organisms (Ekdale and Bromley, 1984). For Stinnesbeck *et al.* (1996), Keller *et al.* (1997) and Ekdale and Stinnesbeck (1998), the multiple and discrete horizons of bioturbation recognized could not be related to a short-term K/T impact-generated K/T tsunami event, and also throws doubt on current alternatives such as a turbidite triggered by an impact-generated tsunami or earthquake, or a sea-level regression-transgression.

At the Agost section, no detailed ichnological analysis were performed, and only occasionally bioturbation is mentioned in the literature in reference to the absence of burrowing mixing of sediments or illustrated when lithological columns were figured (Canudo *et al.*, 1991).

Trace fossil analysis

Ichnological approach in the K/T boundary transition at Agost was performed by analyzing ichnotaxa, relative abundance, horizontal and vertical distribution of trace fossils, and cross-cutting relationship.

The study of the macroscopic biogenic structures was performed directly on outcrop and complemented by laboratory analysis. Field works were mainly focused on detailed observations after the section was trenched and cleaned to obtain a fresh rock, and sometimes the rock surface was wetted to accentuate ichnological features. The study in laboratory was performed on rock samples, polished blocks and thin sections. The study on rock samples and polished blocks perpendicular to bedding was made directly without any treatment (bioturbation by the naked eye), and after impregnation with water and light-weight oil ("modified Bushinsky oil technique", Bromley, 1981; Bromley and Ekdale, 1984), to increase contrast in the rock. Thin sections were performed in order to analyze microfacies, burrows contact and fillings. However, some difficulties were founded when filling material was studied due to the uncompacted character of some samples and the comparatively small size of trace fossils. Thus, at the moment, no satisfactory conclusions have been obtained from thin sections, and a more exhaustive analysis would be performed in posterior researches.

Ichnotaxa

Field observations of K/T boundary transition at Agost, show a relatively abundant and conspicuous trace fossil assemblage at the Upper Cretaceous sediments. The dark trace-fossils filling (dark color similar to that of the lowermost Danian marly clays) highly contracts with the light color of these sediments (grey to cream), that facilitate their differentiation. Even that a diffusely burrow-mottled background and some discrete lightly filled burrows can be recognized, at this moment the preliminary ichnological approach has been focused on the discrete trace fossils, dark infilled, comparatively better differentiated from the Upper Cretaceous light color materials.

The ichnological analysis allow to recognize the following ichnotaxa: *Chondrites*, *Planolites*, *Thalassinoides* and *Zoophycos*. From those, *Chondrites* is the most abundant, followed by *Zoophycos*; *Thalassinoides* and *Planolites* are common but comparatively less abundant. Other ichnotaxa as *Diplocraterion*, *Taenidium*?, *Rhizocorallium* and some unidentified structures were also recognized by its scarcity preclude, at the moment, a detailed analysis.

Chondrites

Chondrites is usually referred to a highly branched burrow, vertically to horizontally oriented, produced relatively deep in the sediment. This trace is considered as a feeding structure created by an unidentified organism (Ekdale and Stinnesbeck, 1998 and cites therein), and sometimes as a fodinichnion originated by a sessile worm that uses an extensible proboscis to exploit sediments, maintaining a fixed position in a central shaft (Locklair and Savrda, 1998 and cites therein). However, several alternative models have been also proposed (Locklair and Savrda, 1998 and cites therein). This burrow is often associated with low-oxygen substrates.

In the section, *Chondrites* specimens represent the most abundant trace fossil, being recognized as isolated structures and in association with *Thalassinoides*, and occasionally with *Planolites* and *Zoophycos*. The *Chondrites* structures exhibit a very regular branching developed mainly in horizontal planes, but slightly inclined and vertical branches are also differentiated. *Chondrites* have been frequently registered disperses in the sediment, but can be also recognized concentrated in particular horizontal planes. Two *Chondrites* assemblages can be clearly differentiated on the basis of the size: large *Chondrites* with branches reaching more than 4 cm long, bifurcations from 0.5 to 1.5 cm in length and tunnel diameters between 0.1 and 0.2 cm, and small *Chondrites*, less than 1 cm long and ≤ 0.1 cm in diameter. Occasionally short segment of the vertical *Chondrites* shafts have been recognized, reaching a maximum of 2.5 cm with horizontal subdivisions 1.3 to 3.5 cm long.

Zoophycos

Zoophycos is a broadly arcuate, spreiten burrow, horizontally to obliquely oriented, that shows a three-dimensional, helicoidal or tongue-like structure as a result of overlapping U-shaped burrows. Although there is a general agreement that *Zoophycos* is a systematic feeding structure (fodinichnia) created by deep, unidentified deposit-feeding worms, the precise ethological interpretation remains controversial. This is probably due the assignation to "Zoophycos" of diverse structures generated by different tracemakers employing different behavior, or even a single tracemaker employing diverse behaviors (Kotake, 1989, 1994; Bromley, 1991; Locklair and Savrda, 1998; MacEachern and Burton, 2000).

In the case study, relatively abundant, horizontal and obliquely oriented burrows belonging to *Zoophycos* have been recognized. However, only tentatively an axial shaft was identified. The analysis of horizontal planes allow the recognition of isolated spreite lobes with variable morphology (circular to elongate). In these cases, measurements can be referred to one (diameter) or to two dimensions. Cross-sectional view allow to appreciate the typical inner spreite structure, as well as to recognize several cases in which different lobes belong to the same structure. The most complete *Zoophycos* registered is composed by five lobes, spaced vertically 2-7 cm apart, increasing size downward from around 4 cm long to a maximal length higher than 14 cm. Structures are 0.1-0.3 cm thick. Occasionally, *Zoophycos* have been recognized in association with *Chondrites*.

Thalassinoides

Thalassinoides is a branching burrow (Y- or T-shaped branches) with either horizontal, oblique, or vertical box-like networks and enlargements at junctions between some branches. Burrows are unlined and unornamented, with smooth walls. *Thalassinoides* is generally interpreted as a fodinichnion structure produced by crustaceans, usually related to oxygenated situations and soft but fairly cohesive substrates (Bromley and Frey, 1974; Kern and Warme, 1974; Ekdale *et al.*, 1984; Bromley, 1990).

In the section, several samples with discrete *Thalassinoides* have been studied. In most cases only the horizontal structures (Y-shaped branches) exit, and only occasionally vertical branches have been recognized. Individual horizontal branches ranging from 1.5 to 4.5 cm in length, with diameters from 0.4 to 0.9 cm. Usually, has been recognized in association with *Chondrites*, and sometimes with *Planolites*, and, probably, *Taenidium*.

Planolites

Planolites is a simple, unlined, unbranched, horizontal burrow. This is interpreted as a pascichnion produced by mobile, infaunal, deposit-feeding worm-like organisms. The burrow was produced very shallow within the sediment. The filling material is structureless and differs slightly from the surrounding sediment, in contrast that occurs in *Palaeophycus* (Pemberton and Frey, 1982; Bromley, 1990).

In the section, horizontal unbranched burrows, poorly preserved, as well as burrow sections have been assigned to tiny *Planolites*. However were recognized other unlined structures, horizontal to slightly inclined, extremely flat, similar to *Planolites*, that it was not possible to reject their assignation to other different ichnotaxa.

Vertical distribution

The analysis of the vertical record of trace-fossil assemblage in the Upper Cretaceous sediment at Agost was performed at first instance on outcrop. Moreover, in some occasions, several thick samples were collected and analyzed in detail in the laboratory, allowing the study of the trace-fossil record from K/T boundary downward, to 10, 12, 13 and 20 cm below. From a biostratigraphical point of view, the vertical interval studied belong to the *Plummerita hantkeninoides* Biozone (Late Maastrichtian). The analysis shows an unhomogeneous distribution of different ichnotaxa, as well as levels of higher concentration of trace fossils.

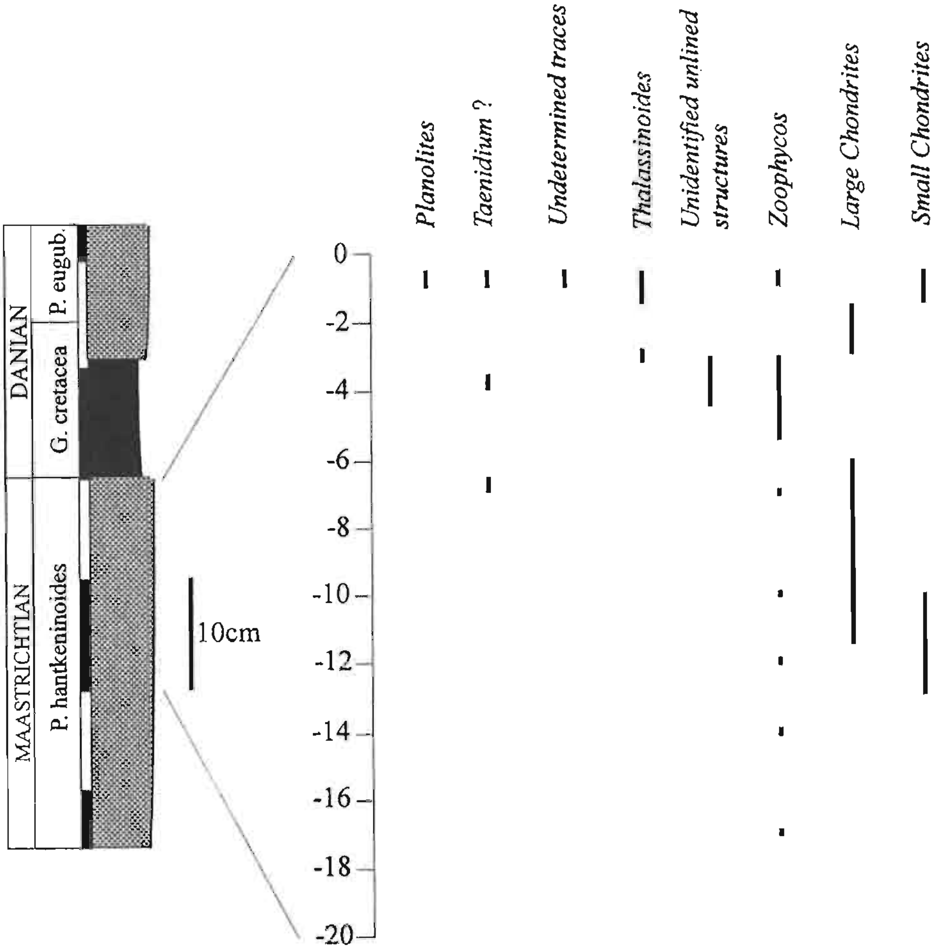

Fig. 3.- Vertical distribution of dark infilled trace-fossils assemblage at the *Plummerita hantkeninoides* Biozone (Late Maastrichtian) in the Agost section.

The vertical distribution of trace fossil in the interval studied is as follow (Fig. 3):

From the K/T boundary to around the 1.5 cm below, the higher concentration of trace fossils is registered. *Planolites* and *Thalassinoides* mainly developed in this interval, and only occasionally have been recognized downward (never below 3-5 cm). Also in this upper part, undetermined traces (mainly small circular and ellipsoidal sections), and probably *Taenidium* were registered. Locally, a high concentration of small *Chondrites* homogeneous distributed or concentrated into other ichnotaxa (see cross-cutting relationship) is also recognized in these upper 1.5 cm. Only occasionally an axial shaft of *Zoophycos* has been tentatively identified in this interval.

From the 1.5 cm downward, to a maximum analyzed of 20 cm below K/T boundary, mainly *Zoophycos* and *Chondrites* have been recognized. Only occasionally simple horizontal and obliquely oriented unlined structures, as well as probably *Taenidium*, have been also registered. A disperse distribution is recognized for *Chondrites*, but some levels of higher concentration can be differentiated, mainly at 6-9 cm and 10-12 cm below K/T boundary. *Chondrites* shows a clear diminishing size downward (data size above). Horizontal to obliquely oriented *Zoophycos* have been registered penetrating a maximum, at least, of 17 cm below the K/T boundary, and increasing size downward in lobes belonging to a particular structure.

Cross-cutting relationship

The analysis of cross-cutting relationship between traces is of special interest. This relationship was approached analyzing in one hand the first 1.5 cm below the K/T boundary, where most of ichnotaxa occur, and in the other hand the rest of the interval studied.

No cases of *Planolites* and *Thallassinoides* cutting other structures have been registered. In most cases, when associated, *Thalassinoides* is cutting by small *Chondrites* (sections of 0.1 cm in diameter), and occasionally the same occurs for *Planolites*. The axial shaft assigned to *Zoophycos* is also cutting by small *Chondrites*.

From the first 1.5 cm below K/T boundary downward to around 20 cm below, *Zoophycos* is occasionally registered cutting different traces as *Taenidium*? or the unidentified unlined structures (see above). However, the most usual cross-cutting relationship recognized, at different levels below K/T boundary, is *Chondrites* of different size cutting the rest of structures: *Taenidium*?, the unidentified unlined structures and *Zoophycos*.

Tiering

Vertical distribution of trace-fossil assemblage from K/T boundary downward, and crosscutting relationship of burrows, allow to interpret, from a preliminary approach, the existence of a well developed endobenthic tiered community located in the Uppermost Cretaceous sediments. Is necessary to note, as was previously introduced, that it refers to those discrete trace fossils, conspicuous, dark infilled, overimposed to the background trace-fossil assemblage that was not analyzed in detail at the moment.

The shallower tiers, localized around the upper 1.5 cm, are mainly composed by *Planolites* and *Thalassinoides* (mainly horizontal structures), and probably must be included *Taenidium*?. In these tiers, *Planolites* probably represents the shallow-burrowing member of the infaunal community, corresponding to the shallowest tier, but at the moment it is difficult to discriminate between tiers in the upper part.

A intermediate tier could be differentiate, probably, for the simple horizontal and obliquely oriented unlined structures, as well as for those burrows assigned to *Taenidium* and located downward in the sediment.

The deeper tiers are composed mainly for *Zoophycos* and *Chondrites*. Cross-cutting relationship between these ichnotaxa could be interpreted as the comparatively latter endobenthic colonization of *Chondrites* producers occupying the deepest tier in the sediment. *Chondrites* of different size could correspond to several tiers into the deeper part.

The endobenthic tiering interpreted from the analyzed data is quite similar to others recognized in Cretaceous chalk from Denmark and Alabama (Ekdale and Bromley, 1984, 1991; Ekdale *et al.*, 1984; Frey and Bromley, 1985; Bromley and Ekdale, 1986; Ekdale, 1988; Bromley, 1990). The structure of these chalk ichnocoenoses is dominated by *Planolites*, *Thalassinoides*, *Zoophycos* and *Chondrites*, even some slight differences in ichnotaxa composition are recognized. In this tiering structure some ichnoguilds were differentiated representing ichnotaxa grouped in ecologic units (Bromley, 1990; Ekdale and Bromley, 1991). Thus, ichnoguilds represented mainly by *Chondrites* and *Zoophycos* (nonvagile, deep deposit-feeder structures), by *Taenidium* (vagile, deposit-feeder structures, lower mid-tier), by *Thalassinoides* (nonvagile, upper mid-tier deposit-feeder structures), and by *Planolites* (vagile, shallow-tier deposit-feeder structures), were recognized.

Interpretation

Previous to the interpretation of the trace-fossil record is necessary to take into account the preliminary character of the conclusions achieved, based on the analysis of the dark infilled traces. These traces, located in upper Cretaceous sediments, could be considered, in a first approach, as produced during the early Tertiary, but a posterior and more complete analysis focusing on filling burrows must be performed to corroborate this assumption.

Tiering of burrows within sea floor deposits in deep-sea trace fossil communities is mainly determined by five major ecologic factor: oxygenation, benthic food content of the sediments, sedimentation rate, grain size, and substrate consistency (Wetzel, 1991). From those, the recognized tiering of dark infilled burrows in the Agost section is interpreted mainly as consequence of environmental changes, mainly affecting oxygenation, substrate consistency, and benthic food content of the sediments.

As it is widely accepted, one of the major factor controlling spatial distribution of trace fossil is the oxygen availability. Vertical changes in trace fossil assemblages into sediments have been interpreted as reflecting fluctuations in oxygen availability. With independence of the general oxygen conditions, usually Chondrites-Zoophycos *ichnoguild* is registered in the deepest tiers, inhospitable zones at the very fringe of habitability, where lower oxygenation levels occurs, while Thalassinoides and Planolites *ichnoguilds* are present in oxygenated situations (Bromley, 1990 and references therein). Thus, the registered tiering in the Agost section, with *Planolites* in the upper part, *Thalassinoides* in upper intermediate position and *Zoophycos* and *Chondrites* in lower locations could be indicative of a diminishing oxygen concentration downward.

Substrate consistency is other limiting factor to be into account. Ekdale *et al.* (1984) analyze the *Chondrites-Zoophycos-Thalassinoides-Planolites* assemblage, in relation to the order of emplacement and substrate firmness. The *Planolites* suite is emplaced in soupy sediments closely beneath the seafloor; the *Thalassinoides* suite is emplaced several decimeters below sea floor in soft substrates, and the *Chondrites-Zoophycos* suite is the deepest tier of trace fossils, developed mainly in firmground (concealed) conditions. Ekdale and Bromley (1991) related, as a general approach, the tiering model in chalk ichnocoenosis with substrate firmness with unknown burrowers in the shallowest tiers in soupy sediments, *Thalassinoides*, *Planolites*, *Taenidium* and *Anconichnus* in intermediate tiers with slightly firmer sediments, and *Zoophycos* and *Chondrites* in the deepest tiers in stiff, compacted sediments. The interpreted tiering at the Agost section could be related to changes from soupy-softground to soft-firmground (concealed) conditions, with the increase in substrate firmness downward into the sediment. If we consider that discrete trace fossil, dark infilled, were emplaced during earliest Tertiary, substrate consistency in sediments just below K/T boundary corresponded to soupy or softground conditions when upper tiers were developed. Thus, of special interest could be the absence of trace-fossil structures related to firm or even hardground conditions upward in the latest Cretaceous sediments, just below K/T boundary. This absence could reflects a comparatively continuous deposition during K/T boundary transition rejecting a long time interval without deposition, at least long enough to determine the increase of substrate firmness.

In relation to benthic food, the diversity of trace fossil registered could be related to an organic-matter content enough to maintain the benthic community. However, variations in benthic-food abundance could be interpreted. Predominantly horizontal *Chondrites* burrow networks registered in apparent layering into the sediment, as well as superabundant *Chondrites*, have been interpreted as due to a selective exploitation of layers particularly rich in organic matter (Savrda and Bottjer, 1988; Vossler and Pemberton, 1988). Thus, we can not reject that some of the levels recognized into sediment of higher concentration of horizontal *Chondrites* could be related to comparatively higher abundance of benthic food.

Probably, there is not an unique factor to be taken into account, and the recognized ichnological features (ichnotaxa, morfological features, relative abundance and tiering) at the Agost section respond to the integration of variations in the three alluded limiting factors; oxigentation, substrate consistency and organic-matter concentration.

From the ichnological analysis performed, some open questions will be approached in posterior ichnological studies: a) the relationship between the trace-fossil background registered in the cretaceous sediments (light filled burrows) and the discrete, dark infilled structures studied and, b) the existence of trace fossils in the lowermost Tertiary sediments, and their relationship to variations in the ecological parameters immediately after K/T boundary event.

MINERALOGY AND GEOCHEMISTRY (F. C. Martínez-Ruiz, M. Ortega-Huertas and I. Palomo)

Mineralogy

The sediments from the K/T boundary section at Agost, with the exception of the 2 mm thick layer marking the boundary, are mostly composed of calcite, clays and quartz (Fig. 4). Clay mineral assemblages essentially consist of smectites, illite and kaolinite (Fig. 4). The K/T boundary layer is characterized by a sharp decrease in the carbonate content and the subsequent increase in the proportion of clays (Martínez-Ruiz *et al.*, 1992; Ortega-Huertas *et al.*, 1995, 1998). Smectite is the main component of the boundary layer as well as diagenetically altered spherules made up of either potassium feldspar or iron oxides (Smit, 1990; Martínez-Ruiz *et al.*, 1997). 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.

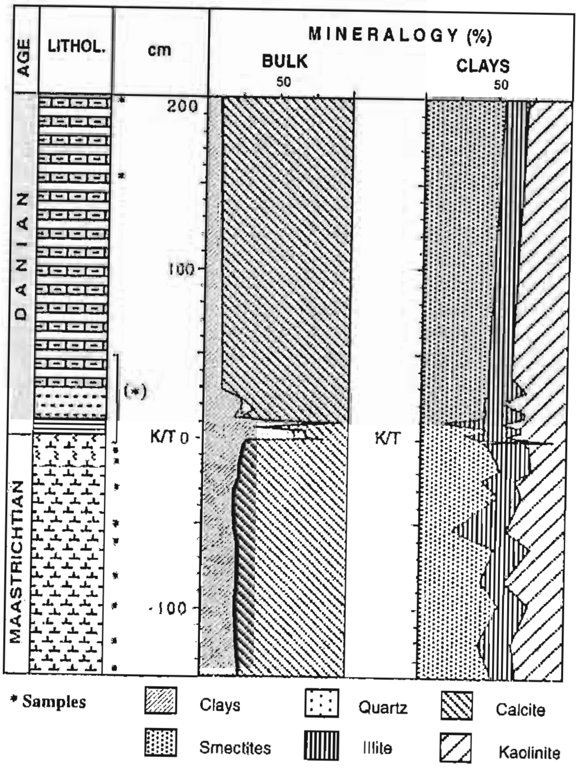

Fig. 4.- Main mineral components across the Cretaceous/Tertiary boundary at the Agost section.

Spherules

K-feldspar spherules are abundant at Agost, with a density distribution of 100-200/cm^3. The size is usually 100-500 µm. They mostly occur as spheres although other morphologies are also common, and are similar to those from the Caravaca section.

They have a porous structure in wich K-feldspar crystals arranged with fibroradial and dendritic textures (see also description of K- feldspar spherule from Caravaca section).

The *Fe-oxide spherules* (Fig. 5) are more abundant at Agost than K-feldspar spherules, with a density distribution of 100-300/cm^3. Different morphologies are observed from spheres to droplet shapes. These spherules also show fibroradial and dedritic textures (Fig. 6) similar to those of K-feldspar spherules (Martínez-Ruiz *et al.*, 1997).

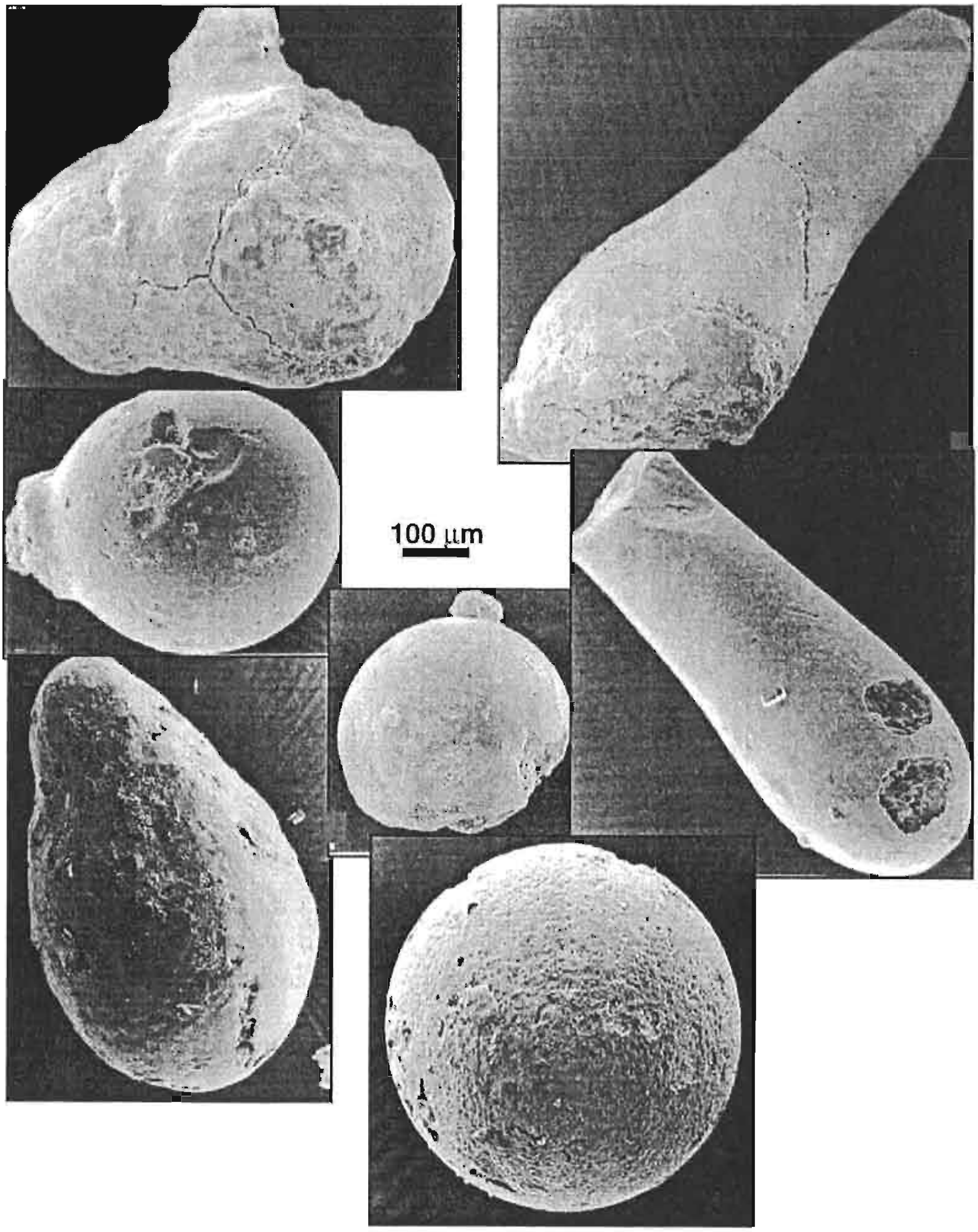

Fig. 5.- SEM photographs of Fe-oxide spherules from the Agost section.

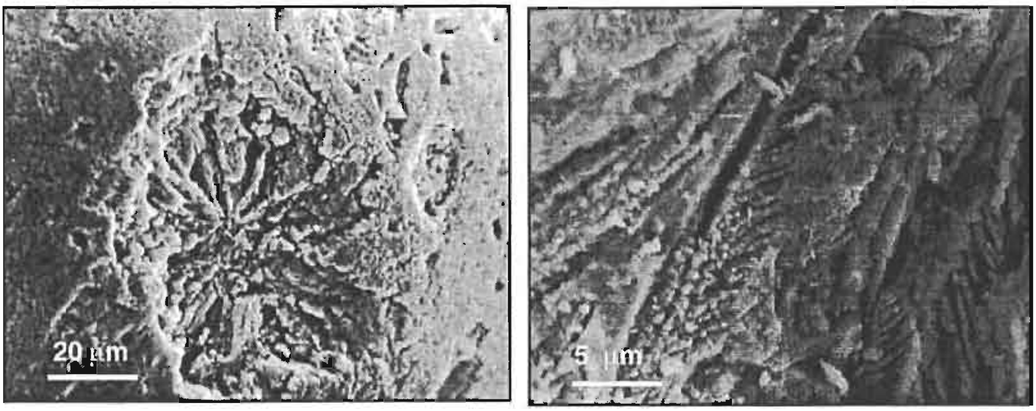

Fig. 6.- SEM photographs of Fe-oxide spherules from the Agost section showing a detail of fibroradial textures.

K-feldspar and Fe-oxides have replaced the original material precursor of the spherules. Both, K-feldspar and Fe-oxide spherules present similar textures and morphologies, which are also similar to those from unaltered clinopyroxene spherules reported by Smit *et al.* (1992) at DSDP Site 577, suggesting the clinopyroxene could have also been the precursor.

Geochemistry

The K/T boundary at Agost is marked by significant geochemical anomalies. The boundary is characterized by a large increase of Ir (Smit, 1990) and other PGEs (Martínez-Ruiz *et al.*, 1992, 1994). Smit (1990) reported 24.6 ppb of Ir at the K/T boundary layer and Martínez-Ruiz *et al.* (1992) reported 24.4 ppb (Fig. 7). The boundary is also marked by high contents of different chemical elements such as Fe, Cr, Co, Ni, Cu, Zn, As or Sb (Fig. 8) (Smit, 1990; Martinez-Ruiz *et al.*, 1992, 1999).

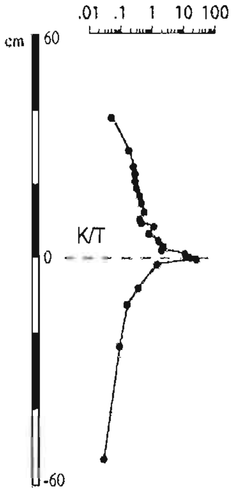

Fig. 7.- Ir profile at the Agost section (data from Martínez-Ruiz, 1994).

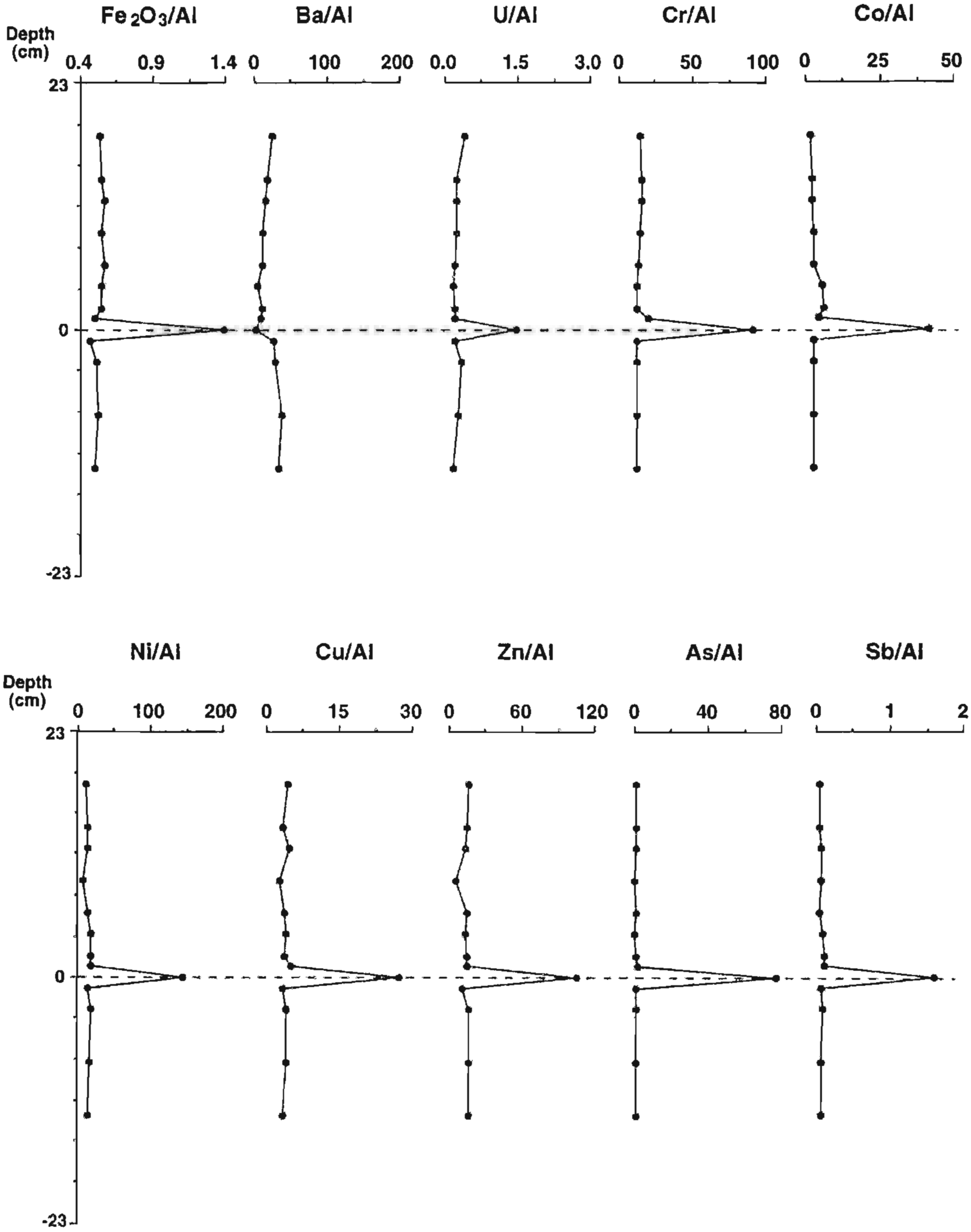

Fig. 8.- Fe and trace element profiles (normalized to Al) from the K/T boundary interval at Agost. The horizontal line indicate the K/T boundary and depths are referred to 0 cm for the boundary (from Martinez-Ruiz *et al.*, 1999).

The geochemical composition of the boundary layer at Agost and the enrichment in typical extraterrestrial elements support the impact scenario at the end of the Cretaceous. However, diagenetic alteration is also an important factor to take into account because trace-element concentrations may have been severely modified during diagenetic alteration and therefore not reflect the original record of the extraterrestrial contamination.

Different geochemical and mineralogical proxies indicate that depositional conditions were unusually reducing during deposition/early diagenetic processes at Agost (Martínez-Ruiz *et al.*, 1999):

1) Elevated U concentration. The Ua (authigenic uranium) content for the K/T boundary layer is extremely high at Agost (Fig. 8) compared to sediments above and below the boundary, and suggests extremely reducing conditions during deposition and early diagenesis.

2) The extensive formation of pyrite during early diagenetic processes. Some pyrite relicts are even observed in Fe-oxide spherules and oxidised framboids (Fig. 9d). Euhedral pyrite crystals also cover the surface of some spherules (Martínez-Ruiz *et al.*, 1997).

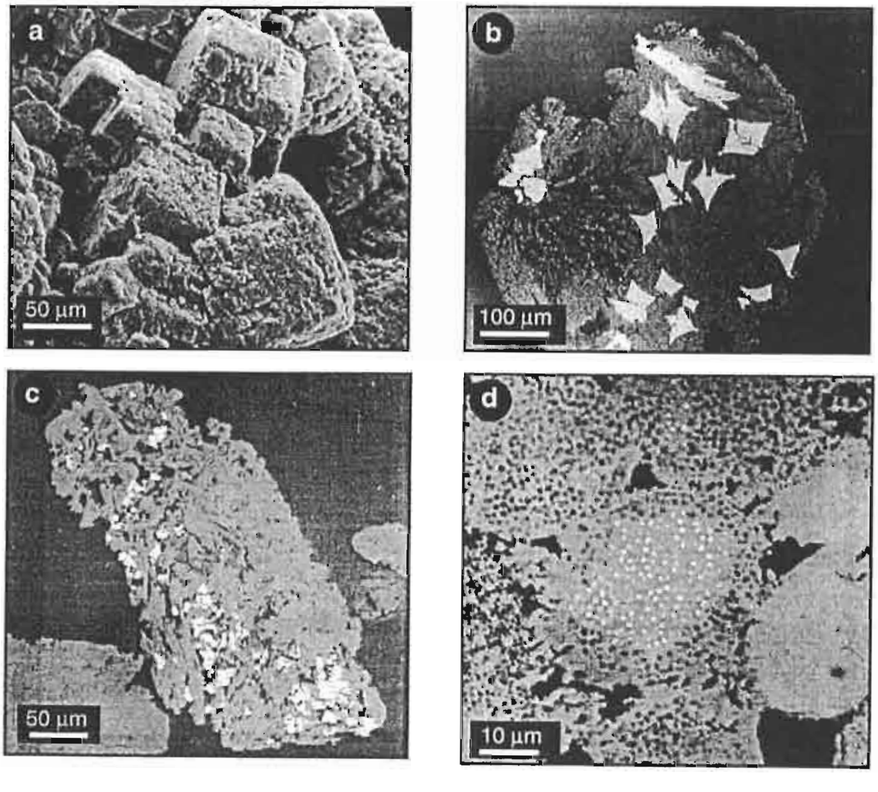

Fig. 9.- Scanning electron microscopy photographs of barite and spherules from the K/T boundary layer at Agost section. a) Micrograph showing barite crystals originated in the ejecta layer during diagenetic alteration. b) Backscattered-electron micrographs of polished sections showing Fe-oxides spherules containing barite fills. c) Backscattered-electron micrograph of a polished section showing K-feldspar spherules containing barite fills. d) Backscattered-electron micrographs of a polished section showing oxidised framboids containing pyrite relicts (from Martínez-Ruiz *et al.*, 1999).

3) The development of positive Eu anomalies. Eu anomalies attributable to diagenesis are not common, since Eu is trivalent under "normal marine conditions". Only a few cases have been reported where Eu have been reduced in sedimentary environments, always under strong reducing conditions (Sverjensky, 1984; Mac Rae *et al.*, 1992). These conditions are known to promote the reduction of Eu which may be removed into solution. Nevertheless, Eu is enriched in these cases in relation to "normal shales", but the enrichment is absent when C-1 normalised-patterns are considered. In contrast, Eu anomalies reported here in the K/T boundary layer at Agost indicate an enrichment when considering both, the NASC normalised-patterns and the C1 normalised-patterns (Fig. 10). Therefore, this enrichment provides further support of the significant mobilisation of Eu under very strong reducing conditions.

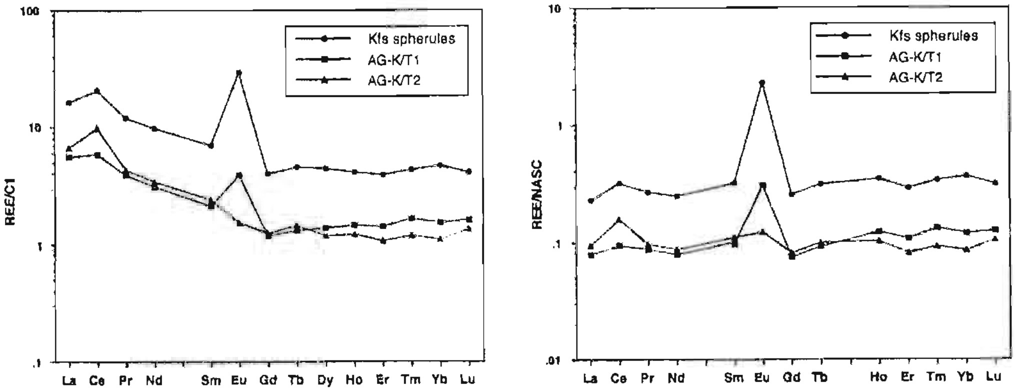

Fig. 10.- Plots showing the Eu anomaly and REE abundances (normalised to C1 chondrite values of Anders and Ebihara, 1982; and NASC values of Haskin *et al.*, 1968) from one enriched-Ba and one poor-Ba sample, and from K-feldspar spherules from Agost (from Martínez-Ruiz *et al.*, 1999).

At Agost section, barite also originated during pyrite weathering and it is also the carrier phase for Eu and responsible for positive Eu anomalies, since Eu would have been coprecipitated with Ba. A detailed study focusing on the diagenetic alteration of the boundary layer and spherules has shown that barite abounds in the boundary layer (Fig. 9a) and also fills some Fe-oxide and K-feldspar spherules (Fig. 9b, c) (Martínez-Ruiz *et al.*, 1999).

The mechanism of PGE behaviour and transport in low-temperature solutions is still poorly known, although Ir remobilization has been reported in relation to microbial activity (Dyer *et al.*, 1989) and in suboxic conditions (De Lange *et al.*, 1991). Considering other K/T boundary sections, Ir concentrations vary widely from place to place (e.g. Evans *et al.*, 1995). This probably resulted from different rates of extraterrestrial/terrestrial contribution at each location but also from the diagenetic evolution of the boundary sediments.

There is still some uncertainty regarding the original Ir concentrations in the K/T boundary sediments, and the first step to determining original concentrations is to address the diagenetic alteration of the ejecta layer, since no evaluation of extraterrestrial fluxes can be based on the altered concentration. This consideration also applies for other trace elements. In this regard, positive Eu anomalies, higher Ua contents and an extensive development of pyrite at Agost suggest a strong reducing environment. Ir content, for instance, is lower than at Caravaca, suggesting that Ir and possibly other trace elements may have been mobilized under stronger reducing conditions.

STOP 2: THE YPRESIAN/LUTETIAN TRANSITION

MICROPALEONTOLOGY (E. Molina and C. Gonzalvo)

The Yresian/Lutetian transition at the Agost section is located at Lomas de la Beata, 1 km North of the village of Agost (Alicante province, Southeast Spain) near several small abandoned quarries (Fig. 1). The lithology consists of marls with interbedded calcarenite strata. The middle part of the section is very detrital. The hemipelagic marls are rich in planktic foraminifera and calcareous nannofossils, whereas some of the turbiditic calcarenite strata contain abundant larger foraminifera.

According to Molina *et al.* (2000) the Agost section is very suitable for an integrated biostratigraphical study across the Early/Middle Eocene (Ypresian/Lutetian) boundary since it is very rich in several microfossil groups. It was first studied by Colom (1954) and Von Hillebrandt (1974, 1976) in the Betic Cordillera. Different biostratigraphical and micropaleontological aspects were also analysed by Márquez (1975, 1983, 1991), Cremades (1982), Márquez and Usera (1984) and Gonzalvo and Molina (1998), but these data have not been integrated in a detailed chronostratigraphical framework.

The biostratigraphy of the Ypresian/Lutetian is needed to define its boundary stratotype. Precise boundary placement depends on establishing and correlating different biozonations. In the Molina et al. (2000) paper we tried to establish an accurate integrated biostratigraphy by studying the most important microfossil groups in detail, with the final aim of improving the chronostratigraphy across the Early/Middle Eocene.

Planktic Foraminifera

The planktic foraminifera were obtained by washing autochtonous marls and quantitatively examined using a modified Otto microsplitter. This analysis was based on representative splits of 400 or more specimens in the size fraction larger than 100 microns. The rest of each sample was scanned for rare species. The planktic foraminiferal assemblages were moderately to well-preserved and very diversified. They were generally characteristic of subtropical to temperate latitudes and deposited in a bathyal environment sporadically affected by turbidity currents, including some reworked fossils.

Agost planktic foraminifera were first studied by Von Hillebrandt (1974, 1976) who defines the *Planorotalites palmerae* Biozone. A more detailed study by Márquez (1975, 1983, 1991) and Márquez and Usera (1984) relegate this zone to a subzone. Cremades (1982) establish a similar biozonation but with an *"Eoglobigerina" frontosa* Biozone instead of the *P. palmerae* Biozone. A new detailed biozonation across the Lower-Middle Eocene transition at Agost and Alamedilla sections (Gonzalvo and Molina, 1998) has the *Acarinina pentacamerata* Zone subdivided in the *Acarinina pentacamerata* Subzone, the *Subbotina boweri* Subzone and the *Truncorotaloides praetopilensis* Subzone and the *Hantkenina nuttalli* Zone including the *Hantkenina nuttalli* Subzone and the *Globigerapsis subconglobata* Subzone. These biozones and subzones are defined by the first occurrence (FO) of the nominated taxon, except the base of the *G. subconglobata* Subzone that is defined by the FO of *Globigerapsis index* (which is easily recognizable since its FO marks the beginning of the typical Middle Eocene assemblages). This biozonation can be correlated with the upper part of zones P8 through P11 of the standard zonation in Berggren *et al.* (1995). Nevertheless, the base of Zone P9 was not placed precisely since only one sample had *P. palmerae* and the base of Zone P11 was not recognized because *Globigerapsis kugleri* was not found (Fig. 2 in Molina *et al.*, 2000).

Seven species (15% of all species) gradually disappeared in the *Acaninina pentacamerata* Zone and five species (11%) in the *Hantkenina nuttalli* Zone, constituting a clear background extinction pattern. During this extinction others species appeared and diversity greatly increased (22 new species and 12 extinct). Appearance was not completely gradual since the diversity rate accelerated at the base of the *Hantkenina nuttalli* Zone, where a cladogenesis process affected the genera *Truncorotaloides* and *Hantkenina*, with 57% of the species evolving at this level. Another increase in diversity was evident in the *S. boweri* Subzone, with 43% of the appearances. In general, the diversity increased from 24 species at the base of the section to 33 at the top (a 27% increase).

The increase in diversity across the Early/Middle Eocene boundary was characterized by the appearance of low latitude dwellers, mainly from the base of the *Hantkenina nuttalli* Biozone. This could be the consequence of an increase in seawater temperature, in turn related to a rise in sea level since the sedimentation became more pelagic and marls were the dominant lithology.

Calcareous Nannofossils

Simple smear slides were prepared for 45 samples (Figs. 3 and 4 in Molina *et al.*, 2000) and studied under light microscope at 1000x magnification. The calcareous nannofossil content varied from rare to common or abundant and the preservation ranged from poor to moderate/good.

The classical calcareous nannofossil zonation was difficult in this section. Markers from Martini (1971) and Okada and Bukry (1980) were either not found or too rare to be used with confidence. In addition, the ranges in Aubry (1983) and Steurbaut (1986, 1988) for additional markers from (mainly) Northern Europe seemed to be only partly useful to subdivide the section and assign ages to the calcareous nannofossil assemblages at Agost.

Discoaster sublodoensis, the marker for the lower boundary of NP14 in Martini (1971), was only found in one sample. *Nannotetrina fulgens* and *Rhabdosphaera gladius*, the zonal markers for NP15, were not found. The NP14/15 boundary was thus set in the interval above the FO of *S. furcatolithoides* and below the FO of *S. gigas* and no attempt was made to indicate the position of the NP15/16 boundary. The presence of *C. solitus* up to the uppermost sample assigned the top of the section to NP16.

Two of the zonal markers in Okada and Bukry (1980), *Rhabdosphaera inflata* and *Nannotetrina fulgens*, were not found (*Sullivania gigas*, *Discoaster bifax* and *Reticulofenestra umbilicus* were present). The total range of *C. gigas* defined the subzone CP13b and the FO's of *R. umbilicus* and *D. bifax* the base of CP14a. The top of CP14a was defined by the LO of both *Chiasmolithus solitus* and *D. bifax*, while the LO of *Chiasmolithus grandis* defined the top of CP14b. *S. gigas* was only found in two samples (at 21 and 38), thus marking the interval of CP13b. *Reticulofenestra* species are difficult to use for biostratigraphy. At Agost, *Reticulofenestra dictyoda* and *R. coenura* (both <10 microns) were present almost from the bottom of the calcarenite interval. Larger forms (>10 microns) assigned to *R. umbilicus* appeared occasionally from sample 21 onwards and consistently above 43. This was considered the base of CP14a since *D. bifax* only appeared at 43 (whose highest occurrence was in 51). *C. solitus* was still present in the uppermost sample with a reasonable assemblage and the whole interval was assigned to CP14a. The presence of *Campylosphaera dela*, a species that usually disappears in CP14a, supports this assignment.

Steurbaut (1988) subdivided NP14 into 4 subunits using additional calcareous nannofossils. Unit XI at the bottom of NP14 is defined by the FO of *Lanternithus minutus*, *Discoaster bifax*, *Discoaster wemmelensis* and *Zygrhablithus crassus.* We found all of these, if *Z. crassus* is regarded as a synonym of *Z. bijugatus* (which has an older first occurrence than NP14 in this section). Of the three remaining species, *D.*

wemmelensis was the first to appear (at 29.00) followed by *D. bifax* and *L. minutus* (at 43.00) in an interval regarded as younger than NP14, based on the presence of *S. gigas*. Aubry (1983) finds the above three forms together in the upper part of NP14. The determination of *D. bifax* by several authors is shown by Wei and Wise (1989) to include *Discoaster praebifax*, a new form with a similar diameter but nearly twice as many rays and only one prominent central stem, as opposed to the two stems of *D. bifax* (they also report *D. praebifax* from CP12 and CP13). If the base of Steurbaut's (1988) unit XI is at the FO of *D. wemmelensis*, it would lie above the FO of *Discoaster saipanensis*, one of the three species defining the base of unit XII. The forms appearing at the base of unit XIII include *Sphenolithus furcatolithoides* and three forms not found at Agost. Both Aubry (1989) and Perch-Nielsen (1985) give the range of *Sphenolithus furcatolithoides* as NP15 and NP16, while Aubry (1983) only reports it from NP16. *S. furcatolithoides* (or a very similar form?) was found in several samples considerably below the first occurrence of *D. wemmelensis* (which defines the base of unit XI and is usually considered to appear in CP12b or the upper part of NP14), far below where it appears at Agost. This suggests that the subdivision used by Steurbaut (1988) cannot be applied at Agost. The NP/CP subdivision shown in Figs. 3 is thus only tentative and we stress that other interpretations of the data are possible.

Modest reworking of Cretaceous coccoliths is present in most samples with the possible exception of 10.00, 17.0 and 18.0. As usual, *Watznaueria barnesae*, a species ranging through the whole Cretaceous, is the most commonly reworked form. It is closely followed by various *Nannoconus* species, a genus not restricted to but most commonly found in Lower Cretaceous sediments. Reworking from Upper Cretaceous sediments is mainly represented by *Micula decussata* (Coniacian through Maastrichtian), *Lithraphidites quadratus* (Maastrichtian) and *Microrhabdulus attenuatus* (Santonian through Maastrichtian) and *Arkhangelskiella cymbiformis* (Campanian and Maastrichtian). Reworking from the Upper Cretaceous was nearly absent in the interval between samples 1 and 27.

The number of species varied greatly among samples and partly depended on the state of preservation of the assemblage and the time spent searching for rare species. Fig. 5a (Molina *et al.*, 2000) shows the number of probable *in situ* Eocene species and reworked Cretaceous species (Fig. 5b) (Molina *et al.*, 2000). Here an interesting pattern can be observed: many *in situ* species were accompanied by low numbers of reworked species and some of the low *in situ* numbers by low numbers of reworked species. This may mean that: a) high Eocene and relatively high Cretaceous diversity is mainly the result of good preservation (which also entices the observer to look for more species...), or b) when preservation is poor, both Eocene and Cretaceous coccoliths are not very diverse and only solution resistant species are found. Comparing these findings with the lithology, it seems that samples close to calcarenite benches have low diversity and those from a softer interval between these benches have a higher diversity.

As deduced from Figs. 3 and 4 (Molina *et al.*, 2000), new species appear and old species disappear at a relatively high rate in the lower and upper part of the section, while the middle part of the section is marked by low change. This is the same interval where Upper Cretaceous reworked coccoliths are absent (except in one sample) and extends for ±10 m on either side of the major limestone band in the section.

Larger Foraminifera

Larger foraminifera were abundant at intervals around 0, 59, 78 and 109 meters, where they may be a few centimetres in diameter. Most were concentrated at the base of the turbidites and were not cemented. The different species represented include the genera *Nummulites*, *Assilina*, *Discocyclina* and *Nemkovella*.

Larger foraminifera at Agost were first studied by Von Hillebrandt (1974) who distinguished three different assemblages across the Early - Middle Eocene transition but did not classify the genera and species. *Nummulites* and *Assilina* were studied in detail by Isuman (1983), who first correlated the planktic foraminiferal biozonation of Von Hillebrandt (1974). *Nummulites manfredi*, the fossil index of Schaub (1981), was not found in the upper part of the Lower Eocene but *Nummulites campesinus* was identified in an assemblage containing *Nummulites praelorioli*, *Nummulites polygyratus*, *Assilina maior* and *Assilina cuvillieri*. The sandy interval deposited during the Early - Middle Eocene transition contained only small *Nummulites* and the barren interval above it was correlated with the planktic foraminiferal *Hantkenina aragonensis* Biozone of Von Hillebrandt (1974). Nevertheless, *Nummulites* of several centimetres in diameter were abundant at meter 59 (in the middle of the *Hantkenina nuttalli* Subzone). Isuman (1983) does not report *Nummulites laevigatus* at these levels but *Nummulites obesus*, *Nummulites praelorioli* and *Assilina cf exponens* are frequent. In the upper part of the section, *Nummulites beneharnensis* was found in an assemblage with *Nummulites cf praeaturicus*, *Nummulites boussaci*, *Nummulites aff alponensis* and *Assilina spira* (Fig. 3).

Orthophragminids have not been studied in detail although they are frequent and well preserved. Their tests are extremely thin and saddle-like shapes are very common. The test shape suggests they used to live in the deeper part of the photic zone, in microenvironments with reduced light, provoked by terrigenous input or nannoplankton blooms. The specimens were reworked since they were bored by some organisms and the tubes were infilled with sparitic matrix and occasionally biomicrites (small nummulitids, globigerinids and corallinaceans) and some specimens were encrusted.

We collected orthophragminids at two levels (meters 0 and 78). The older assemblage was sampled at the base of the section in the planktic foraminiferal *Acarinina pentacamerata* Subzone, and contained *Discocyclina augustae sourbetensis* and *Nemkovella rota*. *Discocyclina augustae sourbetensis* ranges from "Cuisian" (Middle to Upper Ypresian) to Lower Lutetian (Less, 1987, 1998). *Nemkovella rota* is attributed to the Middle Ypresian (Less, 1998).

The younger Orthophragminids assemblage was sampled in the upper part of the section at the base of the planktic foraminiferal *Globigerapsis subconglobata* Subzone. It had a diverse number of species, which could be due to intensive sampling. We found *Discocyclina archiachi archiachi*, *Discocyclina archiaci bartholomei*, *Discocyclina dispansa taurica*, *Discocyclina dispansa hungarica* and *Discocylina aaroni*. According to Less (1987, 1998) some of these species already appear in the upper Ypresian but the assemblage is characteristic of the Middle Lutetian.

According to the biozonation in Less (1987, 1998) and the correlation with the nannofossil biozonation, Orthophragminidal Zones 6 and 10 could be represented in the Agost section. By correlation, the older assemblage could correspond to Zone 6 and the younger assemblage to Zone 9 (Middle Lutetian). According to Less (1987, 1998), the assemblage from the sample of the upper part of the section is characteristic for the Middle Lutetian. These biozones correspond to Zones SBZ12, SBZ13 and SBZ14 in Serra-Kiel *et al.* (1998).

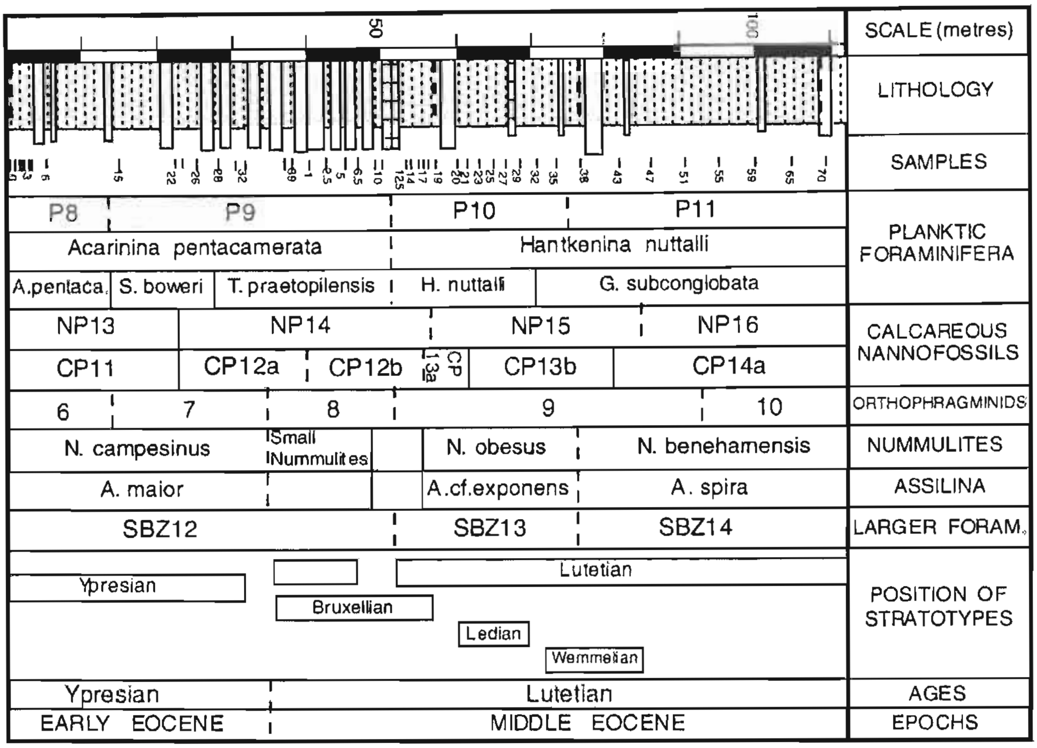

Fig. 3.- Integrated biostratigraphy and chronostratigraphy across the Ypresian/Lutetian transition at the Agost section (from Molina *et al.*, 2000).

Discussion and conclusions

The 112 m thick Lower and Middle Eocene sediments at Agost consisted of marls with interbedded calcarenites and detrital layers in the middle part. They were deposited in a hemipelagic environment receiving turbidites containing larger foraminifera. While the planktic foraminiferal record and zonation were good, the zonation with calcareous nannofossils and larger foraminifera were not ideal.

The study of planktic foraminifera, calcareous nannofossils and large foraminifera was based on the same samples for the first two groups and on four sampling sites for the last. It provided a biostratigraphic framework to discuss the suitability of the Agost section as a GSSP.

It was difficult to correlate our Agost biozonations and the stage stratotypes in Belgium and Paris basins due to their poor pelagic fossil record. Large parts of these basins also appear to have a hiatus of nearly 2 million years between the Ypresian and Lutetian, although more continuous sections occur across the French-Belgian frontier (Nolf and Steurbaut, 1990; Hooyberghs, 1992, 1999). The Ypresian seems to cover up to the lower part of Zone NP14, which corresponds to a level within Zone P9. The Bruxellian belongs to the upper part of Zone NP14 and seems to include parts of Zone P9 and the lower part of Zone P10 and correlates with the base of the Lutetian. According to Hooyberghs (1992), the Brussel Sand Formation (=Bruxellian of previous authors) at St.-Stevens-Woluwe (Belgium) can be assigned to Zone P9. Planktic foraminiferal markers do not seem to be present in Belgium and nannofossils indicate the upper part of Zone NP14 (Steurbaut, pers. comm.). Nevertheless, in the Mont-des Recollets at Cassel (France) the Brussels Sands are dated as Zone P10 (Hooyberghes, 1999).

The base of the Lutetian defines the Early/Middle Eocene boundary (Jenkins and Luterbacher, 1992). The Lutetian was defined by De Lapparent in 1883 and revised by Blondeau (1981) who proposed a new stratotype 50 km North of Paris. Calcareous nannoplankton is present in the new stratotype and spans the upper part of Zone NP14 to the lower part of Zone NP16 (Aubry, 1983). Planktic foraminifera are infrequent and not typical although the P10, P11 and P12 Zones of Blow (1979) (Bignot and Le Calvez, 1969; Hooyberghs, 1992, 1999) can be recognised. The Ledian and Wemmelian are regional stages formerly used in Belgium and both belong to Zone NP15 (Martini, 1971; Cavelier and Pomerol, 1986; Steurbaut, 1986).

The Lower/Middle Eocene boundary is usually placed at the base of the *H. nuttalli* Zone, at the FO of the marker species (Cavelier and Pomerol, 1986; Berggren *et al.*, 1995). This event occurs at about 52 meters in sample 12.5 in marls just above the thickest limestone bank of the section. Calcareous nannofossils seems to correlate with the upper part of Zone NP14, similar to Berggren *et al.* (1995). Although there are three planktic foraminifera FO's at this level, the level fell in the "low change interval" of the calcareous nannofossils and no FO or LO was observed. The three FO's were at the top of an approximately 25 m interval, with only one new species and three disappearances. After these three incoming species at the base of the *H. nuttalli* Zone, six new species came in during the time of deposition of the next 20 m (the *H. nuttalli* Subzone) while only two disappeared. Three or four new forms of calcareous nannofossils appeared in the middle of the latter interval and the same number disappeared. Above the *H. nuttalli* Subzone, about 12 new calcareous nannofossil species appeared over about 30 m while some 26 old ones disappeared over the same interval.

The boundary between the Lower and Middle Eocene, if placed at the usual level — at the base of the *H. nuttalli* Zone, at the FO of the marker species — coincides with a level marked by the two additional FO's of planktic foraminifera. Since there is a facies change from a limestone bank to marls just below the FO of *H. nuttalli*, there is a chance that the FO's of three species at the same level also implies a short hiatus at this lithological boundary. Nevertheless, there is no indication of a major hiatus in the planktic foraminiferal biozonation nor in the calcareous nannofossil assemblages which are, however, generally poorly preserved in the interval just below and above the limestone bed below the proposed boundary. Two other levels marked by major microfossil changes appear between samples 22 and 26 at the *S. boweri/T. praetopilensis* subzonal boundary (close to the NP13/NP14 zonal boundary) and samples 38 and 43 at CP13b/CP14a. They are not very relevant however and fall in the Upper Ypresian and Lower Lutetian stages respectively (Fig. 3).

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NOTES

The Cretaceous/Tertiary and Paleocene/Eocene boundaries of the Caravaca section (Murcia Province, Betic Cordillera)

LOCATION

The Caravaca section is located in the Barranco del Gredero, 4 km south of the town of Caravaca de la Cruz, Murcia province, southern Spain. The section is easily accessible by the road from Lorca to Caravaca (Fig. 1). Geologically, the section is located in the Subbetic Zone of the Betic Cordillera.

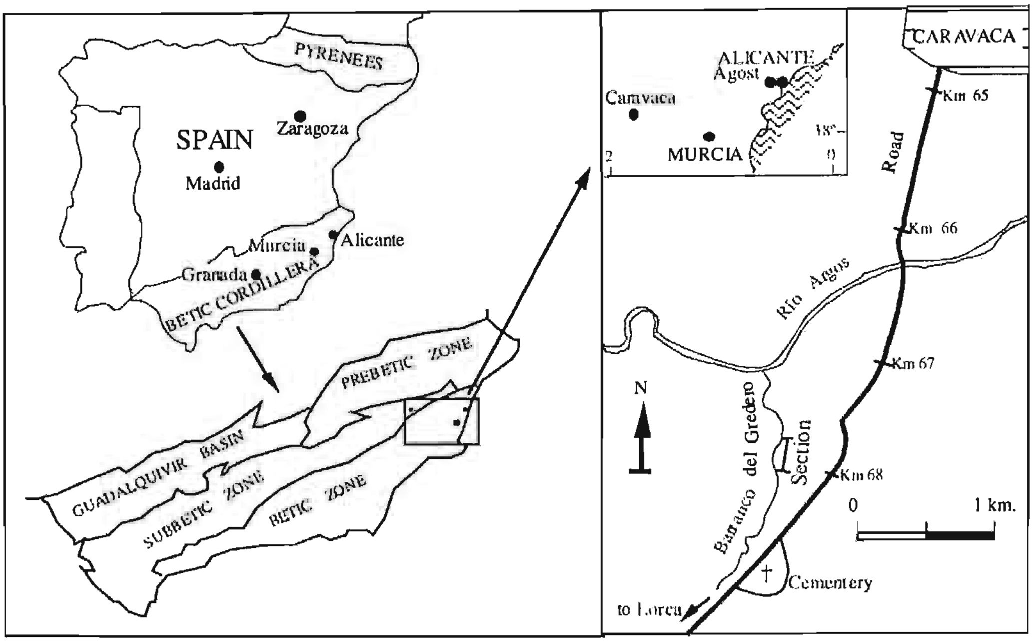

Fig. 1.- Geographical and geological location of the Caravaca section.

The classical Caravaca section, very well known world wide because of the Cretaceous/Tertiary boundary (Smit, 1977, 1979; Smit and Hertogen, 1980), contains a nearly continuous marine record spanning from the Late Cretaceous to the Middle Eocene. The section was initially studied by Durand Delgá and Magné (1958) and later in more detail by Von Hillebrandt (1974) based on foraminifera and by Romein (1979) based on calcareous nannoplankton. Lately, the K/T boundary was restudied by Canudo *et al.* (1991) and the Paleocene/Eocene boundary by Molina *et al.* (1994).

STOP 1: THE CRETACEOUS/TERTIARY BOUNDARY

MICROPALEONTOLOGY (E. Molina, L. Alegret, I. Arenillas and J. A. Arz)

The famous Cretaceous/Tertiary (K/T) section at Caravaca was discovered by Smit (1977) and has been studied by numerous specialists. At Caravaca, the uppermost Cretaceous and lowermost Paleocene are composed of hemipelagic marls and marly limestones, interspersed with minor amounts of hard pelagic limestone and calciturbidites. The upper 15 cm of the Maastrichtian are pierced by burrows, filled with dark material from overlying boundary marl bed (Smit and ten Kate, 1982). At present, a more detailed ichnological analysis, similar to that carried out at the Agost section, is being performed at the Caravaca section (results in preparation). The Maastrichtian marls of the Caravaca section contain a rich, subtropical association of planktonic foraminifera and nannofossils. Benthic foraminifera form a minor constituent of the microfauna. A dark, clayey-marl bed, 10-12 cm thick, separates these well-dated sequences. With the unided eye the boundary marl bed can be subdivided into a basal rust-red layer (about 1 mm-thick) and a dark grey (about 10 cm-thick). This red layer contains the Ir anomaly and other impact evidence such as the Ni-rich spinels, shocked quartz and microspherules, which have been described as altered microtektites (Smit, 1982, 1990).

Planktic Foraminifera

Planktic foraminiferal stability in the Upper Maastrichtian and the catastrophic mass extinction at the K/T boundary at Caravaca, were revised by Molina *et al.* (1998) and Arz *et al.* (2000). The planktic foraminiferal quantitative and biostratigraphic study across the K/T boundary at the Caravaca section provides proof of the stratigraphical range continuity and the evolutive stability of species in the Upper Maastrichtian (Fig. 2).

Molina *et al.* (1998) and Arz *et al.* (2000) identified five biozones across the K/T boundary at Agost: *Abathomphalus mayaroensis* Biozone, *Plummerita hantkeninoides* Biozone, *Guembelitria cretacea* Biozone, *Parvularugoglobigerina eugubina* Biozone and *Parasubbotina pseudobulloides* Biozone. At Caravaca, the planktic foraminiferal extinction pattern is a catastrophic mass extinction since 74% of the species went extinct in coincidence with the K/T boundary and with the evidence of impact (Arz *et al.*, 2000). This pattern can be similarly identified in other Tethyan sections (Arz *et al.*, 1992, 1999; Molina et al., 1996; Arenillas *et al.*, 2000a,b) and, for this reason, we consider that the supposed extinctions suggested by other authors in Caravaca could be caused by the "Signor-Lipps" effect (Smit, 1994; Molina 1994, 1995).

In this study, we found that possibly 17 Cretaceous species survived the K/T event. These Maastrichtian species belong to *Guembelitria, Hedbergella, Heterohelix, Pseudoguembelina* and *Globigerinelloides* and could be considered possible Cretaceous survivors since most of the specimens show almost no evidence of reworking. However, there is no clear evidence that all of them are survivors and, therefore, must be only be considered as possible Maastrichtian survivors. The only certain survivors are guembelitrids because their abundance seems to increase into the lowermost Danian and they play a clear role in the phylogeny of new danian taxa. The controversial extinction of these species in the early Danian could be related to the long term effect of the impact. Guembelitrids species were disaster species that bloomed immediately after the K/T boundary in the *G. cretacea* Zone. Hedbergellids, heterohelicids and globigerinellids may have been opportunistic pre-adapted survivors and ecological generalists.

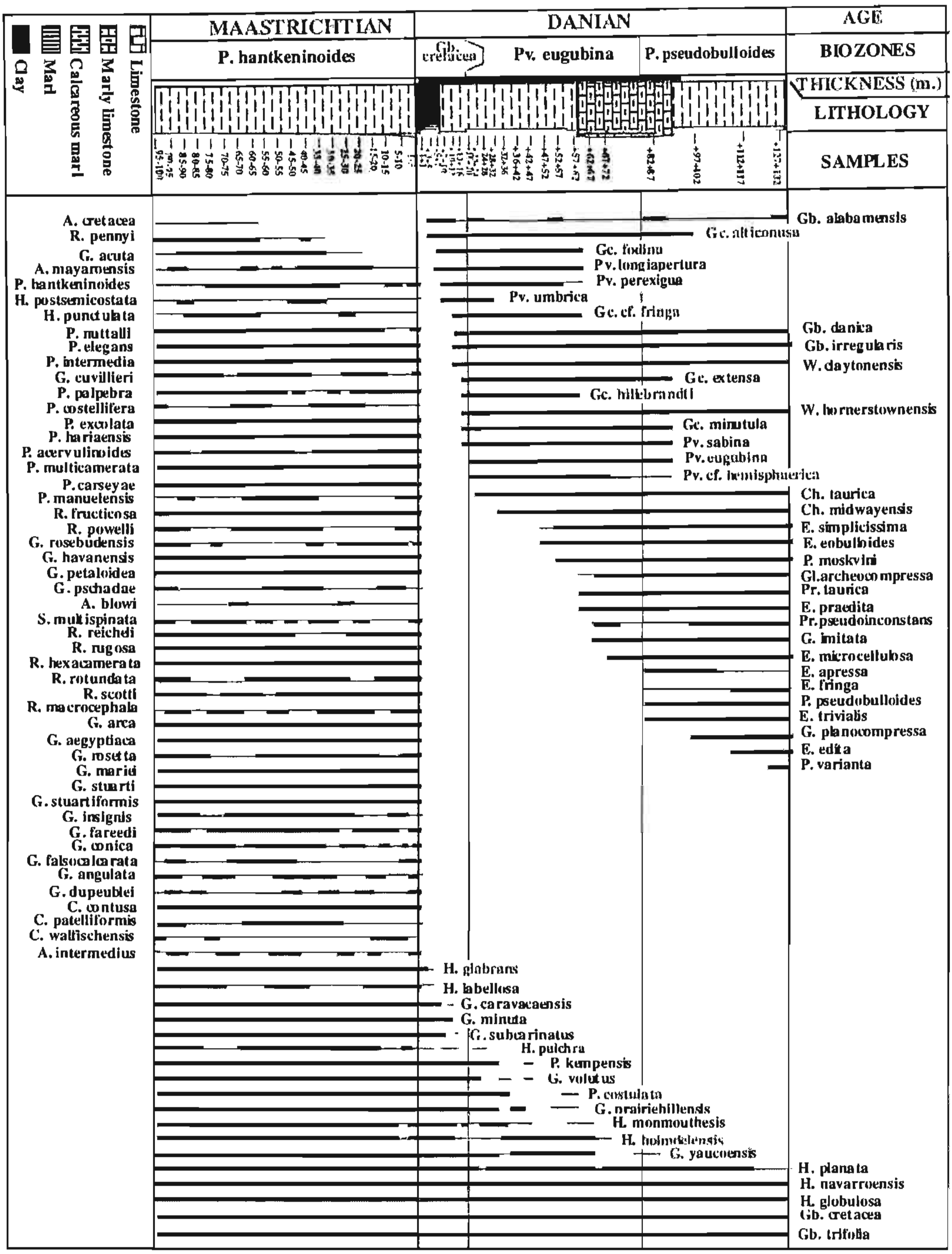

Fig. 2.- Species ranges of planktic foraminifera in the Caravaca K/T-section (modified from Molina *et al.*, 1998).

The relative abundance of these possible planktic foraminiferal survivors suddenly drops above the K/T boundary (Fig. 3). This decrease may be due to the progressive decline in abundance of the cretaceous species that survived due to biological competition with the new tertiary species or, simply, to the decrease in the relative proportion of reworked specimens. Independently of the fact that some species survived the K/T event, the existence of a gradual extinction pattern in the lowermost part of the Danian does not refute the hypothesis of a catastrophic event in coincidence with the K/T boundary. The K/T planktic foraminiferal catastrophic mass extinction of more than 70% is very compatible with the hypothesis of the impact of a large asteroid and its effects in the short, middle and long term.

In fact, a recent study on stable isotopes ($\delta^{13}C$) and foraminiferal abundance carried out by Kaiho and Lamolda (1999) and Kaiho *et al.* (1999) indicated that the post-K/T ocurrences of Cretaceous planktonic species in lower Danian sediments at Caravaca are the result or reworking. Rapid decreases in the percentage abundance and in the number of specimens per gram of carbonate for these species also suggest reworking and abrupt extinction at the K/T boundary. The near synchronous extinction of planktic foraminifera at the K/T boundary suggest an extraterrestrial cause (Smit and Hertogen, 1980; Molina *et al.*, 1998).

Arenillas *et al.* (2000c) and Arz *et al.* (2000) showed four quantitative stages or acmes in the planktic foraminiferal population in the lowermost Danian at the Caravaca section. The lowermost assemblages were dominated successively by *Guembelitria* (Stage 1), *Parvularugoglobigerina* and *Globoconusa* (Stage 2), *Chiloguembelina* and *Woodringina* (Stage 3) and *Eoglobigerina, Parasubbotina, Praemurica* and *Globanomalina* (Stage 4). After the K/T catastrophic mass extinction, two evolutionary radiations of new paleocene species began just above the K/T boundary. The first radiation of new opportunistic species occurred across the boundary between the *G. cretacea* and *Pv. eugubina* Biozones, with the first appearance of small species of *Parvularugoglobigerina, Globoconusa*?, *Woodringina* and *Chiloguembelina*. These new species were also opportunistic and some of them proliferated, but most of them can be considered failed crisis progenitors since they soon became extinct in the *Pv. eugubina* Biozone. The second radiation of new tertiary species occurred across the boundary between the *Pv. eugubina* and *P. pseudobulloides* Biozones, with the first appearance of species with perforate cancellate wall texture. In this interval, the planktic foraminifera became larger once again and $CaCO_3$ and $\delta^{13}C$ returned to similar values as those recorded in the Maastrichtian.

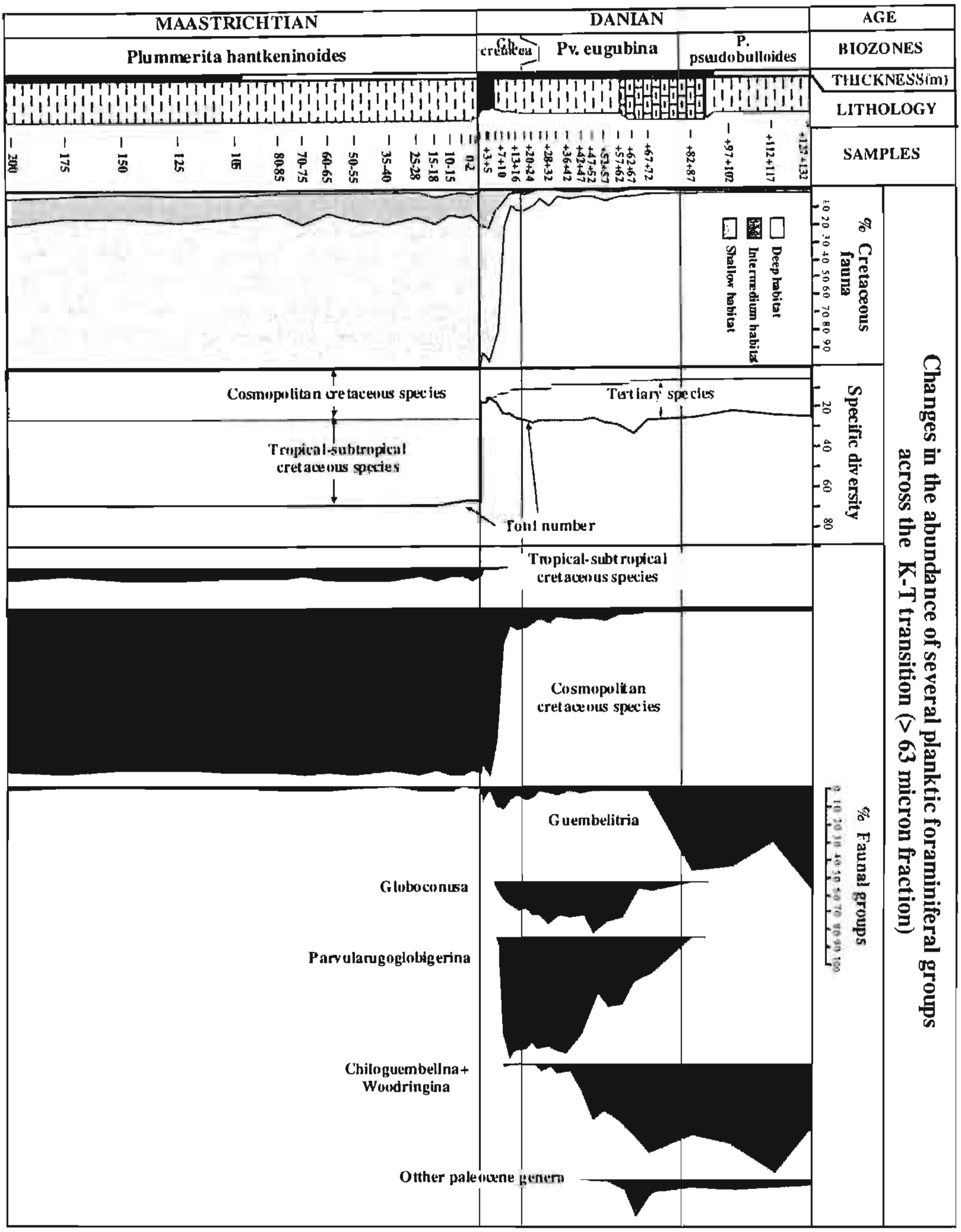

Fig. 3.- Planktic foraminiferal quantitative changes across the K/T boundary at Caravaca (modified from *Arz et al.*, 2000).

Benthic Foraminifera

Benthic foraminifera from Cretaceous and Tertiary sediments at Caravaca are well preserved, and indicate middle bathyal depths of deposition (Coccioni *et al.*, 1993). Upper Cretaceous benthic foraminifera are represented by both calcareous and agglutinated forms; the most abundant morphogroups are flattened tapered (*Spiroplectammina*, *Coryphostoma*) and cylindrical tapered (*Clavulinoides*, Laevidentalinids, *Praebulimina*) among the infaunal foraminifera, that inhabited the deepest layers of the sediment, and biconvex trochospiral (i.e., *Gavelinella*, *Osangularia*) and planoconvex trochospiral (*Stensiöina*) among the epifaunal ones (belonging to the upper 2 cm of the sediment). Benthic foraminiferal assemblages are politaxic, with a complex trophic structure, and indicate environmental stability with well oxygenated bottom-water conditions.

No major extinction of benthic foraminifera are recorded at Caravaca section during the K-T transition. The lack of relevant extinction in benthic foraminifera has been documented in sections from all over the world (Dailey, 1983; Thomas, 1990b; Widmark and Malmgren, 1992). According to Thomas (1990a), the cause is that the deep benthic foraminifera are used to low nutrient levels and because of their feeding habits. The most important change in benthic foraminifera is a drastic decrease in diversity recorded just after the K/T boundary. According to Coccioni *et al.* (1993), an increase of the opportunistic infaunal *Spiroplectammina* and *Bolivina* (*Coryphostoma*) indicate an exceptionally large nutrient flux (organic matter) resulting from the mass mortality at the K/T boundary. Such an amount of organic matter lead to anaerobic conditions on the sea-floor (Jorissen *et al.*, 1995). Upper in the section, a decrease in infaunal morphogroups is recorded as a consequence of a collapse in primary productivity. Benthic foraminiferal assemblages show a stepped pattern through the lower Paleogene; they became more diversified, with somewhat higher percentages of epifaunal groups such as *Anomalinoides*, *Gyroidinoides*, *Stensioina* or *Osangularia*.

Calcareous nannoplankton

The calcareous nannofossils were lately studied by Gardin and Monechi (1998) and were previously studied by Romein (1977). Latest Maastrichtian calcareous nannofossil assemblages are abundant and diverse at Caravaca. Coccolithophores did not seem to be in decline in the latest Maastrichtian, through periods of stress are indicated by peaks in relative abundance of *Micula decussata* and increase in abundance of the genera *Cribrosphaerella* and *Prediscosphaera*.

At the K/T boundary there was a drastic decrease in almost all Cretaceous species, blooms of *Thoracosphaera*, followed by acmes of few opportunistic survivors including *Braarudosphaeare bigelowii*, *Cyclageosphaera reinhardtii*, *Markalius inversus*, *Octolithus multiplus* and new Tertiary, dwarf species (*Neobiscutum romeinii*, *N. parvulum*). Early Tertiary coccoliths may indicate the ecosystem's adjustment to unfavourable environmental conditions, increased primary productivity, poor stratification of surface water and anomalous nutrient availability. Conditions not favourable to calcification of coccoliths may explain the long-lasting calcareous nannofossil low-production and diversity in the earliest Danian.

Conclusions

The K/T section at Caravaca is mainly composed of marls, except for the so-called boundary clay layer that is composed of the blackish-gray clays (about 10 cm thickness) and a basal 1-mm thick red layer. Benthic foraminifera from cretaceous and tertiary sediments at Caravaca are well preserved, and indicate middle bathyal depths of deposition. The planktic foraminiferal extinction pattern is a catastrophic mass extinction since 74% of the species went extinct in coincidence with the K/T boundary and with the evidence of impact. Most of the extinct species are large, complex and low-latitude deeper- to intermediate-dwelling forms, and this event is considered to be the most important catastrophic mass extinction in the history of planktic foraminifera.

After the K/T catastrophic mass extinction, planktic foraminiferal evolutionary radiations of new paleocene species began just above the K/T boundary. Benthic foraminiferal turnover across the K/T boundary, the drastic environmental changes just after the boundary and the decrease in the food supply (after a sudden accumulation of organic matter due to the mass mortality) are consistent with a meteoritic impact occurred at the K/T boundary. Conditions not favourable to calcification of coccoliths may explain the long-lasting calcareous nannofossil low-production and diversity in the earliest Danian. These biotic turnovers and extinctions are very compatible with the catastrophic effects caused by the impact of a large extraterrestrial asteroid (Alvarez et *al.*, 1980; Smit and Hertogen, 1980).

MINERALOGY AND GEOCHEMISTRY (F. C. Martínez-Ruiz, M. Ortega-Huertas and I. Palomo)

Mineralogy

The mineral composition of sediments from the K/T boundary interval at Caravaca section is similar to that from the Agost section. Thus, with the exception of the 2 mm thick layer marking the boundary, are mostly composed of calcite, clays and quartz (Fig. 4). Clay mineral assemblages also consist of smectites, illite and kaolinite (Fig. 4) (Ortega-Huertas *et al.*, 1995, 1998). The boundary is recorded by a smectite layer 2-3 mm thick where abundant spherules are observed. These spherules were diagenetically altered to K-feldspar, being Fe-oxide spherules scarce at Caravaca. Since Smit (1977) reported the K/T boundary at this section, and specially since Smit and Klaver (1981) first reported the K-feldspar spherules, an intense research has been focused on this section. It is not the purpose here to review the extensive literature but to provide a short description of the mineralogy and geochemistry of the K/T boundary interval.

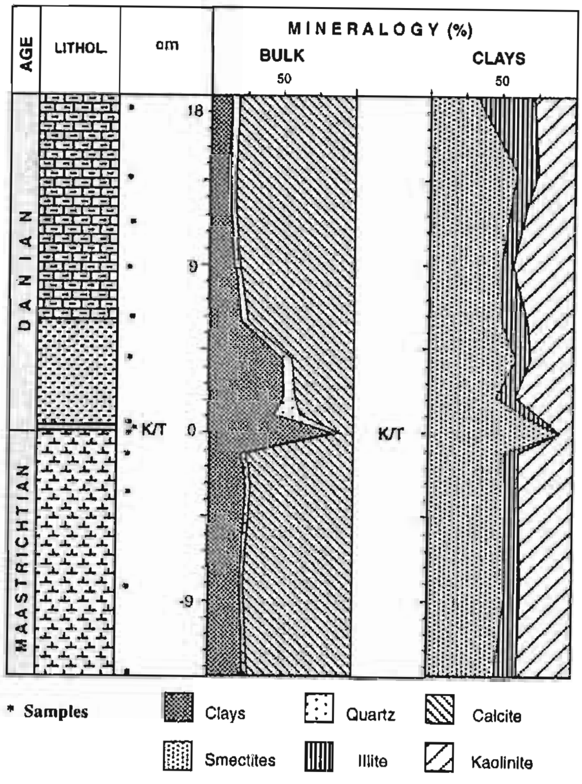

Fig. 4.- Main mineral components across the Cretaceous-Tertiary boundary at the Caravaca section.

Spherules

K-feldspar spherules are very abundant at Caravaca, with a density distribution of 100-300/cm^3. The size is usually 100-500 μm. They mostly occur as spheres and droplet shapes. Although the spherules are diagenetically altered to K-feldspar, their morphologies and textures have been preserved. They have a porous structure in which K-feldspar crystals arranged with fibroradial and dendritic textures (Fig. 5) (e.g., Smit and Klaver, 1981; Montanari *et al.*, 1983; Montanari, 1991, Martínez-Ruiz *et al.*, 1997). These fibroradial and dendritic textures (quench-crystal textures) are similar to those also reported in Fe-oxide spherules from the Agost section (Martínez-Ruiz *et al.*, 1997) and to those from unaltered K/T clinopyroxene spherules (Smit *et al.*, 1992) suggesting the clinopyroxene could have also been the precursor.

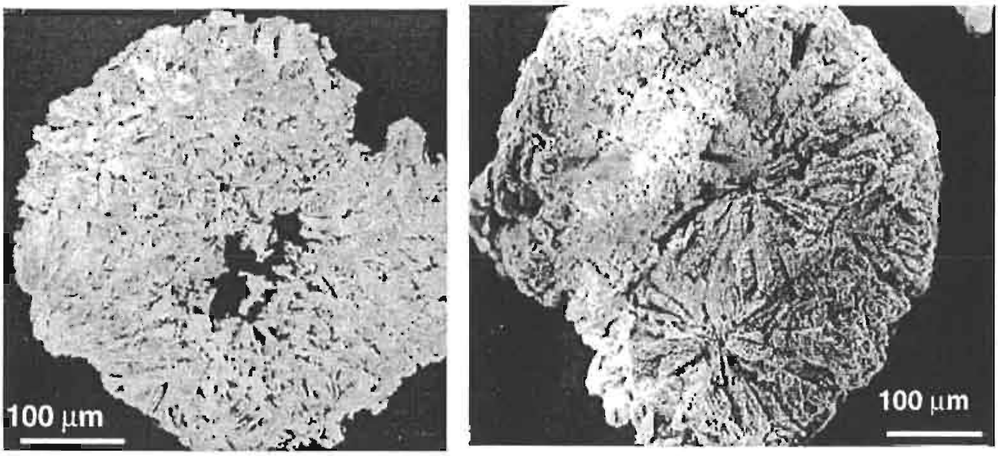

Fig. 5.- SEM photographs of K-feldspar spherules from the Caravaca section showing internal textures.

Although at Caravaca diagenetic alteration led to the almost complete replacement of the spherule precursor, carbon-rich cores have been observed in K-feldspar spherules also containing high concentrations of Ir, Pt, Pd and Ni (Martínez-Ruiz *et al*, 1997) which may provide some clues on the original precursor. Such C-rich cores (Fig. 6) could represent a relict of the original material. These cores present a high concentration of noble metals (Ir: 0.59 ppm, Pt: 2.89 ppm, Pd: 15.70 ppm) and Ni (3000 ppm) suggesting an important extraterrestrial contribution, and therefore an extraterrestrial origin.

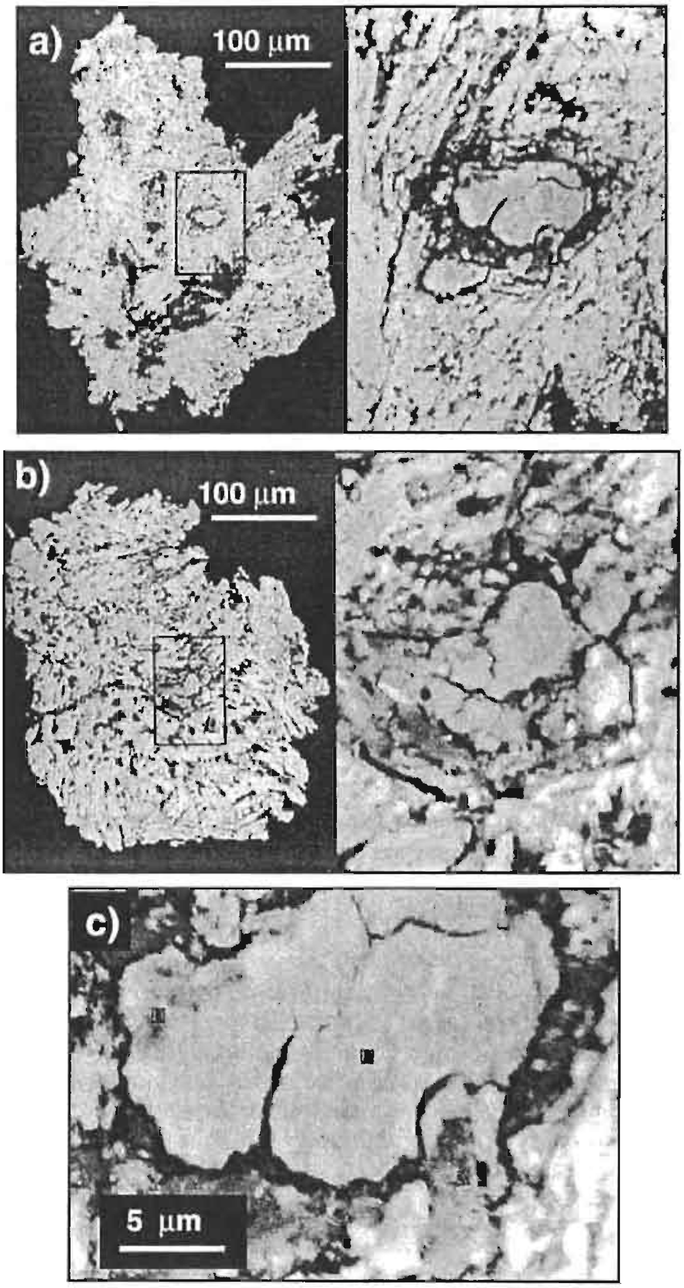

Fig. 6.- BSE images showing C-rich cores observed in K-feldspar sphereules from Caravaca (a, b) and (c) detail of the core showed in photograph a).

Geochemistry

The geochemistry of the K/T boundary at Caravaca has been reported in many papers, showing that this boundary is marked by a large increase of Ir (Fig. 7) and other geochemical anomalies (Fig. 8) (e.g., Smit and Hertogen, 1980; Smit and ten Kate, 1982; Kyte *et al.*, 1985, Rocchia *et al.*, 1987; Smit, 1990, Martínez-Ruiz *et al.*, 1999). Other impact markers such as Ni-rich spinels, interpreted as the result of an infall of extraterrestrial material (e.g., Bohor *et al.*, 1986; Robin *et al.*, 1991), and the Cr isotope composition (Shukolyukov and Lugmair, 1998) also evidence the significant extraterrestrial contribution.

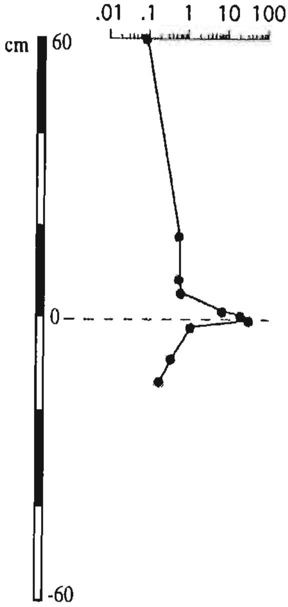

Fig. 7.- Ir profile at the Caravaca section (data from Martínez-Ruiz, 1994).

At Caravaca the Ua content and the extensive pyrite formation also support reducing conditions at time of deposition and during diagenetic processes. Such conditions have been also reported in other K/T boundary sections. Thus, the reduction and leaching of iron in the White Beds below the K/T boundary in the Gubbio section (Italy), suggest that the K/T boundary clay in Italy was deposited under anomalously reducing conditions (Lowrie *et al.*, 1990). Montanari (1991) also detailed early diagenetic processes in the K/T boundary clay from Italy, demonstrating that the K/T boundary facies are consistent with reducing environments. On the other hand, benthic fauna evidences (Coccioni and Galeotti, 1994), foraminiferal indices and S isotopes (Kaiho *et al.*, 1999) also indicate reducing conditions at the K/T boundary in Caravaca. However reducing conditions here do not seem to be as stronger as Agost, which could be probably related to depth and to the extension of the oxygen minimum zone. Reduction conditions could have led to a significant trace element remobilization, although it was not as severe as at the Agost section. This is suggested by higher content of Ir at Caravaca an also by the PGE normalized patterns (Fig. 9) which are flat at this section.

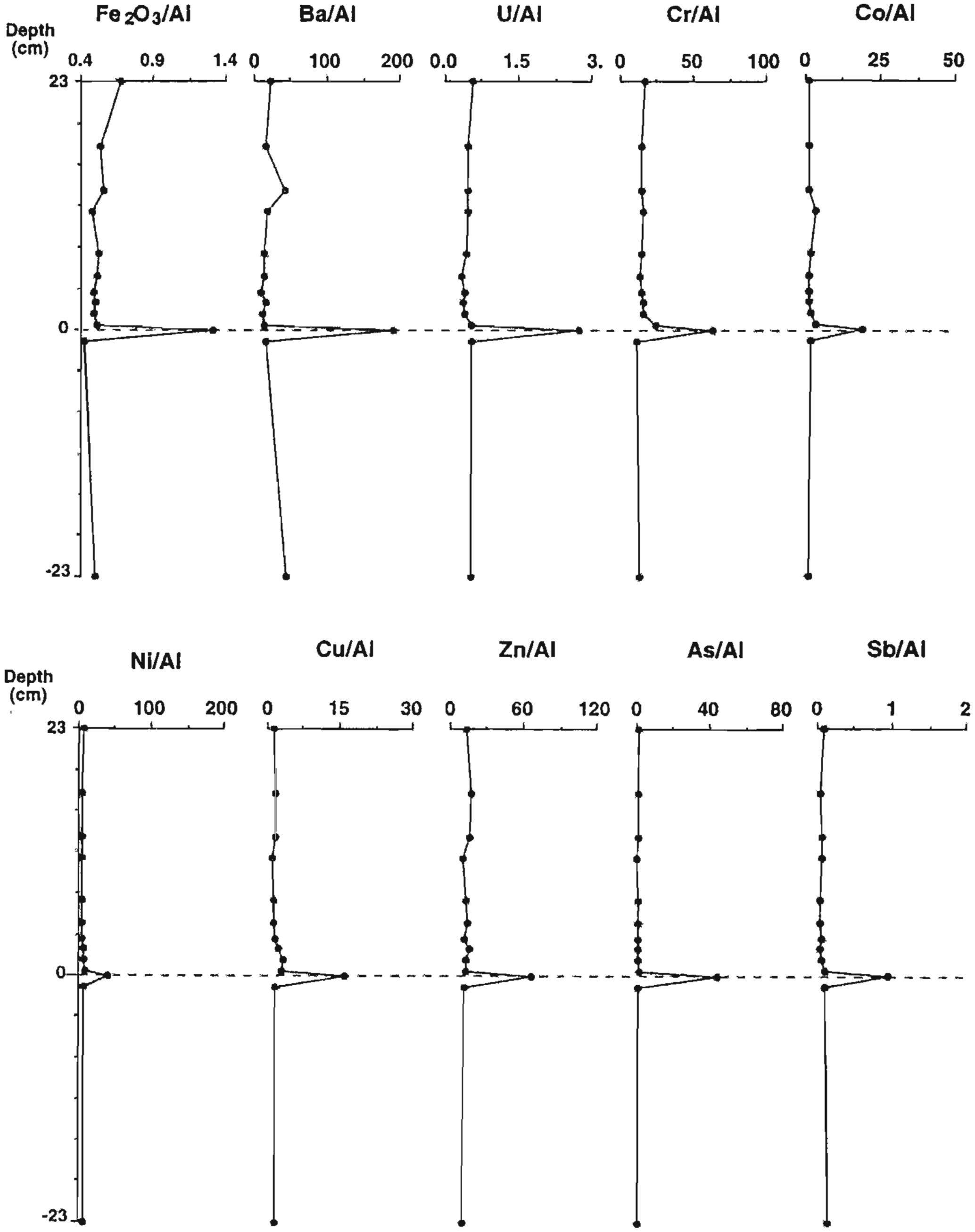

Fig. 8.- Fe and trace element profiles (normalized to Al) from the K/T boundary interval at Caravaca. The horizontal line indicate the K/T boundary and depths are referred to 0 cm for the boundary (from Martinez-Ruiz *et al.*, 1999).

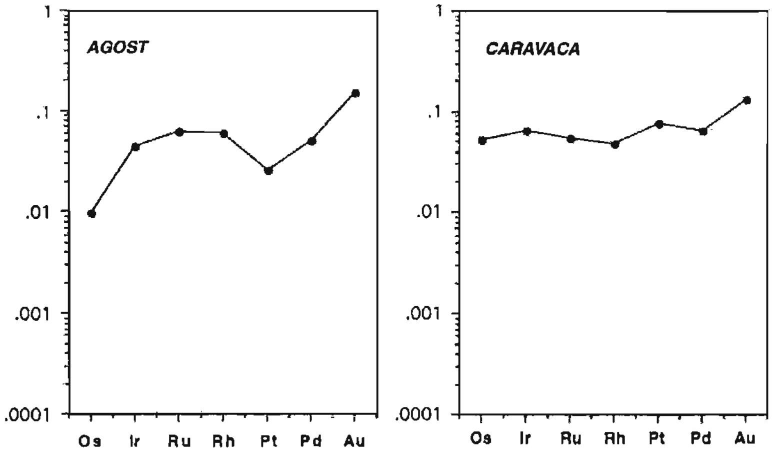

Fig. 9.- C1-normalized PGE patterns of the K/T boundary layer from Agost (a) and Caravaca (b) sections (data from Martínez-Ruiz, 1994).

STOP 2: PALEOCENE STAGE BOUNDARIES

MICROPALEONTOLOGY (I. Arenillas and E. Molina)

In eastern Spain, latest Senonian-Paleocene time was characterized by a widespread regression, which culminates in the emergence of large parts of the carbonate platform (De Ruig, *et al.*, 1991). The platform emergence was accompanied during the Paleocene by occasional sandy turbidites in the bathial environments such as Caravaca.

The Danian sediment consists of marls, clay, and marly limestone with abundant pelagic fauna, and few turbiditic strata. About 100 metres above the K/T boundary in the Selandian, pelagic sedimentation is interupted by a thick turbidite strata, containing glauconite-encrusted debris and larger foraminifera (*Ranikothalia* sp., *Miscellanea* sp., *Daviesina* sp., etc.) of paleocene shallow water limestone.

The Danian-Selandian interval was first studied by von Hillebrandt (1974) and by Romein (1979) who established the planktic foraminiferal and calcareous nannofossil biozonations respectively. Romein (1979) identified the biozones NP1, NP2, NP3, NP4, NP5, NP6, NP7, NP8 and NP9. Smit (1979) studied the K/T boundary and Smit (1982) accomplished the magnetostratigraphy of the Danian at Caravaca section, identifying the chrons C29, C28 and C27 (Fig. 10).

The planktic foraminiferal biostratigraphy and the correlation with all the other data have been recently studied by Arenillas and Molina (1997). The quantitative study of the paleocene planktic foraminifera from Caravaca (Betic Cordillera, SE Spain) allowed us to establish a detailed biozonation, solve some chronostratigraphical problems, and analyze the evolution of the assemblages and their paleoceanographical implications.

The following biozones were recognized across the Paleocene: *Guembelitria cretacea*, *Parvularugoglobigerina eugubina*, *Parasubbotina pseudobulloides*, *Globanomalina compressa*, *Acarinina trinidadensis*, *Acarinina uncinata* and *Morozovella angulata* (Danian); *Morozovella crosswicksensis* and *Igorina albeari* (Selandian); *Luterbacheria pseudomenardii*, *Muricoglobigerina soldadoensis* and *Igorina laevigata* (Thanetian).

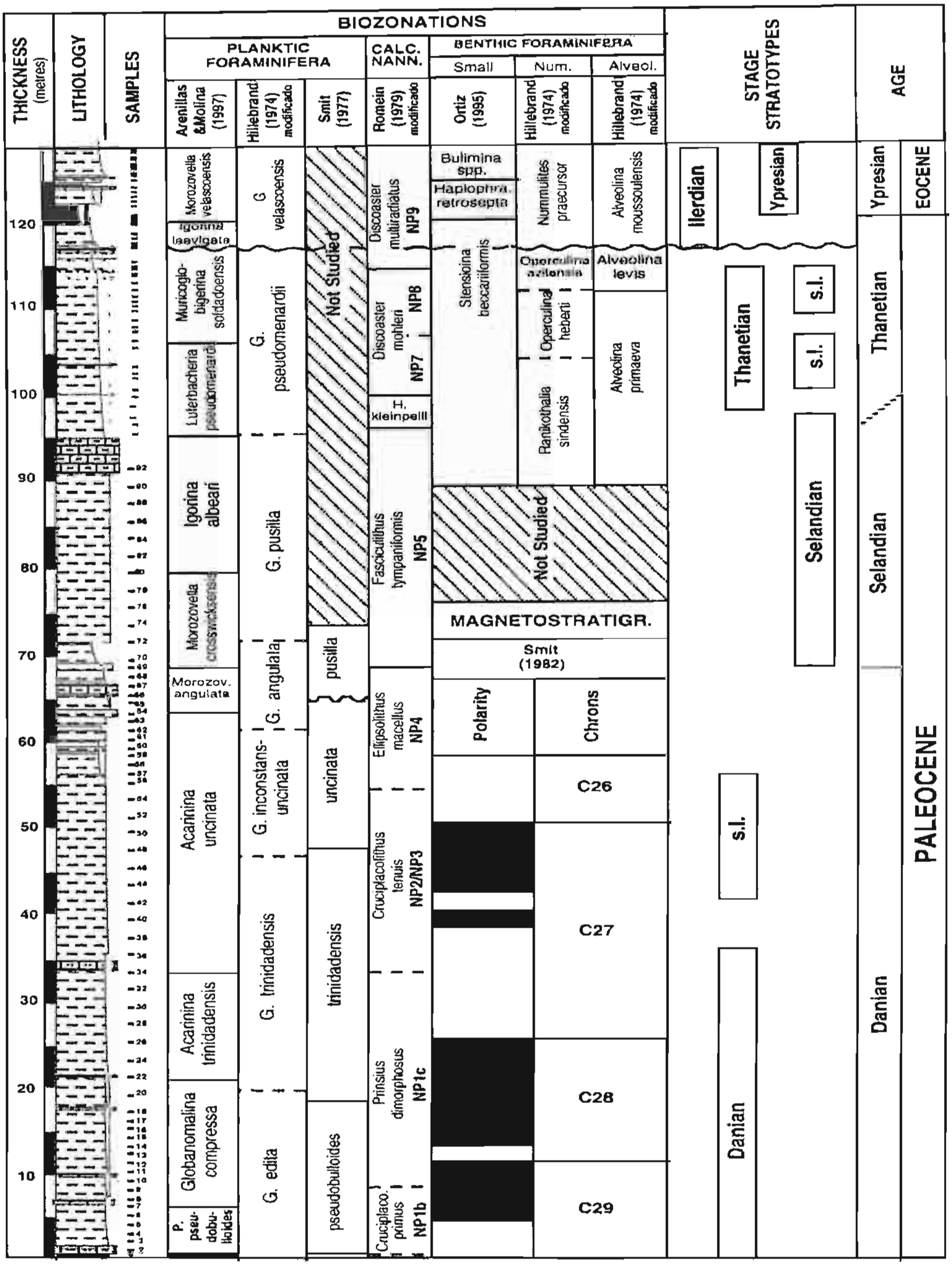

Fig. 10.- Integrated stratigraphy across the Paleocene at Caravaca section (modified from Arenillas and Molina, 1997).

STOP 3: THE PALEOCENE/EOCENE BOUNDARY
(E. Molina, I. Arenillas and F. C. Martínez-Ruiz)

High resolution sample analysis across the Paleocene-Eocene transition at Caravaca based on integrated microfossil and geochemical data allow to establish a high resolution stratigraphy. The study revealed a series of events (extinctions, originations and geochemical shifts) that allowed the establishment of a detailed chronostratigraphical framework. The text that follows was published by Molina *et al.* (1994) and has been modified selecting and up-dating the most important aspects for the field trip guide.

Introduction

In 1989 a working group was organised in order to define a Global Stratotype Section and Point (GSSP) for the base of the Ypresian stage, corresponding to the Paleocene/Eocene boundary. According to the International Subcommission on Paleogene Stratigraphy the Paleocene/Eocene (P/E) boundary should coincide with the base of the Ypresian stage (Jenkins and Luterbacher, 1992). Several sections have been proposed as candidates and are being evaluated as potential P/E boundary stratotype. The Caravaca section apparently satisfies most of the criteria for the definition of GSSP proposed by Odin (1992) and it was initially proposed as one of the candidates by the Spanish working group on P/E boundary stratotype, in the meetings of Fontainebleau in 1990 and Brussels in 1991.

The P/E boundary stratigraphy involves a series of problems that have to be solved before the GSSP can be officially defined. Many of these problems are related to the precise chronostratigraphic location of this boundary. In order to find a solution certain authors have recently studied the area of the Ypresian stratotype (Aubry, 1983, 1986; Dupuis *et al.* eds., 1988; Schuler *et al.*, 1992, Pardo *et al.*, 1994), to determine the position of the lithological formations and the stratotypes involved in the P/E boundary. However, the Belgian, Paris and London basins have shown almost no continuity in marine facies across the P/E boundary, a necessary condition for a boundary stratotype. Consequently, it has to be defined in a continuous marine section somewhere else in the world.

Evaluation of a potential boundary stratotype section requires high resolution and integrated stratigraphical studies in order to locate precisely regional or global bioevents that unequivocally could be used to define the P/E boundary.

Materials and methods

The Paleocene-Eocene transition is within the Jorquera Formation (Van Veen, 1969), which consists of 225 m of marls interbedded with sandy limestones. The Paleocene part is predominantly marly whereas the Lower Eocene is calcarenitic with interlayers of marls and clays. Several stratigraphic horizons containing larger foraminifers (nummulitids, alveolinids, discocyclinids) are present in the calcarenitic sediments. These lithified strata frequently show cross bedding, convolute lamination and other sedimentological structures, indicating a high energy environment, with possible transport from an inner platform area.

The Paleocene-Eocene transition examined stratigraphically spans 80 m of sediments, of these 40 m spanning the P/E boundary were analyzed in closely spaced samples. The Upper Paleocene is composed of gray marls with two thin interbeds of calcarenite. The P/E boundary interval consists of 20 m of gray marls and clays with the clay interval containing two intervals of strong carbonate dissolution. At the base of the clay layer the sediment colour is dark grey to black and benthic taxa suggest an anoxic event. The Lower Eocene is composed primarily of yellow-gray limestones and sandy limestones intercalated with marls. The top of the section is predominantly marly. The marly intervals contain rich calcareous microfossil assemblages. Planktic foraminifera and calcareous nannoplankton are abundant and well preserved. Small benthic foraminifera are relatively few to common throughout the section, whereas larger foraminifera are present only in certain strata. Ostracods and siliceous microfossils are rare.

The Upper Paleocene to Lower Eocene interval was sampled at 30 cm to 50 cm with closer sample spacing of 10 cm to 20 cm intervals across the P-E transition (Zones P4-P6b). For foraminiferal isotope and faunal analyses, samples were disaggregated in tap water and then washed through a 63 µm sieve and dried at 50°C. Isotopic analyses were conducted on the benthic foraminifera *Nuttallides trumpyi* except for the $\partial^{13}C$ shift interval where *N. trumpyi* is absent and *Lenticulina* spp. was analyzed. Specimens were picked from the 180-250 µm size fraction, ultrasonically cleaned to remove sediment infilling of chambers and roasted under vacuum at 380°C. Isotopic measurements were conducted with a Finnigan MAT 251 linked to a Kiel carbonate extraction system at the stable isotope laboratory of the University of Michigan, Ann Arbor. Analytical error was measured at 0.05% for $\partial^{13}C$. The data are reported in values referenced to PDB. No species correction factors were applied to the data because species offset studies are still in flux.

The bulk sample mineralogy was studied by X-ray Diffraction at the Departmento de Mineralogía y Petrología of the Universidad de Granada (Spain). Geochemical analyses were carried out at the XRAL Laboratories in Ontario (Canada) by X-ray Fluorescence, Inductively Coupled Plasma and Neutron Activation. Elements data have been normalized on a carbonate-free basis.

Biostratigraphy

Planktic foraminifera are very abundant in the marly intervals and were studied by Von Hillebrandt (1974), establishing a biozonation from the uppermost Cretaceous to the Middle Eocene, but he did not give any range chart. Recently, a very detailed quantitative study has been accomplished (Canudo *et al.*, 1995), evaluating the planktic foraminiferal turnover across the Paleocene-Eocene transition. The following biozones have been recognized: *Igorina pusilla, Planorotalites pseudomenardii, Morozovella velascoensis, Morozovella edgari, Morozovella subbotinae* and *Morozovella formosa*, according to the Toumarkine and Luterbacher (1985) biozonation. These biozones correspond to P3b, P4, P6a, P6b, P6c and P7, according to the Berggren and Miller (1988) biozonation. The biozone P5 and the lower part of P6a were not identified and the reason is the presence of a hiatus, as it is shown by the simultaneous disappearance of seven species (*Zeauvigerina teuria, Morozovella conicotruncata, Morozovella angulata, I. pusilla, Morozovella mcknaii, Acarinina subsphaerica* and *P. pseudomenardii*) and the subsequent appearance of four species (*M. subbotinae, Chiloguembelina wilcoxensis, Morozovella marginodentata,* and *Planorotalites capdevilensis*). This hiatus is placed 2.5 m below the dissolution interval that marks the Paleocene/Eocene boundary.

(NOTE: A recent revision of the P/E planktic foraminiferal biostratigraphy carried out by Molina *et al.* (1999) allowed to apply a new biozonation at Caravaca and other sections. The three classical zones have been recognized across the P/E boundary at Caravaca: *Luterbacheria pseudomenardii* Biozone, *Morozovella velascoensis* Biozone and *Morozovella subbotinae* Biozone. The high resolution study allowed to define new subzones which are very detailed especially across the P/E boundary. The *Morozovella velascoensis* Zone has been divided into the following subzones: *Morozovella aequa* Subzone, *Morozovella gracilis* Subzone, *Acarinina berggreni*

Subzone, *Acarinina sibaiyaensis* Subzone and *Pseudohastigerina wilcoxensis* Subzone. All these subzones may be recognized at Caravaca, except to *A. berggreni* Subzone, which may be lacking due to dissolution interval. The lower part of the *M. aequa* Biozone is absent due to the hiatus).

Nine species (*Acarinina pseudotopilensis, Muricoglobigerina chascanona, Planorotalites troelseni, Morozovella simulatilis, Igorina laevigata, Igorina albeari, Subbotina velascoensis, Morozovella occlusa* and *Muricoglobigerina aquiensis*) disappear gradually at or below the boundary indicating that the planktic foraminifera were affected by the event but not so much as the small benthic foraminifera. Five species (*I. laevigata, I. albeari, S. velascoensis, M. occlusa* and *M. aquiensis*) seem to become extinct, but their distribution compared with other sections (Molina *et al.*, 1992; Canudo *et al.*, 1995) shows that in Caravaca *I. albeari* and *M. occlusa* constitute local disappearances. Another species (*M. aquiensis*) also becomes extinct later in the area of the Ypresian stratotype in Belgium (Pardo *et al.*, 1994). Consequently, only *Igorina laevigata* and *Subbotina velascoensis* become extinct at the P/E boundary.

The small benthic foraminifera have been recently studied quantitatively (Ortiz, 1993 unpubl.) for the P-E transition evaluating the faunal turnover across the P/E boundary. In this paper the following biozones have been recognized: *Pyramidina rudita, Stensioina beccariiformis, Haplophragmoides retrosepta, Bulimina tuxpamensis/Tappanina selmensis, Nuttallides trumpyi,* and *Cibicidoides subspiratus.* This new biozonation is correlated with the Berggren and Miller (1989) biozonation. At the top of *S. beccariiformis* Biozone that coincides with the BB1/BB2 boundary, 50% of the bathyal and abyssal species disappeared and this can be considered a mass extinction; among them the more significant are: *S. beccariiformis, Anomalinoides rubiginosus, Cibicidoides velascoensis, Gyroidinoides globosus, Neoflabellina semireticulata, Osangularia velascoensis, Dorothia retusa, Eponides megastoma, Pullenia coryelli* and *Tritaxia globulifera.* The *H. retrosepta* Biozone is very poor in microfossils probably because of the dissolution. The uppermost part of the section can be dated as BB3 Biozone because an assemblage that characterized this biozone (*Gaudryina hiltermanni, Cibicidoides micrus* and *Anomalina capitata*) and *Cibicidoides* cf. *subspiratus* were found. According to the small benthic foraminifera the depositional depth appears to have been upper bathyal to upper middle bathyal depth (P4 to P6b about 600 m and P6b to P7 about 300 m), as it is suggested by a buliminid dominated fauna including *N. trumpyi, Bulimina cahallani, Bulimina trinitatensis and Anomalinoides capitatus.*

The larger foraminifera were studied by Von Hillebrandt (1974), who found four strata containing nummulitids, alveolinids and discocyclinids. In the lower level, placed at the boundary between P4 and P6a Biozones, an assemblage was identified that characterizes the *Operculina azilensis* Biozone. The second level contains an assemblage that characterizes the *Nummulites praecursor* Biozone and the *Alveolina moussoulensis* Biozone and the third level the *Nummulites involutus* Biozone and the *Alveolina trempina* Biozone. The fourth level was found in the P7 Biozone and contains an assemblage of the *Nummulites planulatus* Biozone. The biozonations established by von Hillebrandt (1974), that were based on the alveolinids biozonation of Hottinger (1960) and on the nummulitids biozonation of Schaub (1951), have been modified according to our revision. Our most detailed sampling allows to recognize an older new level, which is placed in the top of P3b, containing very rare and primitive nummulitids that according to Serra-Kiel (personal communication), are: *Ranikotalia soldadensis, Miscellanea* sp. and *Daviesina* sp. This assemblage has never been found before in the Spanish Betic Cordillera and they were previosly found mainly in the Paleocene of the French Guiana.

The calcareous nannoplankton was studied by Romein (1979) who established the vertical distribution of the Paleocene and Early Eocene species, defining a detailed biozonation. For the Paleocene-Eocene transition interval the following biozones were recognized: *Fasciculithus tympaniformis, Heliolithus kleinpellii, Discoaster mohleri,* *Discoaster multiradiatus, Tribrachiatus contortus, Discoaster binodosus* and *Tribrachiatus orthostylus*. These biozones correspond to NP5, NP6, NP7, NP8, NP9, NP10, NP11 and NP12 of the biozonation of Martini (1971). According to Romein (1979) all samples, except those from the upper part of the *D. multiradiatus* Biozone and the lower part of the *T. contortus* Biozone contained rich nannofossil floras. *T. contortus* did not occur in the Early Eocene floras from this sequence and the boundary between the *T. contortus* Biozone and the *D. binodosus* Biozone was arbitrarily drawn between the appearance of *T. orthostylus* and the entry of *Discoaster barbadiensis*. A new and more detailed study on calcareous nannofossil assemblages across the P/E boundary at Caravaca was carried out by Angori and Monechi (1995). They identified the biozones NP8, NP9, NP10 and NP11. The synchronous first appearances of *Discoaster multiradiatus* and *Campylosphaera eodela* indicate that the lower-middle part of *D. multirradiatus* Zone NP9 is missing. The consistent stratigraphic ranges of *Rhomboaster* and *Tribachiatus* lienages attest to the continuity of the P/E boundary at Caravaca.

Geochemistry

Some aspects of the carbon and oxygen isotopes were previously discussed by Canudo *et al.* (1995) correlating the planktic and benthic foraminiferal turnovers and the $\partial^{13}C$ and $\partial^{18}O$ isotopes across the Paleocene-Eocene transition at Caravaca and Zumaya, representing the first isotopic records from the western Tethys Seaway. The isotopic data are integrated in this paper with the bulk mineralogy, the trace and major elements and the biostratigraphy, in order to clearly characterize the P/E boundary event (Fig. 11).

The $\partial^{13}C$ isotope measured on *N. truempyi* shows a relatively constant positive value through P4 Biozone, indicating very stable conditions at the Caravaca section. Nevertheless, just above the hiatus in P6a Biozone there is a small excursion into negative values that coincides with deposition of an anoxic dark grey shale. The biggest shift occurred in the upper part of P6a Biozone where there is a rapid decrease of 4 permil in the benthic *Lenticulina* values. This excursion coincides with the sudden extinction of 50% of the small benthic foraminifera and with a clay layer where most of the calcareous foraminifera are dissolved. At the top of P6a Biozone there is a second dissolution interval where *Lenticulina* values are stable around -4 permil and in the lower part of P6b Biozone *N. trumpyi* gradually increase by 2.5 permil.

The $\partial^{18}O$ isotope has also been measured on *N. trumpyi* and where it was absent *Lenticulina* was analysed. In P4 Biozone there is a small shift that coincides with another in $\partial^{13}C$ and just above the hiatus another small shift is observed. Furthermore, at the transition between the P6a and P6b biozones a similar excursion, not so strong as in $\partial^{13}C$, was observed.

The mineralogy of the section consists mainly of calcite, phyllosilicates, feldspar and quartz. Above the Paleocene/Eocene boundary we have detected a significant decrease in carbonate content. This is also evident by the dissolution of most of the calcareous foraminifera, but in the middle part of this interval some foraminifers were preserved. The carbonate decrease is accompanied by an important increase in the quartz content that reaches high proportions in the Lower Eocene. Different elements were analyzed across the P/E boundary and the most significant changes are observed in Fe_2O_3, Al_2O_3, TiO_2, MnO, Cr, Cu, Zn and REE. In the interval above the P/E boundary we have detected higher contents in Fe_2O_3, Al_2O_3 and TiO_2, and lower contents in MnO, Cr, Cu, Zn and REE.

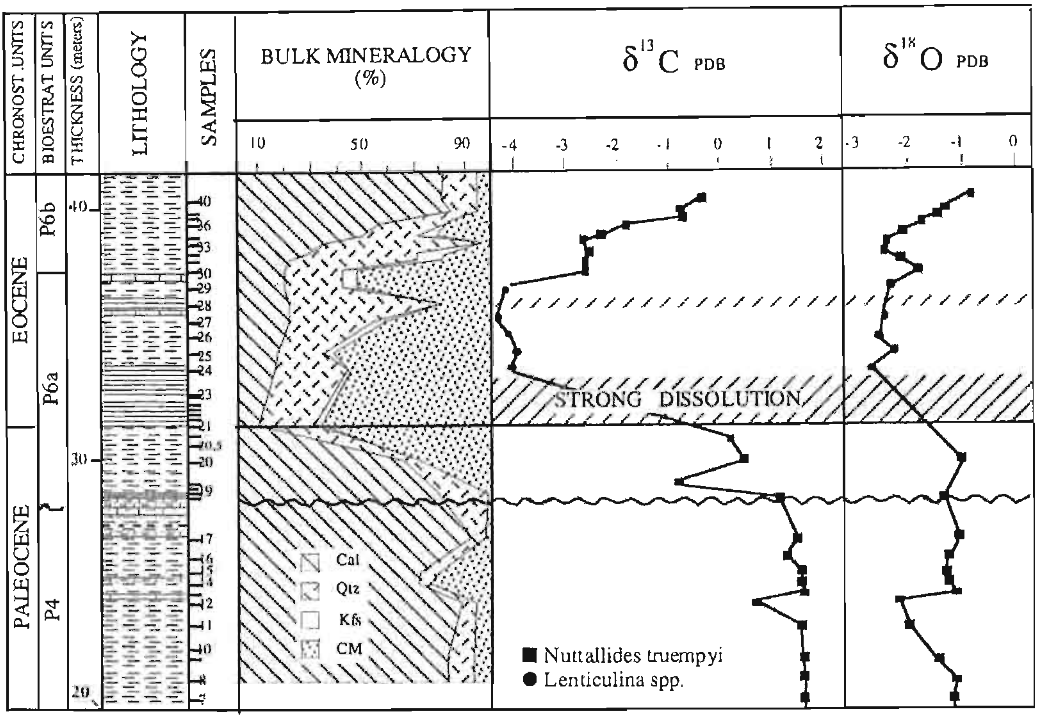

Fig. 11.- Isotopes and bulk sample mineralogy across the Paleocene/Eocene boundary.

Sequence Stratigraphy

As the depositional depth of Caravaca appears to have been of upper bathyal to upper middle bathyal (intervals with small benthic foraminifera) and outer neritic (levels with larger foraminifera) depth (200-600 m), the sedimentation reflects the sea level changes quite clearly. Based in the study of this section, as well as in regional observations, several depositional sequences have been recognized. The highstands are represented by shallow marine sandstones containing larger foraminifera and the lowstands and trangressive-systems tracts by mudstones containing planktic microfossils. The marly intervals are thicker than the calcarenitic ones indicating deposition mainly on an outer platform.

The boundary between our depositional sequences 1 and 2 is clearly placed in the lower part of P 4 Biozone just above a calcarenitic short interval, including larger foraminifera, where evidence of reworking exists. Our depositional sequence 2 seems to correlate with the TA2.1 of Haq *et al.* (1987) and clearly corresponds to the Thanetian stage. The hiatus at the base of depositional sequence 3 represents about 0.7 Ma missing the Lower Ilerdian, the TA2.2 and possibly the TA2.3 sequences of Haq *et al.* (1987). Our depositional sequence 3 could correspond to TA2.3 and mainly to TA2.4 and constitutes a very high sea level rise that coincides with the anoxic event, which marks the P/E boundary. The rest of the sequences 4, 5 and 6 are not so clearly defined, due to the interference between the global eustatic changes and the local tectonic, but could correlate with TA2.5, TA2.6 and TA2.7 respectively of Haq *et al.* (1987). This correlation is tentative and provisional since the global depositional sequences for this time interval are under revision (Hardenbol, personal communication).

Discussion

Although the Caravaca section was studied biostratigraphycally by several authors (Durand Delgá and Magné, 1958; Von Hillebrandt, 1974; Romein, 1979) none of them found the hiatus that has been recently discovered by means of planktic foraminifera (Canudo *et al.*, 1995) and it is also documented in this paper by the simultaneous disappearance of at least six small benthic foraminifera (*Aragonia velascoensis, Bolivinoides delicatulus, Cibicidoides hyphalus, Pyramidina rudita, Tritaxia paleocenica* and *Tritaxia trilatera*). This hiatus comprises from the uppermost part of P4 Biozone to the upper part of P6a Biozone and according to the calibration of the Berggren and Miller (1988) biozonation the hiatus could represent about 0.7 Ma, since the top of P4 Biozone was dated at 58.64 Ma and the ∂^{13}C excursion at 58.0 Ma by Pak and Miller (1992) at Site 577 where good chronostratigraphic control is available.

The hiatus is located 2.5 m below the small benthic foraminifera extinction and just above a calcarenitic strata containing nummulitids of the *O. azilensis* Biozone (Late Thanetian). About 17 m above Von Hillebrandt (1974) found another level with nummulitids of the *N. praecursor* Biozone (Middle Ilerdian) and he attributed the marly clay interbedded interval to the *N. fraasi* Biozone (Early Ilerdian). Nevertheless, because of the hiatus this biozone could not be represented and neither the alveolinids *A. cucumiformis* and *A. ellipsoidalis* Biozones (Early Ilerdian). When this section is compared with the Zumaya section (Canudo and Molina, 1992a) the 2.5 m between the P/E boundary and the base of the hiatus at the P4 Biozone in Caravaca correspond to about 19 m at Zumaya, where the P/E transition is very well represented in continuous marine facies (Fig. 12).

The 2 m interval of clay with some dissolution resistant foraminifers between the two strong dissolution levels in Caravaca is represented by about 13 m at Zumaya (Canudo *et al.*, 1995), but at this interval no evidence of a hiatus exists, consequently the sedimentation has to be condensed at this interval at Caravaca where the ∂^{13}C excursion maintains the minimum values of -4 permil. At the base of the clay with dissolution the smaller benthic foraminifera suffer a dramatic extinction in coincidence with the carbon and oxygen isotopes shifts. Consequently, although condensed in comparison with Zumaya the P/E boundary event is well represented at Caravaca, which is an excellent expanded section compared with any deep-sea record known so far.

The mass extinction horizon of small benthic bathyal and abyssal foraminifera appears to be the more suitable event to mark the Paleocene/Eocene boundary, since it coincides with the ∂^{13}C excursion, which has been determined to be globally synchronous (Thomas, 1990b; Kaiho, 1991; Kennett and Stott, 1991; Pak and Miller, 1992; Lu and Keller, 1993). Nevertheless, the placement of the P/E boundary has not been officially defined and many biostratigraphers still place this boundary at the extinction of *M. velascoensis* that marks the P6a/P6b boundary in accordance with Berggren *et al.* (1985). Some others place the P/E boundary at the extinction of *P. pseudomenardii* that defines the top of P4 Zone in accordance with Cavelier and Pomerol (1986). The *M. velascoensis* extiction is supposed to coincide with the *Pseudohastigerina wilcoxensis* appearance, but in Caravaca both species overlap. In contrast, in the Pyrenean sections (Zumaya and Campo) and in the area of the Ypresian stratotype (Knokke borehole) *P. wilcoxensis* appears later (Molina *et al.*, 1992; Canudo and Molina 1992a,b; Pardo *et al.*, 1994). Consequently, these horizons are not isochronous, especially the *Pseudohastigerina* "datum", and are less reliable than the benthic extinction horizon. Furthermore, the base of the Ypresian stratotype appears to be closer to the mass extinction (about 50%) of the small benthic foraminifera than to the *M. velascoensis* extinction (Pardo *et al.*, 1994). According to planktic foraminifera and the Spanish sections, the markers to identify the P/E boundary considered in this paper are the simultaneous extinctions of *Igorina laevigata* and *Subbotina velascoensis.*

In addition, the $\partial^{13}C$ event is associated with a major planktic foraminiferal turnover marked by the gradual extinction and evolution of 33% and 18% of the species respectively.

Stable isotope $\partial^{18}O$ indicates that during the Paleocene-Eocene transition, which coincides with the small benthic foraminifera mass extinction, temperature increased reaching values comparable to the Late Cretaceous. This event has been previously documented in other regions mainly by Shackleton (1986), Thomas (1990b), and Kennett and Stott (1991). In the Caravaca section we have found two slight shift below and above the hiatus and a strong shift coinciding with the small benthic extinction at the base of a clay interval with a strong carbonate dissolution. The negative $\partial^{13}C$ excursion can be dated very precisely at Caravaca in the middle P6a Biozone persisting up to the P6a/P6b boundary and declining at the lower part of the P6b Biozone, just above a second strong dissolution interval. The $\partial^{18}O$ shows a similar contemporary trend indicating an increase in temperature. These can be considered high resolution records since the entire shift and recovery interval is represented by 8 m at Caravaca compared with less than 20 cm at DSDP Site 577 (Pak and Miller, 1992). Even so, this interval is less expanded than in the Zumaya section (Pyrenees, Northern Spain) where it is represented by 18 m (Canudo *et al.*, 1995).

In the geochemically studied Paleocene/Eocene transition interval, a significant change in the concentration of different elements suggests a change in palaeoceanographic conditions. Above the P/E boundary the increase in Fe_2O_3, Al_2O_3 and TiO_2, suggests an important increase in the detrital accumulation around this boundary, which is also indicated by the increase in the quartz content. Although hydrothermal activity is a potential source of Fe, detrital input plays a more important role in the supply of Fe to the ocean sediments. In addition, typical continent derived-elements such as Al and Ti also increase their concentration. Statistical analyses of the obtained data reveal a good correlation among Fe-Al-Ti (r=0.96 for 16 samples). These data suggest a common terrestrial source for these elements.

The sharp decrease in MnO content across the boundary could indicate a change in the paleoenviromental conditions. The main source for this element is volcano-hydrothermal activity (Klinkhammer, 1980; Andrianiazy and Renard, 1984). In this sense, changes in the tectonic regime of mid-ocean ridges have been documented at the P/E boundary (Aubry *et al.*, 1988; White and MacKenzie, 1989) and as a consequence, an increase in the hydrothermal activity (Olivarez and Owen, 1989). Therefore an enrichment in Mn can be expected in the area of the oceanic ridges due to hydrothermal input (Lyle, 1979). However the influence of oceanic ridges as source of Mn is less important in continental margin environments, such as at Caravaca, where a decrease is observed across the boundary and not the expected increase as a consequence of hydrothermal activity. Redox conditions seem to be the main control of Mn concentrations. The decrease in Mn across the boundary suggests a significant change to reductive conditions in which Mn decreases because it would be essentially soluble.

Other elements, such as Cr, Cu, Zn or REE, are usually associated with the clay fraction, in addition organic material also plays an important role in the Cu and Zn concentrations. In reductive conditions, similar to those of the interval above the P/E boundary (Irwin *et al.*, 1977; Schmitz, 1985; Schmitz *et al.*, 1988), an increase in these elements could be expected; however the significant increase in siliciclastic input could have masked such enrichment. The decrease in REE also indicated siliciclastic accumulation since higher size fractions than silt present less REE concentration due to the dilution effect of quartz (sea Cullers *et al.*, 1988).

In summary, trace minerals and major elements reveal an important increase in the detrital input as a probable consequence of the tectonic instability across the P/E transition, as well as a change across this boundary to more reductive conditions.

Regarding the sequence stratigraphy, the P/E boundary approximately coincides with a sea level change (Haq *et al.*, 1987). The P/E boundary event placed in the lower part of our depositional sequence 3 seem to be related to a strong sea level rise. According to Leinfelder and Seyfried (1993) during very long-lasting greenhouse episodes the sea level is very high, climate and circulation systems are stable and biotic crises often develop as a consequence of oxygen deplection. The P/E boundary event is mainly characterized by the extinction of the small bathyal and abyssal foraminifera in coincidence with a strong rise in temperature and an anoxic interval, as it is evident at Caravaca. Consequently, the interrelated rise in sea level and temperature, together with a stabilisation in oceanic deep water circulation, because of the temporal cessation of polar cool water supply that caused a sharp deep-sea warming at the P/E boundary, could produce oxygen deplection in the deep sea, causing partial collapse of the benthic bathyal and abyssal marine ecosystems.

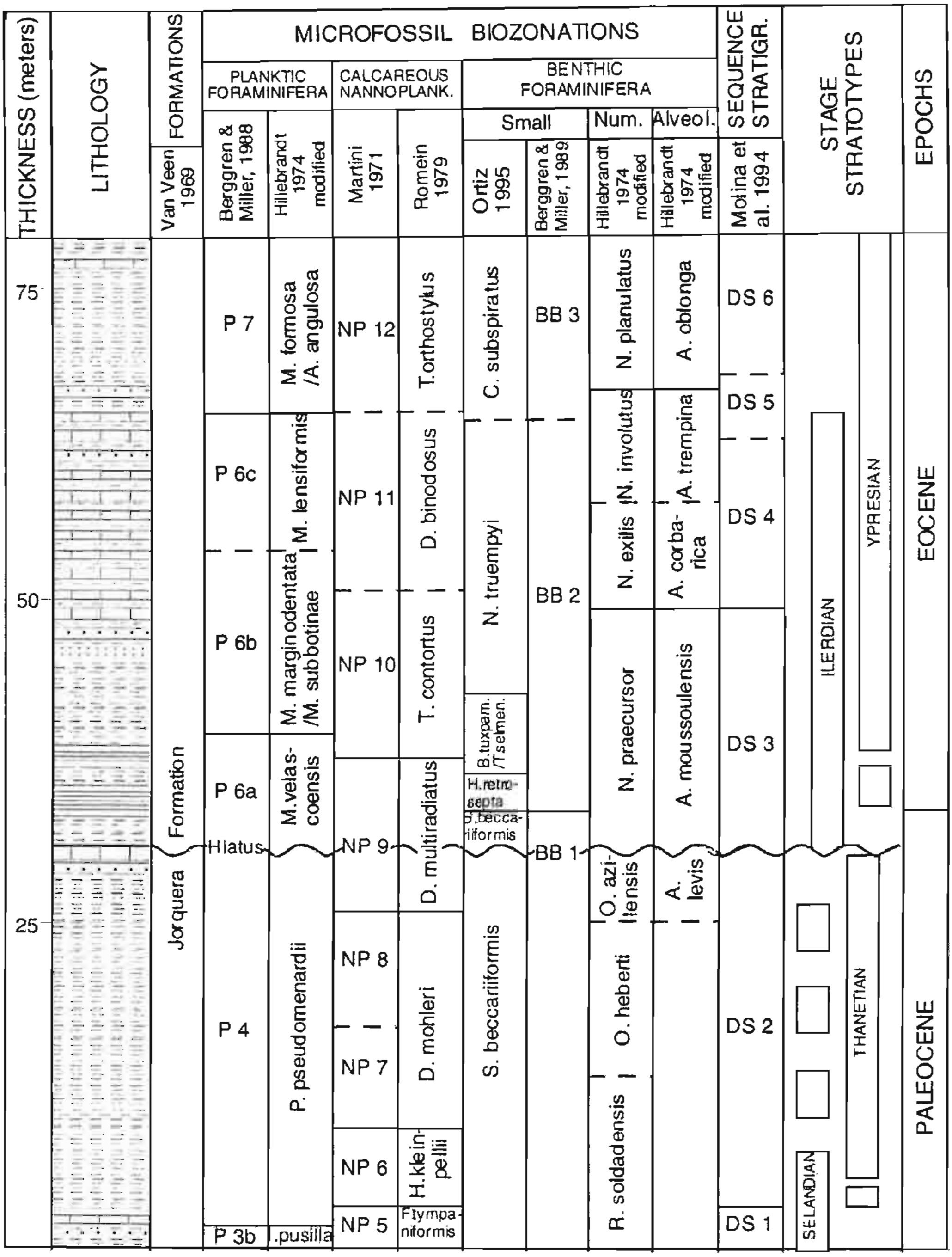

Fig. 12.- Integrated stratigraphy throughout the Paleocene-Eocene transition (modified from Molina *et al.*, 1994).

Conclusions

The high resolution study and the integrated approach allow us to establish a detailed stratigraphy of the Paleocene/Eocene transition at Caravaca. The chronostratigraphical study spans from the Middle Selandian to the Middle Ypresian. A short hiatus was detected between the P4 and P6a biozones and is evaluated at about 0.7 Ma. missing the Early Ilerdian (nummulitid *N. fraasi* Biozone and alveolinids *A. cucumiformis* and *A. ellipsoidalis* Biozones). Above the hiatus we detected significant changes in the concentration of several elements (TiO_2, MnO, Cr, Cu, Zn and REE), coinciding with a carbonate dissolution interval, a dark anoxic level, a major increase in the quartz content and excursions in $\partial^{13}C$ and $\partial^{18}O$. A high increase in temperature, a very high sea level rise, volcanism and hydrothermal activity could have caused the physical and chemical changes that caused the biotic effects observed in different groups of foraminifers. The geochemical and mineralogical shifts coincide with a mass extinction in the small benthic bathyal foraminifera at a horizon that is very reliable to place the P/E boundary because of its possibilities of global correlation and its proximity to the base of the Ypresian stratotype. The Paleocene/Eocene boundary falls within the middle part of the P6a (*M. velascoensis*) Biozone, the upper part of NP9 (*D. multiradiatus*) Biozone, the top of BB1 (*S. beccariiformis*) Biozone, the base of *N. praecursor* and *A. moussoulensis* Biozones. In conclusion, the Caravaca section is not optimal as potential Global Stratotype Section and Point for the Paleocene/Eocene boundary, mainly because of the hiatus near the boundary event, but is a very good reference section and it allows the integration of geochemistry and biostratigraphy based on different groups of microfossils.

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