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Palaeogeography, Palaeoclimatology, Palaeoecology 224 (2005) 27–52

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Nannofloral extinction and survivorship across the K/T boundary at Caravaca, southeastern Spain

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Received 7 April 2004; received in revised form 19 November 2004; accepted 23 March 2005

Abstract

Detailed qualitative and quantitative studies of the calcareous nannofloral assemblages were carried out on 65 cm across the K/T boundary interval of the Caravaca section. Preservation of nannofloral assemblages is moderate to good. Reworking was identified in the lowermost Danian, but did not essentially influence the rest of the section studied. The nannofloral study shows that most of the Cretaceous taxa disappeared in the “fallout” lamina, a bio-event which is synchronous with the mass extinction of the planktonic foraminifera and with significant geochemical anomalies. Beside these events, a rapid decline of the calcareous nannofossils is recorded in the uppermost 12 cm of the Maastrichtian (about 4 ky prior to the K/T boundary). Such decline becomes more pronounced in the transitional layer, just below the K/T boundary, therefore predating the main extinction event. This pattern is in agreement with other evidences of an unstable ecosystem and inputs of cold-water taxa in this area with typical Tethyan upper Maastrichtian nannofossil assemblages. Two successive blooms, of *Thoracosphaera* spp., followed by that of *Braarudosphaera bigelowii*, were identified at the base of the Danian. In the upper part of the studied sequence, nannoflora records are already dominated by survivor as well as by incoming taxa, showing an early pioneer calcareous nannofloral ecosystem about 25 ky after the K/T boundary mass extinction event.

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Keywords: Calcareous nannofossils; Mass extinction; Biogeography; Paleoecology; K/T boundary; Caravaca

1. Introduction

Since publication in 1980 of Alvarez et al.’s paper, a remarkable number of works have been published that focus on the Cretaceous/Tertiary boundary interval. Thus, detailed investigations of many groups of organisms have determined that a mass extinction

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event took place around the K/T boundary. This particular bioevent affected especially the planktonic faunas and floras, and in many areas it is synchronous with high geochemical anomalies of Ir, Os, Ni, etc.

The voluminous data collected in the various studies also became a base for the beginning of one of the most exciting debate within the geologic community. The most significant question related to the K/T mass extinction has been especially of its tempo: was it catastrophic or gradual? Also, another question pertains to whether or not the exact time of this bioevent could be accurately constrained. Was the mass extinction produced by a single major event (the Chicxulub meteoritic impact) or by the compounded effects of many coincident causes (such as strong tectonic movements, intense volcanism that modified the composition of the atmosphere, or changes in the distribution pattern of paleoclimatic zones)?

One of the most sensitive groups of organisms that may offer some answers related to the character of the K/T mass extinction is represented by the calcareous nannofossils. Their distribution pattern around the K/T boundary has been the subject of many published studies, with a significant number of them focused on the nannofloras related to the low- to middle-latitude successions of the K/T boundary interval (Romein, 1977; Perch-Nielsen, 1979, 1981; Thierstein, 1981; Lamolda et al., 1983; Varol, 1983; Gorostidi and Lamolda, 1991, 1995; Lamolda and Gorostidi, 1992, 1994; Aguado, 1993; Pospichal, 1994, 1995; Gardin and Monechi, 1998; Gardin, 2002; Tantawy, 2003).

The Caravaca section is known to include one of the most continuous successions across the K/T boundary interval of the European Tethys Realm, and as such it has been studied for its micropaleontological record since the past three decades. An early zonation based on planktonic and larger foraminifera was published by von Hillebrandt (1974), followed by the paper of Abtahi (1975), which also focused on both benthonic and planktonic foraminifera, and Smit (1982) on planktonic foraminifera. Romein (1977) was the first to study the detailed succession of calcareous nannoplanktons across the K/T boundary in the Caravaca section.

Micropaleontological studies of the K/T succession at Caravaca was revitalized in the last decade with the work of Smit (1990) and Canudo et al. (1991). Kaiho and Lamolda (1999) further established that a plank-

tonic foraminiferal mass extinction occurs at the stratigraphic level assigned to the top of the Cretaceous. In addition, other high-resolution geochemical studies of the section were recently published by Arinobu et al. (1999) and Kaiho et al. (1999).

The scope of the present study is to provide a detailed qualitative and quantitative temporal distribution of the calcareous nannofloras around the K/T boundary interval from the Caravaca section. The study also provides a paleoenvironmental interpretation based on the results.

2. Section studied

The Caravaca section is located in the Betic Cordillera of SE Spain, at 38°5'N latitude and 1°50'W longitude (Fig. 1). The sequence that includes the K/T boundary is exposed on the east bank of Barranco del Gredero, at 4 km southwest of the town of Caravaca.

Lithologically the K/T section is composed of marlstones and marly limestones, with a distinct 7–10 mm thick dark gray marl layer that separates the Cretaceous units from the Tertiary ones. This basal layer of the Danian, or the so-called “boundary clay layer” in the literature, contains an average of 57% insoluble residues in HCl (Kaiho et al., 1999); its lower part shows parallel lamination, whereas its upper part is somehow disturbed. The upper part of the marl layer changes gradually, becoming more enriched in carbonate, and the sediment turns light gray in color towards the top. A rusty-orange colored layer (1–2 mm thick) is found at the bottom of the marl layer, and it represents the “fallout” lamina of the literature, which contains high Ir concentrations (Smit and Hertogen, 1980). Also, a 3-mm-thick greenish transitional layer is present just below the rusty layer, and contains 41.3% insoluble residues (Fig. 1).

We estimate that the sequence studied across the K/T boundary at Caravaca (between –25 cm and +40 cm), covers the last 8.1 ky of the Maastrichtian, and approximately the first 29.9 ky of the Danian. These estimates are based on the sedimentation rate calculated by Arinobu et al. (1999) for the Caravaca section. Assuming that the depositional flux of insoluble residues was constant, these rates are considered to be approximately 3 cm/ky for the Maastrichtian and 1.7 cm/ky for the Danian. Arinobu et al. (1999) also

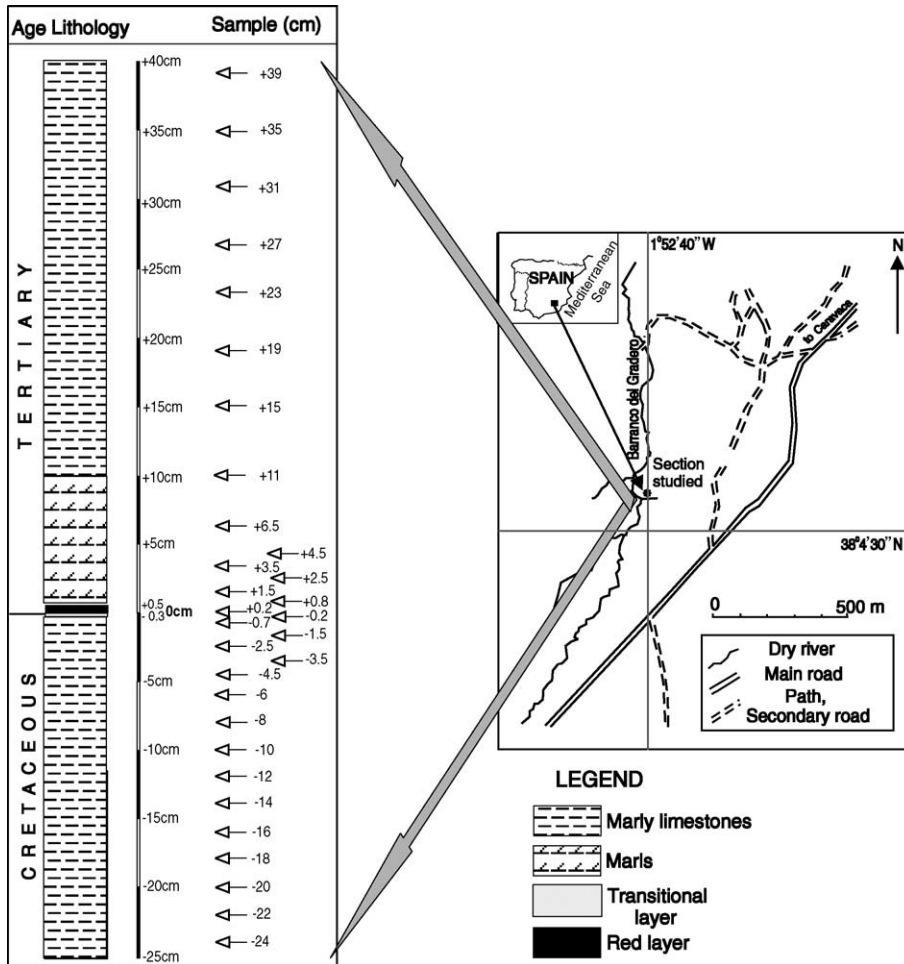


Fig. 1. Geographical location and stratigraphical column of the Caravaca section.

indicated a lower sedimentation rate of 0.8 cm/ky for the boundary marl, while the fallout lamina is assumed to be an instantaneous deposit.

Paleodepth of the Caravaca deposit have been estimated to more than 1000 m (Pat Doyle's data; after Smit, 2005), and its paleolatitude was approximately at 27°N, according to the paleogeographical maps of Smith et al. (1981).

In the first study of the nannofossils from the Caravaca section published by Romein (1977), he identified several acmes in the *Biantholithus sparsus* Zone, e.g., *Thoracosphaera operculata* and *Braarudosphaera bigelowii*. He further indicated that during the latest Maastrichtian and earliest Danian there was migration of northern cold-water species, such as

Crepidolithus neocrassus (= *Neocrepidolithus neocrassus*), *Cyclagelosphaera reinhardtii*, and *Markalius astroporus* (= *Markalius inversus*) in low latitudes areas such as Caravaca. A later study published by Gardin and Monechi (1998) included a comparison between the calcareous nannofloral assemblages present at Caravaca and those found in other K/T sections elsewhere. These authors recognized several steps in the recovery of the calcareous nannoflora ecosystem after the K/T event, but despite evidence for some stressed conditions during latest Maastrichtian they indicated that there were no major changes in such a diversified ecosystem. Romein (1977) followed Hay (1960) and Worsley (1974) in favoring a drop of temperature during the

late Maastrichtian as the cause for the extinction, which was probably triggered once temperature values fell below a critical limit of species tolerance. However, Gardin and Monechi (1998) argued that the mechanisms involved look more complex, and preferred the idea of a sudden extinction which may be correlated with a bolide impact at the end of the Cretaceous. Nonetheless, they did not rule out the plausible role of environmental perturbations during late Maastrichtian.

3. Material and methods

We collected 31 samples for nannofossil study from a 65 cm interval across the K/T boundary at Caravaca (Fig. 1), where the samples were distributed as follows: 16 were collected below the K/T boundary (the fallout lamina, noted as 0) and 15 above the zero marker level.

The samples were taken at successively 2 cm intervals, except for the K/T transitional bed where samples were collected between 0 and 0.3 cm below (noted -0.2 cm) and respectively 0 to 0.5 cm above (noted $+0.2$ cm) the boundary (Fig. 1). Samples studied are fractions of those of Kaiho and Lamolda (1999).

Preparation of the smear slides followed the procedures described in Lamolda et al. (1994). In order to achieve quantitative analyzes, at least 500 specimens were counted in each smear-slide, in randomly distributed longitudinal transverses. We, therefore, achieved a 99% ($p < 0.01$) confidence level of not overlooking any taxon present at 1% or more of the total population (Dennison and Hay, 1967).

Smear-slides were analyzed under a Nikon polarizing microscope, with $1250\times$ magnification. The individual abundance of the taxa observed was considered as follows:

- P—present: 1 specimen/ >50 Fields of view;
- R—rare: 1 s/21–50 FOV;
- F—few: 1 s/11–20 FOV;
- C—common: 1 s/2–10 FOV;
- A—abundant: >1 s/FOV.

The relative abundance of each individual taxon was calculated as a percentage from the total count

of all taxa, and absolute abundance was the number of specimens/field of view. Because *Thoracosphaera* spp. are usually fragmented, we counted as one specimen either a whole coccosphere, or fragments which represented at least 3/4 of a coccosphere. Fragments smaller than one-half of a coccosphere were added one to one, following the procedures used by Jiang and Gartner (1986) and Pospichal (1995).

4. Results

4.1. Nannofloral diversity and abundance

The Caravaca section contains well diversified, and generally well preserved calcareous nannofossil assemblages. Preservation of the taxa can be considered as moderate to good, and only a few specimens showed evidence of dissolution and/or overgrowth, which did not hinder specific identification.

We identified a total number of 88 taxa, with a maximum diversity (number of taxa/sample) of 61 recorded in the lower part of the sequence studied (sample $-17/-15$ cm), and a minimum diversity of 18 observed in the “fallout” lamina (sample $+0/+0.5$ cm). Based on the fluctuation of the diversity, the sequence that includes the K/T boundary at Caravaca can be divided as follows (Fig. 2):

- Interval I, between -25 cm and -11 cm, with well diversified nannofloral assemblages, containing 51 to 61 taxa/sample; the species *Ahmuellerella octoradiata*, *Cylindralithus biarcus*, *Eiffellithus gorkae*, *Quadrum svabenickae*, *Semihololithus* spp. and *Tegumentum stradneri* are last recorded in this interval, and they are all minor components of the assemblages.
- Interval II, between -11 cm and -0.3 cm, characterized by small changes of species richness, varying between 43 and 35 taxa/sample. About 25% of the taxa decreased as compared to the assemblages in the underlying interval I (Fig. 2). The species *Calculites obscurus*, *C. ovalis*, *Ceratolithoides aculeus*, *Ceratolithoides kamptneri*, *Discorhabdus ignotus*, *Helicolithus trabeculatus*, *Prediscosphaera spinosa*, *Zeugrhabdothus erectus* and *Tranolithus gabalus* last occurred within this

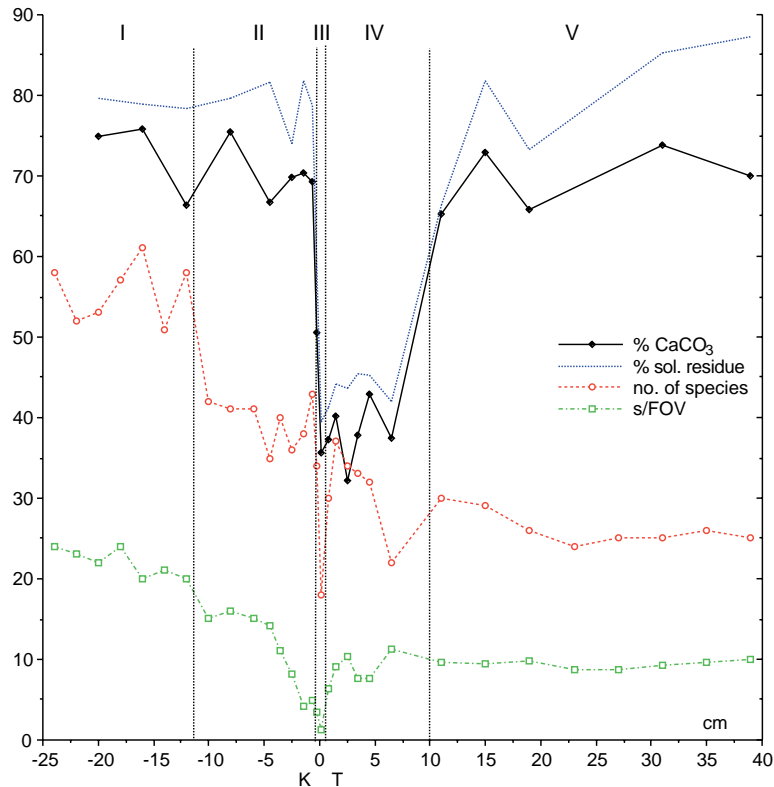


Fig. 2. Changes in the number of species, absolute abundance total nannofossils, and percentages of CaCO_3 and soluble residue in samples studies in the Caravaca section.

interval (Fig. 3), and they are all minor components of the assemblages.

- Interval III, in the transitional green layer (sample $-0.3/0$ cm) up to the fallout lamina (sample $0/+0.5$ cm), is characterized by a marked drop in diversity. The transitional layer contains 34 taxa, whereas the fallout lamina shows a significant decrease in diversity containing only 18 taxa (Fig. 2).
- Interval IV, between 0.5 and 10 cm above the K/T boundary, shows an increase in richness with the number of taxa between 22 and 37. The lowest value was observed in sample $+6/+7$ cm (Fig. 2), where the calcareous dinoflagellate *Thoracosphaera* spp. increased significantly at that level (Fig. 4).
- Interval V, between 10 and 40 cm (to the top of the sequence studied), in which diversity shows minor changes with small decreases towards the top. Number of taxa/sample varies between 30 and 24 (Fig. 2).

Fluctuation in the absolute abundance of taxa (number of specimens/field of view) follows a general pattern that coincides with the diversity curve (Fig. 2), first showing a strong decrease in the uppermost 5 cm of the Maastrichtian, from 14.1 to 3.5 s/FOV, then another drop in the fallout lamina (sample $0/+0.5$ cm above the K/T boundary) where the count of s/FOV is 1.2. By contrast, there are important differences between vanishing, persisting and incoming species (Fig. 4).

The abundance of the vanishing Cretaceous taxa has an average of 22 specimens/FOV in the interval between -25 and -6 cm, where it decreases continuously from 24 to 15 specimens/FOV. This is in contrast with the sharp decrease observed in the uppermost 5 cm of the Maastrichtian where the values drop from 14 to 3.3 specimens/FOV. Nonetheless, the most significant drop is situated in the fallout lamina (sample $0/+0.5$ cm), containing less than 0.8 s/FOV (Fig. 4).

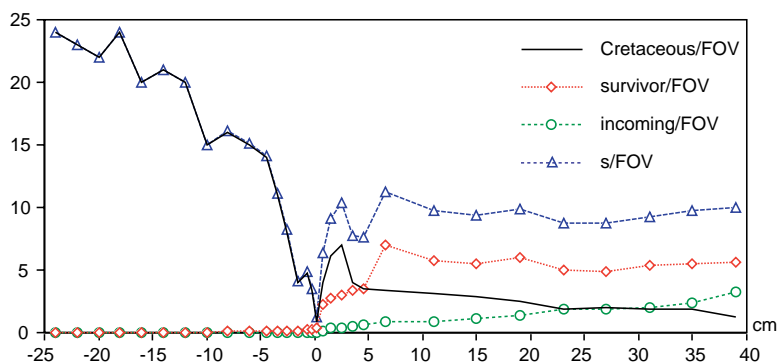


Fig. 4. Changes in the absolute abundance (specimens/FOV) of Cretaceous (vanishing), survivor and incoming taxa, and total nannofossils, in the Caravaca section.

The abundance of vanishing Cretaceous taxa shows an apparent recovery, reaching 7 s/FOV (around 70% of total encountered taxa), up to +2/+3 cm in the lowermost Danian. Above that level the Cretaceous taxa decrease continuously (Fig. 4), e.g., in sample +4/+5 cm, 3.5 s/FOV (55% of total nannofloras).

The relative abundance of the survivor taxa is very low below the K/T boundary (up to 2–5%), whereas above the fallout lamina these taxa start to increase, showing two pulses within the intermediate layer (Fig. 4). For instance, at the level of sample +6/+7 cm their relative abundance (around 65% of survivor taxa, including the calcareous dinoflagellate *Thoracosphaera*) significantly exceeds the abundance of the vanishing taxa (which represent only 30% of total nannofloras).

The abundance of the incoming Danian taxa *B. sparsus*, *Cyclagelosphaera alta*, and *Neobiscutum parvulum* continuously increases from sample 0/+0.5 cm towards the top of the sequence studied. At the level of sample +22/+24 cm the abundance of vanishing taxa is almost equal (around 20%) to that of the incoming ones. Above that level, the incoming species are more abundant than the vanishing ones, but less abundant than the survivors (Fig. 4).

4.2. Cretaceous nannofossils

Of a total of 84 Cretaceous nannofossil species encountered, only 28 have shown a consistent occurrence.

The dominant nannofloral assemblages within most of the Maastrichtian samples consist of *Micula*

spp. (20–30% from the total assemblages), *Watznaueria barnesae* (20–22%), *Prediscosphaera* spp. (5–15%), *Arkhangelskiella cymbiformis* (5–15%), and *Cribrosphaerella ehrenbergii* (9–14%) (Fig. 5). These taxa represent 70–85% of the total nannofloral assemblages. Other nannofossils identified as common in the Cretaceous assemblages of the Caravaca section are *Ahmullerella* spp., *Chiastozygus* spp., *Cribracorona gallica*, *Eiffellithus* spp., *Lithraphidites quadratus*, *Microrhabdulus* spp., and *Tetrapodorhabdus decorus* (Fig. 3).

The genus *Micula* is the most abundant, with similar percentages (around 25 to 20%), in uppermost Maastrichtian and the lowermost 5 cm of the Danian (Fig. 5). This genus is represented by the species *Micula decussata* (the most abundant of all, about 75–80% of the total *Micula* spp.), *Micula concava*, *Micula cubiformis*, *Micula murus*, *Micula praemurus*, *Micula prinsii*, *Micula swastica* and *Micula* sp.1 (sensu Pospichal, 1995; *Micula?* sp., after Pospichal and Bralower, 1992). However, not all the *Micula* species have a similar distribution pattern. In fact, *M. decussata*, *M. concava* and *M. murus* have a consistent presence below the K/T boundary, whereas *M. swastica*, *M. praemurus*, and especially *M. prinsii*, have a discontinuous occurrence, with a moderate frequency. *Micula* sp.1 (sensu Pospichal, 1995) shows a range apparently restricted to the latest Maastrichtian, being common just 5 cm below the boundary in the Caravaca section (Fig. 3).

Absolute abundance of all *Micula* spp. drops from 7.1 to 5 s/FOV at level –7/–5 cm below the K/T boundary, then further decreases rapidly to 0.9 speci-

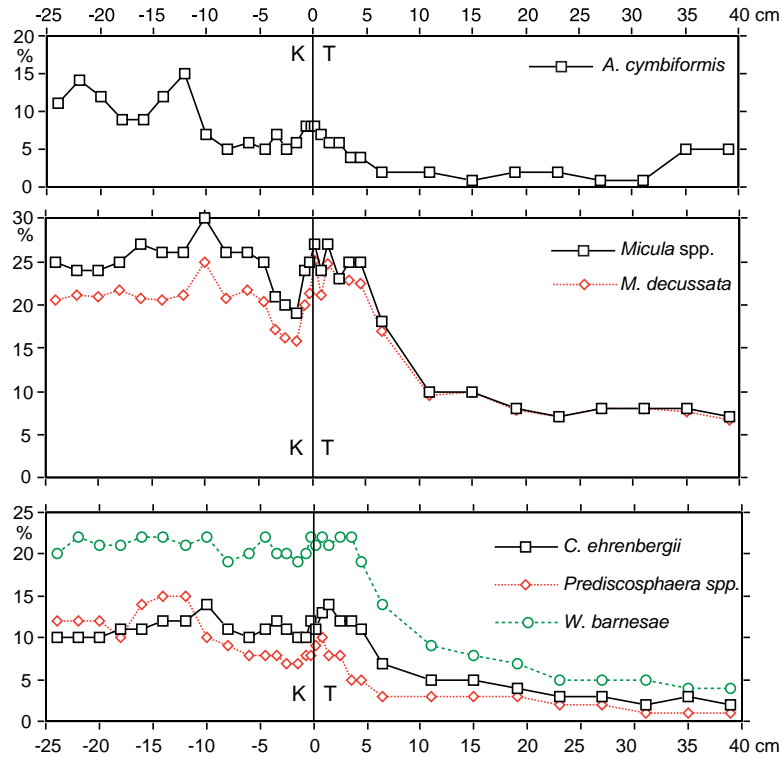


Fig. 5. Relative abundance of main nannofossil Cretaceous taxa in the Caravaca section.

mens/FOV in the sample $-0.3/0$ cm just below the K/T boundary. In the first 5 cm of the Danian there is a slight increase of *Micula* spp., with average values of 2.1 s/FOV. Farther upward its absolute abundance is lower, usually less than 1 specimen/FOV (Fig. 6).

The species *W. barnesae* is the second most frequent taxon in the Maastrichtian samples, with percen-

tages similar to *Micula* spp. up to 5 cm above the K/T boundary (Fig. 5). Its absolute abundance decreases sharply just 2 cm below the K/T boundary from about 4 to less than 1 s/FOV, and lower again (down to 0.4 s/FOV) in the fallout lamina (Fig. 6).

Prediscosphaera cretacea is the dominant species of the genus *Prediscosphaera*, as it comprises about

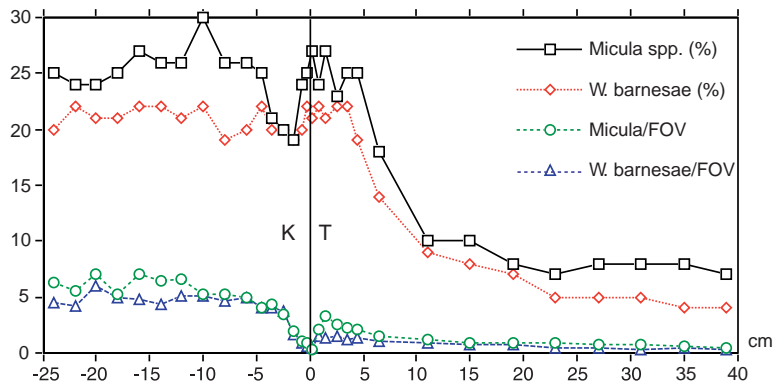


Fig. 6. Relative and absolute abundance of *Micula* spp. and *Watznaueria barnesae* in the Caravaca section.

80–85% of its total taxa. In contrast, other species such as *P. arkhangelskyi*, *P. ponticula*, *P. spinosa*, and *Prediscosphaera stoveri* are less frequent, and all together they constitute about 15–20% of all *Prediscosphaera* spp. This genus has its maximum abundance in the interval between –16 and –11 cm, below the K/T boundary (Fig. 5). Maximum abundance of *P. stoveri* also coincides with that interval (–16 to –11 cm), whereas the abundance peak of *P. cretacea* is further constrained in the sample interval –15/–13 cm, where the genus *Prediscosphaera* composes almost 16% of the total nannofloras (*P. stoveri* is 6% and *P. cretacea* almost 10%). On the overall, in the interval between –19 and –11 cm the ratio *P. cretacea*/*P. stoveri* is close to 1.5, but the relative abundance of *P. cretacea* is much higher in the rest of the samples where the ratio is around 7. Percentages of *Prediscosphaera* spp. remain similar from –10 to +3 cm across the K/T boundary, whereas above level +3 cm the values decrease permanently from 5% to 1%. Fluctuations in percentages recorded for the genus *Prediscosphaera* are similar to those previously mentioned for *Micula* spp. and *W. barnesae* (Fig. 5), except that the values for *Prediscosphaera* increase around –15 cm, coincident with the highest percentage of *P. stoveri*, as mentioned above.

C. ehrenbergii reaches its maximum within a short interval at about 10 cm below the K/T boundary, at a level slightly younger than the level of peak abundances recorded for *Prediscosphaera* spp. and *P. stoveri*. *C. ehrenbergii* reaches percentages of approximately 12% around 4–5 cm above the K/T boundary, and decreases gently to 2% above that level in the remainder of the section studied (Fig. 5).

A. cymbiformis shows a pattern of occurrence that is quite similar to *Prediscosphaera* spp., but with a more remarkable decrease around level –10 cm below the K/T boundary where it drops from 15% to 7% (Fig. 5). Small size specimens (<14 µm of diameter) of *A. cymbiformis* occur in all the Cretaceous samples studied and constitute about 60% of the species, while the rest of the specimens have diameters larger than 14 µm.

4.3. Survivors

The term survivors was applied to the Cretaceous taxa which we believed crossed the K/T boundary,

because they have a consistent and continuous occurrence in the Tertiary nannofossil assemblages, where they may even show higher abundance.

The dominant survivor taxa in the samples studied are *Thoracosphaera* spp. and *B. bigelowii*. The calcareous dinoflagellate genus *Thoracosphaera*, represented mainly by the species *T. operculata*, was identified in all the Cretaceous and Tertiary samples from Caravaca. This taxon was rare below the K/T, but became already common in the first sample collected above the K/T boundary (0/+0.5 cm). *Thoracosphaera* spp. increased significantly to a percent abundance of nearly 20% at +0.5/+1 cm above the boundary. The relative abundance of *Thoracosphaera* taxa constantly increased above this level, reaching a peak of 54% at the level of sample +14/+16 cm (the absolute abundance of survivors is 5.5 s/FOV), then slightly decreased thereafter. Their lowest value (25%; absolute abundance of survivors 5 specimens/FOV), recorded in the upper part of the sequence studied (sample +22/+24 cm), is coincident with the bloom of the nannofossil *B. bigelowii* (Fig. 7). From that level upward, the frequency of *Thoracosphaera* spp. increased again, reaching a value of 41% (absolute abundance of survivors 5 specimens/FOV) in the youngest Tertiary sample studied.

We also consider *B. bigelowii* as a major component of the survivor nannofossils, although this taxon is very rare below the K/T boundary interval at Caravaca. *B. bigelowii* became frequent, reaching 12% of the total nannofloral assemblages in sample +6/+7 cm, which is the interval where *Thoracosphaera* also increased significantly from 30 to 42%. On the whole, the percentages of *B. bigelowii* increased following the same pattern as *Thoracosphaera*. In fact, as can be seen in Fig. 7, *Thoracosphaera* reached a peak of 54% at the level of sample +14/+16 cm above the base of the Tertiary, shortly thereafter *B. bigelowii* became more abundant showing a bloom that makes up 40% of the nannofossils in sample +22/24 cm. Subsequently the relative abundance of *B. bigelowii* decreased again to 19% in the youngest Tertiary samples studied (up to +38/+40 cm).

In the Caravaca section studied *Thoracosphaera* spp. and *B. bigelowii* represent over 98% of the survivors and more than 50% of the total assemblages up to +6/+7 cm above the K/T boundary (also taking into account the Cretaceous taxa). In low–middle

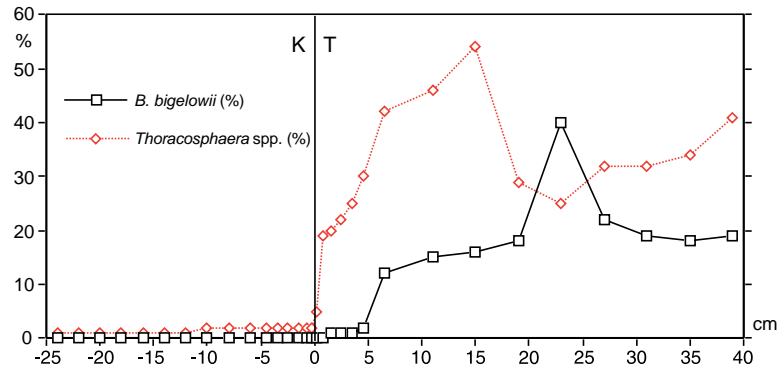


Fig. 7. Relative abundance of *Braarudosphaera bigelowii* and *Thoracosphaera* spp. in the Caravaca section.

latitude sections, two successive blooms of *Thoracosphaera* spp. and *B. bigelowii* are usually recorded. In our study, however, because we focused on a relatively short interval (40 cm above the K/T Event) of the lowermost Danian, we identified only the first of the two successive blooms of *Thoracosphaera* spp. and *B. bigelowii*.

Among other taxa, *Cyclagelosphaera margerelii* was cited by Perch-Nielsen (1985) as a survivor species of the K/T boundary extinction. Burnett (1998) also included this taxon in a list of nannofossils crossing the K/T boundary. In the Caravaca samples the occurrence of *C. margerelii* was also more consistent and more abundant in the Danian than in the Maastrichtian (Fig. 8). In fact, the distribution pattern of *C. margerelii* is similar to those of well-known survivors such as *C. reinhardtii* and *Octolithus multiplus* (Fig. 8). Other survivors that are minor components of the nannofossil assemblages encountered are

Biscutum melaniae, *Braarudosphaera alta*, *Chiastozygus ultimus*, *Goniolithus fluckigeri*, *M. inversus*, *N. neocrassus*, and *Zeughrabdotus sigmoides* (Fig. 3). All these taxa are rare and discontinuous during the Maastrichtian, but become constant within the Danian.

4.4. Incoming nannofossils

We considered as incoming taxa the nannofossils that have their first record above the K/T boundary. Hence, *B. sparsus* is described as an incoming taxon, although we should note that it was observed as rare in a sample below the boundary (−3/−2 cm). Above the K/T boundary, this species remained always rare and sporadic in the samples (Fig. 3). *C. alta* was first identified in sample +0.5/+1 cm, and showed increasing frequency in the earliest Tertiary that corresponds to the upper part of the sequence studied. It became

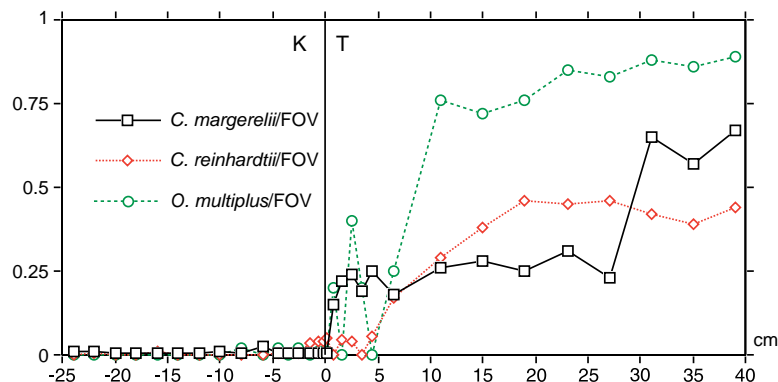


Fig. 8. Absolute abundance of the survivor species *Cyclagelosphaera margerelii*, *Cyclagelosphaera reinhardtii* and *Octolithus multiplus* in the Caravaca section.

common in sample +6/+7 cm above the K/T boundary and farther up section (Fig. 3). In fact, the genera *Cyclagelosphaera* and *Octolithus* replaced dominant forms such as *M. decussata* and *W. barnesae* in the lowermost Danian nannofloral assemblages at the level of 20 cm above the K/T boundary (1.99 and 1.65 s/FOV, Figs. 6 and 8 respectively for each group, which continues in the overlying levels).

N. parvulum is the youngest occurrence in the sequence studied, as it was first recorded in sample +2/+3 cm, where it occurs with moderate frequency and continues to increase in the Tertiary samples up to the top of the succession investigated (Fig. 3).

5. Biostratigraphy

The nannofloral biostratigraphy of the K/T boundary interval of the Caravaca section is similar with the biostratigraphy observed in other low–middle latitudes sections from Spain (Betic Cordillera, Romein, 1977; Aguado, 1993; Pospichal, 1995, and Northern Spain, Lamolda and Gorostidi, 1994), Southern France (Seyve, 1990; Gorostidi and Lamolda, 1995), Italy (Gubio, Monechi and Thierstein, 1985), Tunisia (El Kef, Perch-Nielsen, 1981; Pospichal, 1995; Èlles, Gardin, 2002), Czech Republic (West Carpathians, Bubík et al., 1999), Romania (East Carpathians, Melinte, 1999), and Bulgaria (Balkan area, Sinnyovsky and Stoykova, 1994).

The nannofossil *M. prinsii*, although present sporadically in the samples, provided the basis for zone assignment of the sequence studied at Caravaca. Thus, based on the presence of this taxon all Cretaceous nannofloras identified in the Caravaca sequence were assigned to the UC20d Subzone of Burnett (1998), to the CC26 Zone of Sissingh (1977) and CC26b Subzone of Perch-Nielsen (1985), respectively. Furthermore, *Nephrolithus frequens*, index species for the CC26 nannofossil Zone of Sissingh (1977), was identified only as rare specimens in a few samples. By contrast, the species *M. murus* is constant, usually common (1 specimen/FOV), except in the last 5 cm of the Maastrichtian (Fig. 3) where its abundance is lower (1 s/11–20 FOV).

As we indicated earlier, the nannofossil *B. sparsus* was recorded below the K/T boundary in the Caravaca section, although its presence was observed only in

one sample (–3/–2 cm). Its occurrence below the K/T boundary could be considered either as resulting from burrow contamination, or alternatively as a genuine Cretaceous taxon. In fact, although many authors commonly described *B. sparsus* as an incoming species occurring from the base of the Danian, earlier occurrences have also been reported elsewhere in the uppermost Maastrichtian (Van Heck and Prins, 1987; Perch-Nielsen in Herman et al., 1988; Pospichal and Bralower, 1992; Bubík et al., 1999). Similarly, Romein et al. (1996) reported other so called “incoming” nannofossils such as: *Neobiscutum romeinii*, *N. parvulum* and *Cruciplacolithus primus*, already from the top of the Maastrichtian in the section nearby Maastricht. Among other taxa of questionable Tertiary origination, *N. romeinii* was further identified in the Maastrichtian at Èlles, Tunisia (Gardin, 2002). These three nannofossils taxa have also been identified in upper Maastrichtian sediments from the sections at Brazos River in Texas; at El Kef in Tunisia, in Jordan, etc. (Mai et al., 2003). Thus, the wide occurrence of these taxa in Maastrichtian sediments may, in fact, reveal that these forms had already evolved at the end of the Cretaceous.

The nannofossil assemblages identified in the Tertiary sequence studied at Caravaca can be assigned to the *B. sparsus* Zone (sensu Romein and Smit, 1981) and to the *N. parvulum* Sub-zone (sensu Perch-Nielsen, 1981).

In terms of nannoflora, the Cretaceous/Tertiary Boundary of Caravaca is considered to coincide with the boundary between the *M. prinsii* and the *B. sparsus* Zones. The base of the *B. sparsus* Zone is represented by mass extinction of the Cretaceous nannofloras, which decreased in absolute abundance from 24 to 1.2 s/FOV within the last 25 cm of the Maastrichtian. This interval of rapid decline is equivalent to approximately 8 ky (Arinobu et al., 1999). Increasing frequency of *Thoracosphaera* and *B. bigelowii* (Fig. 7) also characterizes the base of the Danian.

6. Taphonomy

6.1. Preservation

We estimated the degree of preservation of the different specimens observed by using a preservation

index based on preservation criteria proposed by Roth and Thierstein (1972), as follows: P=poor, severe dissolution, fragmentation and/or overgrowth; the specific identification is hindered up to 75%; M=moderate, dissolution and/or overgrowth; the specific identification is hindered up to 25%; G=good, little dissolution and/or overgrowth; diagnostic characteristics are preserved, the specimens could be identified to species level (up to 95%).

W. barnesae is considered to be a good index taxon to indicate alteration of the assemblages (Roth and Krumbach, 1986; Lamolda et al., 1994). This species is one of the Cretaceous nannofossils most resistant to dissolution and diagenesis, therefore assemblages containing more than 40% of its specimens are seen as heavily altered (Roth and Krumbach, 1986). Beside these factors, consideration should also be given to the assumptions that *W. barnesae* increases as well under low productivity conditions (Erba et al., 1995). Furthermore, *W. barnesae* seems to also be more characteristic of low–middle latitude areas, being rare in high-latitude sites (Pospichal and Wise, 1990; Švábenická, 1999; Tantawy, 2003).

Interpretation of the percentages of *W. barnesae* also has a more complex implication when *M. decussata* occurs, as it does in Maastrichtian samples (Gorostidi and Lamolda, 1995). Indeed, both species are known to be dissolution resistant, but they are related to different paleolatitudinal domains (*W. barnesae* at low to middle latitudes, and *M. decussata* at high latitudes). For instance, as shown in Fig. 5, *W. barnesae* varies between 19% and 22% of the total nannoflora assemblages in Cretaceous samples, and up to the first 5 cm above the K/T boundary. These variations are concurrent with those of *M. decussata* that shows values between 16% and 25%. Both taxa have a minimum value of 19% and 15.8%, respectively, at level 1.5 cm, below the K/T boundary, and an increase of several percent points just below and above the boundary (Fig. 5). Increases of these two taxa are certainly not a clear index of worst preservation, because specimens in those samples have moderate to poor, or moderate to good preservation and, even, a good preservation between +1 and +5 cm (Fig. 3). These values are similar to those found at Bidart, within the last 40 cm of the Maastrichtian, where preservation is also moderate (Gorostidi and Lamolda, 1995). Also, both species have similar percentages at

Agost, but the trend is slightly different especially with *M. decussata*. This species shows a marked increase just within the 10-cm interval below the K/T boundary where specimens have moderate to poor preservation, as compared to specimens from underlying levels, which have moderate preservation (Pospichal, 1995).

Species richness undergoes moderate changes in the last 11 cm of the Maastrichtian (Fig. 2), where its values fluctuate between 43 and 34, with the higher value immediately below the transitional layer and the lowest value just below the K/T boundary in the transitional layer. Excluding the last 1 cm of the Cretaceous, changes between maximum and minimum values represent 17%, although there is no clear trend (Fig. 2). At similar levels in the Bidart section taxonomic counts feature about 30 species/sample, but the total number of 69 species found is less than at Caravaca where 88 species were recorded. Values are similar at Agost, except for the samples within the top 5 cm of the Maastrichtian (Pospichal, 1995). At that locality count values are slightly higher with 41 and 52 species, whereas at Caravaca the values are 38 and 37. Such changes do not seem to be related to respective preservations.

There is no particular distinctive characteristic in the preservation of the Maastrichtian samples studied (Fig. 3), as in fact they yielded nannoplankton specimens of moderate preservation with minor modifications, except for one sample that showed distinctly poor preservation. The transition interval between 10 cm below and 5 cm above the boundary, showed fluctuation in preservation that changed from moderate to poor, moderate to good, and good, but these variations do not follow the trend of absolute abundance and species richness (Figs. 2 and 3). In fact, the temporal pattern of nannofossil preservation does not coincide with intervals characterized by variations in absolute abundance or number of species. Therefore, changes of both absolute abundance and species richness in that critical interval around the K/T boundary must be related to controlling factors other than preservation.

6.2. Reworking

Evidence for definite reworking is found essentially in samples from the uppermost Maastrichtian which

include taxa such as *Amphyzigus brooksii*, *Quadrum gartneri*, *Reinhardtites levis* and *Uniplanarius gothicus*, previously reported to have become extinct in the late Campanian–early Maastrichtian interval. Such phenomenon may be of importance as, for instance, *Q. gartneri*, occurs in the lowermost samples studied at level –25 cm from the boundary (Fig. 3), and its frequency is recorded even as ‘common’ species (1 s/2–11 FOV). At Agost this same taxon occurs irregularly up to the stratigraphic levels corresponding to the Danian (Pospichal, 1995), although it is not mentioned as a reworked taxon by that author. At Caravaca Romein (1977) further identified *Lucianorhabdus cayeuxii* and *Nannoconus* spp., as reworked taxa, both of them are rare in Danian samples close to the K/T boundary. The changes that we recorded in the percentages, and absolute abundances of Cretaceous species throughout the lower Danian have been related to reworking of Cretaceous taxa in the Danian rock (Percival and Fisher, 1977; Romein, 1977; Maurrasse et al., 2005, and others).

The Danian samples that we analyzed show a maximum of absolute abundance of Cretaceous species (mainly *Micula* spp. and *W. barnesae*) around 2 to 3 cm above the K/T boundary (Fig. 5). This interval is almost coincident with a secondary $\delta^{13}\text{C}_{\text{max}}$, in the fine fraction that occurs between 2 and 4 cm above the K/T boundary (Fig. 1 in Kaiho and Lamolda, 1999). The close proximity of these two maxima leads us to argue in favor of the input of Cretaceous reworked nannofossils as the cause of this $\delta^{13}\text{C}$ positive excursion during the earliest Danian. This argument is further supported by concurrent increase, within the Danian interval studied, in the number of Cretaceous planktonic foraminifera tests (Fig. 1 in Kaiho and Lamolda, 1999) which these authors also considered as reworked specimens. Thus, all these data provide support for the reworking origin of Cretaceous species recorded in our Danian samples.

Another factor to consider relevant to possible mixing of taxa from different stratigraphic levels, either from the Maastrichtian into the Danian, or vice versa, is related to burrow filling associated with burrowing activity during the earliest Danian. Actually, in the Caravaca section, some burrows across the K/T boundary penetrate 10 to 12 cm deep into the Maastrichtian. Nonetheless, there is no apparent reciprocal mixing of lowermost Danian taxa into

the uppermost Maastrichtian caused by bioturbation. Besides evidence from the fossil record, biomarkers (pyrosynthetic compounds shown in Fig. 1 of Arinobu et al., 1999) show a narrow peak just above the K/T boundary (sample 0/+0.5 cm) consistent with a geologically instantaneous event related to combustion of a large proportion of the above-ground terrestrial biomass (Arinobu et al., 1999). In the intermediate layer, at sample level –0.3/0 cm below the K/T boundary, the values of these biomarkers are less than 1/5 of those documented above the boundary, which may indicate some degree of downward export probably caused by infilling from the overlying basal Danian layer. This pattern is similar to the Ir peak (Smit and Ten Kate, 1982). No additional evidence, neither from $\delta^{13}\text{C}$ (both carbonate and kerogene), Benthic Foraminifera Oxygen Index (BFOI), nor other indices (Kaiho et al., 1999) support mixing of sediments from the superjacent Danian sediments into the uppermost Cretaceous levels of the K/T boundary at Caravaca. As discussed previously, a minor exception may be argued for infilling of very small particles bearing Ir and the biomarkers found in the intermediate layer just below the boundary.

7. Extinction and survivorship patterns

The results of our study of the calcareous nannofossil allow us to identify a pattern of nannofloral extinction and survivorship across the K/T boundary in the Caravaca section.

Among other possible causes, we recognize that the absolute abundance of the nannoflora taxa is also controlled by the sedimentation rate. Aware of this aspect, since our values have not been corrected to take account of sedimentation rates (Arinobu et al., 1999; see Section 2 above), we caution that absolute abundance values reported for the Danian might be lower than estimated. This may apply especially for the boundary marl, which is relatively condensed with respect to Maastrichtian sediments.

It is frequently argued in the literature that absolute abundance values are complementary to those of relative abundance (percentage of different taxa in fossil assemblages). Nonetheless, when all facts are considered, the resulting patterns of relative abundance of a taxon are dependent on changes of accompanying

taxa. Therefore, the absolute abundance of a given taxon may remain the same while its percentage change, conversely its absolute abundance may change but its percentage does not, e.g., if other taxa modify their absolute abundance accordingly. Such oversight may be misleading in paleoecological analyses, e.g., some changes in patterns of abundances might be actually artifacts (Paul, 1992).

At Caravaca, Cretaceous nannofloral diversity and abundances are high in the lower part of the section studied (interval between –25 cm and –11 cm), then they decline toward the boundary marl. Taking account of the sedimentation rate, this first nannofloral decline took place around 4 ky prior the K/T event. A second decline is recorded within the top 5 cm of the Maastrichtian, which is mainly reflected in the absolute abundance that drops from 15 to 4.9 specimens/FOV in sample –1/–0.3 cm below the K/T boundary. By contrast, species richness shows no corresponding changes, as there are about 40 existing species during this interval, which is approximately 2 ky prior to the K/T event (Fig. 2).

The distribution pattern in the absolute abundance of survivor species shows a trend contrary to the one shown by the vanishing Cretaceous taxa. In fact, this category of taxa shows a twofold expansion above stratigraphic level –10 cm (0.05 s/FOV), then another increase at –5 cm (0.1 specimen/FOV), to eventually reach values up to 0.2 s/FOV at –1/–0.3 cm below the K/T boundary (Fig. 4). *Thoracosphaera* spp. is the main component in this category, except for the top 5 cm of the Maastrichtian, where *M. inversus* is the main component of the survivor taxa.

From the green transitional layer (sample –0.3/0 cm), which covers the last 0.15 ky prior to the K/T event, to the rusty lamina (sample 0/+0.5 cm) the trend in diversity and absolute abundance of vanishing and survivor Cretaceous species is the following:

- diversity dropped from 43 to 34 species/sample in the transitional layer, and to 18 in the rusty lamina;
- absolute abundance of the Cretaceous taxa decreased from 4.9 to 3.5 specimen/FOV in the transitional layer, and to 1.2 specimen/FOV in the rusty lamina (Fig. 2).

Increasing abundance of the survivors from 0.2 to 0.4 specimen/FOV (including also the calcareous

dinoflagellate *Thoracosphaera*) is observed from the transitional layer to the rusty lamina. In fact, *Thoracosphaera* shows a twofold increase in absolute abundance.

Our study also shows that some vanishing Cretaceous taxa recur in the interval just above the rusty lamina (up to +5 cm above the K/T boundary, or the first 4 ky of the Danian), where they may again reach pre-boundary values. They show increase in species richness as well as in absolute abundance. The main components of the Cretaceous assemblages, *M. decussata*, *W. barnesae*, *A. cymbiformis*, *C. ehrenbergii* and *Prediscosphaera* spp., increase in percentages in the boundary marl (Fig. 5). However, *M. decussata* and *W. barnesae* represent together up to 48% of the total nannofloras in the basal Danian sediments, whereas they constituted 38% of the assemblages at level –2 cm, below the K/T boundary (Fig. 5). Such a pattern could also be interpreted, in part, as a taphonomic enrichment, e.g., both species are known as the most dissolution resistant Upper Cretaceous nannofossils.

These levels also show a marked increase in the absolute abundance of survivor species, which are also part of the main components of the nannofossil assemblages. Their absolute abundance changed from 2.2 to 3.5 specimens/FOV, especially *M. inversus*, which constitutes between 7% and 4.5% of the assemblages in the lowest part of the Danian, and *Thoracosphaera* spp., which forms 25% to 30% of the assemblages, at slightly higher up in the section. Incoming species are in reduced number at first, but they rapidly increase from 0.1 s/FOV at level 0.8 cm to 0.55 s/FOV at 4.5 cm above the K/T boundary (Fig. 4).

Above 5 cm of the K/T boundary, the vanishing Cretaceous taxa diminished from a maximum of 3.4 to a minimum of 1.2 specimens/FOV (Fig. 4). These taxa include all five major components of the Cretaceous nannofloral species listed above, which decrease considerably in their percentages (Fig. 5), and especially in absolute abundance. By contrast *Thoracosphaera* spp. increases significantly in frequency (Fig. 7), and its peak of relative abundance in sample +14/+16 cm is preceded by the first successive occurrences of the incoming Paleocene taxa *B. sparsus*, *C. alta* and *N. parvulum* (Fig. 3). The absolute abundance of incoming and vanishing species is similar at level +23 cm, where they reach values of 1.9 and 1.8

s/FOV, respectively (Fig. 4). Above this level the incoming species are always more abundant than the vanishing ones.

Our data for the interval studied in the Caravaca section indicate that below the K/T boundary the Cretaceous assemblage is stable and well diversified up to about level –25 cm. From that level up to –10 cm below the boundary, the assemblage is affected by a decline of 37% in absolute abundance within an estimated time interval of approximately 4.5 ky. This initial deterioration intensified strikingly during the last 4 ky prior to the K/T event, with an additional drop of 77% in absolute abundance. In fact, the fluctuation pattern observed outlines a parabolic curve with values of 3.5 specimens/FOV just below the K/T boundary (Fig. 4). These particular decreases in absolute abundance of nannofossils have not been found in other sections elsewhere, e.g., Bidart in southwestern France (Lamolda and Gorostidi, 1994), El Kef in Tunisia (Pospichal, 1994), Agost in southern Spain (Pospichal, 1995), El Mimbral and El Mulato in eastern Mexico (Pospichal, 1996), and Èlles in north-western Tunisia (Gardin, 2002). Perhaps, this discrepancy was caused by sampling resolution, because at Caravaca our sampling density was higher compared to the sampling densities reported in those sections. Fossil preservation and completeness of the sections are other possible factors that may be invoked to explain the differences. For instance, the sections at El Mimbral and El Mulato (Mexico), and Èlles (Tunisia) have no helpful sedimentological characteristics to ensure their completeness. Such uncertainties make it difficult to ascertain a direct comparison between our data from Caravaca and those from the sections mentioned. By contrast, the section at Wadi Hamama of the central Eastern Desert region of Egypt shows that absolute abundance of nannofossil assemblages decrease throughout the last 45 cm of the Maastrichtian in the *M. prinsii* Zone (Fig. 7 in Tantawy, 2003). This pattern in the Egyptian section is remarkably similar to our data from Caravaca, and sampling density of both sections were carried out at high resolution close to the K/T boundary transition interval. Nevertheless, coevality of the decreases observed at Caravaca and Egypt remains to be established with certainty, because Tantawy (2003) reported a hiatus in the Egyptian section just at the level of the K/T boundary.

At Caravaca, the period of rapid decrease in the abundance patterns of dominant nannofloras such as *Micula* spp. and *W. barnesae* is coincident with a fast increase of survivor species by a factor of ten, mainly the well-known disaster dinoflagellate *Thoracosphaera*, and the survivor nannofossil *M. inversus*. Comparable increases of *Thoracosphaera* (1% to 2%) in uppermost Maastrichtian sediments have been reported elsewhere from several sections in Spain and southwestern France (Gorostidi and Lamolda, 1995). Recently similar observations have been reported in the central Eastern Desert sections of Egypt (Tantawy, 2003), and the Southern Peninsula of Haiti (Aguado et al., 2005) where relative abundances of *Thoracosphaera* may vary from 3% up to 5%, or even up to 7% and 8%, throughout several meters within the *M. prinsii* and part of the *M. murus* nanofossil Subzones.

Several nannofossils, such as *A. octoradiata*, *C. obscurus*, *C. ovalis*, *C. aculeus*, *C. kamptneri*, *C. biarcus*, *D. ignotus*, *E. gorkae*, *Gartnerago segmentatum*, *H. trabeculatus*, *Kamptnerius magnificus*, *N. frequens*, *P. spinosa*, *Q. svabenickae*, *Semihololithus* spp., *T. stradneri*, *T. gabalus* and *Z. erectus* have their last record of occurrence within the last 25 cm of the Maastrichtian interval studied at Caravaca. As shown in Fig. 3, we should note that most of these taxa are rare and have a discontinuous temporal record in the samples studied. Therefore, we do not favor their latest Maastrichtian extinction as a stepwise extinction, because we cannot rule out the possibility of an artifact of preservation and/or palaeoecological setting (the Signor–Lipps effect—false extinction, discussed by Gardin (2002) for the K/T boundary at Èlles, Tunisia). Moreover, the range (FO and LO) of some these taxa (e.g., *C. kamptneri*, *Semihololithus* spp.) may show apparent diachrony due to the effects of paleolatitude (Self-Trail, 2002).

We pointed out previously that the upper part of the section studied above the K/T boundary is characterized by a decrease of the Cretaceous taxa, and by the dominance of the survivors. This pattern is well illustrated by *Thoracosphaera* and *B. bigelowii*, which have their successive blooms in the interval between +15 and +22 cm, with 54% and 40% of the total assemblage, respectively (Fig. 7). Other survivor species, such as *C. margerelii*, *C. reinhardtii* and *O. multiplus*, also became important components, repre-

senting 8% to 12% of the total nannofloras. If we agree that the Cretaceous taxa that include the five major components listed above are reworked in the Tertiary sediments (fact indicated by their distribution pattern as described in the Taphonomy section above), hence the genera *Cyclagelosphaera* and *Octolithus* represent together 25–30% of the in situ assemblages. Incoming nannofossils became a significant component of the assemblages beginning only at about 30 cm above the K/T boundary, although their absolute abundance is only half that of the survivor species (Fig. 4).

The temporal distribution of nannofloral assemblage patterns observed at Caravaca can be argued to represent a typical scenario following a biotic crisis proposed by the model presented by Kauffman and Harries (1993). The features exhibited imply stressful environmental conditions leading to the first successive blooms of disaster taxa such as *Thoracosphaera* and *B. bigelowii*, and afterwards they show small changes upwards of their respective blooms.

8. Paleocology and biogeography

The palaeobiological changes documented by the calcareous nannofossils across the K/T boundary took place in a time interval marked by multiple geological events. Undoubtedly, this period was marked by strong tectonic movements related to the Laramian orogenic phase, and high volcanism (e.g., Decan Traps), which may have affected atmospheric composition, ocean circulation and the distribution pattern of palaeoclimatic zones (Frakes and Francis, 1990; Hay, 1995; Matsukawa et al., 1995). In addition to these activities, Barrera and Savin (1999), studied $\delta^{18}\text{O}$ fluctuations in the Southern and Northern Atlantic, the Indian, and the Pacific oceans, and argued that global temperatures increased by 3–4 °C between 66.3 and 65.5 Ma, followed by a cooling interval at 65.2 Ma. More cooling episodes were apparently recorded at Èlles (Tunisia), as Keller et al. (2002), based on oxygen isotope study, advocated climatic oscillations in the latest Maastrichtian with three cooling intervals at 65.50–65.55 Ma, 65.26–65.33 Ma, and 65.04–65.12 Ma, respectively. In addition, major changes in ocean circulation during the Maastrichtian may have led to deep-water flow reversed from equatorial

to the polar regions (Hay, 1995). These perturbations in the late Maastrichtian were most likely aggravated by the assumed bolide impact at the end of the Cretaceous, which added catastrophic changes to the ecosystems. The compounded effects of climatic deterioration and rapid fluctuations in sea-level affected mostly low- to mid-latitude planktonic organisms, and particularly the nannofloras that are very sensitive to environmental changes (Wind, 1979; Wise, 1983; Lamolda and Gorostidi, 1994; Gardin and Monechi, 1998; Gardin, 2002).

The presence of certain nannofossil taxa (Fig. 3), such as *C. aculeus*, *C. kamptneri*, *Cylindralithus sculptus*, *L. quadratus*, *M. murus* and *M. prinsii*, identified as low–middle latitude forms (Worsley and Martini, 1970; Perch-Nielsen, 1979, 1985; Thierstein, 1981; Wagreich and Krenmayr, 1993; Burnett, 1998; Tantawy, 2003), and *Micula* sp. 1 (sensu Popichal, 1995), which is probably also restricted to low–middle latitudes, allows us to infer that the main biogeographic character of the uppermost Maastrichtian nannofloras from Caravaca is Tethyan.

Our inference agrees with previous studies which indicated an inverse relationship between the occurrence of *M. decussata* and both *W. barnesae* and *C. margerelii*, during late Campanian and middle Maastrichtian (Wind, 1979). Spatial relationships showed that *W. barnesae* and *C. margerelii* are more abundant in samples from locations attributable to low and middle latitudes, whereas *M. decussata* is more numerous in high latitudes. Doeven (1983) confirmed this relationship in Campanian and Maastrichtian samples from the Atlantic margin of Canada, and proposed a *Micula* spp. temperature value: (*M. decussata*+*M. concava*)/*W. barnesae*+*C. margerelii* as a paleotemperature index. This ratio changes between 1.2 and 0.8 in the Cretaceous samples studied at Caravaca, and these values are similar to those found at Bidart and Zumaya at the same stratigraphic levels with respect to the K/T boundary (Gorostidi and Lamolda, 1995). However, a cold interval reported at those localities has not been found at Caravaca, perhaps it would have been recorded in samples older than ours. In fact, considering similar sedimentation rate at both sites, in the Bidart section it is between 1 and 2 m below the K/T boundary, whereas the lowermost interval studied at Caravaca is only 25 cm below the boundary.

Some taxa normally confined to cold-temperate waters also occur in the uppermost Maastrichtian nannofloral assemblages at Caravaca. They include the following species: *P. stoveri*, *K. magnificus*, *E. gorkae* and *N. frequens* (Worsley and Martini, 1970; Perch-Nielsen, 1979; Thierstein, 1981; Burnett, 1998; Wagreich et al., 1999; Švábenická, 1999; Lees, 2002; Ovechkina and Alekseev, 2005), with occurrences that are poor or rare, or even discontinuous in the last 10 cm of the Maastrichtian (Fig. 3). *P. stoveri* is an exception, because it has a relative percentage of 6% of the total assemblage at level –15 cm below the K/T boundary. Similarly, *M. inversus*, another species common in northern latitude sites, exhibits a relative maximum at the top of the Maastrichtian in Caravaca (last 5 cm), as was previously noted by Romein (1977). These relative maxima can be correlated with the same trends observed just below the K/T boundary at Èlles in Tunisia (Gardin, 2002) that have been interpreted as cold-water pulses. It is of interest to note that a similar event is also reported at Beloc, Haiti (Aguado et al., 2005).

Further evidence to indicate unfavorable conditions heralding the K/T boundary extinction was discussed by Girgis (1989), who recognized that the trend of increasing size in *A. cymbiformis* from the Campanian to the Late Maastrichtian was reversed about 2.5 m below the K/T boundary in sections he studied in the Sinai (Egypt). He described that particular interval below the K/T boundary to be distinct, because most specimens of *A. cymbiformis* have smaller size than usual. These dwarf specimens in the assemblages coincide with levels with increasing *T. operculata*, and a drop in absolute abundance of nannofossils with respect to the underlying beds. These observations were corroborated at Caravaca, where all the Cretaceous samples studied include 60% of small specimens (<14 µm) of the species *A. cymbiformis*. Lamolda and Gorostidi (1994) discussed a similar trend in the section at Bidart (southwestern France), thus providing further supporting evidence that suggests instability of the ecosystem at the end of the Cretaceous. Since the trend observed for *A. cymbiformis* is also synchronous with the other indices discussed above, it further reinforces the idea of an unstable environment at that time. Stressed environmental conditions are especially shown by a decrease in absolute abundance of nannofossils close to the K/

T boundary: first with the rare species, and later with the common and abundant taxa, e.g., *W. barnesae* and *Micula* spp., mainly *M. decussata* as the dominant species of this genus (Figs. 4 and 5).

Despite these nannofloral changes that could have ensued from stressed conditions, as observed in previous studies of the Caravaca section (Gardin and Monechi, 1998), the relative abundance of *Cribrosphaerella* (*C. ehrenbergii*), and *Prediscosphaera* spp., increased at stratigraphic levels between –15 to –10 cm below the K/T boundary. The minor discrepancy between these two taxa is that *Prediscosphaera* increased shortly before *C. ehrenbergii* (Fig. 5). A similar increase in *Prediscosphaera* spp. was also recorded in the Agost section around 10–15 cm below the K/B boundary, although the percentage for *C. ehrenbergii* is more disparate (Pospichal, 1995). The pattern of abundance of *Prediscosphaera* spp. also showed a corresponding relative increase just below the K/T boundary in the Bidart section (Gorostidi and Lamolda, 1995). Gardin and Monechi (1998), and Gardin (2002) reported the same trend in both taxa in their studies of Caravaca and Èlles sections, respectively. Since Erba et al. (1995) indicated that these taxa may bloom during relative availability of nutrients in surface waters, Gardin and Monechi (1998) argued that such variations might signal some perturbations of surface-water conditions prior to the K/T boundary.

The problem concerning the influence of definite environmental parameters on the composition of nannofloral assemblages is further illustrated by taxa commonly placed in tropical realms, which are also found at Caravaca. For instance, the Caravaca assemblages observed have shown the same characteristic features as upper Cretaceous nannofloral tropical assemblages, which Lees (2002) reported to be well diversified and characterized by abundant *M. staurophora* (= *M. decussata*) and *W. barnesae*. It would also appear that increased nutrients availability would produce increases of r-selected taxa such as *A. cymbiformis*, *C. ehrenbergii*, *K. magnificus*, *M. murus*, *M. staurophora*, *N. frequens*, *Prediscosphaera* spp., *W. barnesae*, etc. (Lees, 2002). The pattern observed in the Caravaca section implies that if a nutrient superabundance caused increases of *Prediscosphaera* spp. and *C. ehrenbergii*, concurrent presence of *A. cymbiformis* and *M. decussata* would support such

assumption (Fig. 5). Nonetheless, other important concurrent taxa e.g., *Biscutum* and *Zeughrabdotos*, cited by Erba (1992) as characteristic of nutrient-rich waters, are absent or rare in the Maastrichtian samples studied (Fig. 3). Therefore, if other local factors such as controlling ambient ecological conditions on productivity, and preservation, had no influences on taphonomy, a definite interpretation of these occurrences related to nutrients availability is conjectural and inconclusive.

Another interesting observation on the debate over the relationship between certain environmental factors and the occurrences of specific taxa in upper Cretaceous sediments concerns *Thoracosphaera* spp., which is recorded everywhere in uppermost Maastrichtian strata. In present environments of the Gulf of Mexico its occurrence is related to unstable planktonic ecosystems, e.g., high-salinity water (Gaarder and Hasle, 1971). In the upper Cretaceous sediments studied in the Caravaca section, its abundance began at around 1% of the nannofossil assemblages, and increased to 2% at the end of the Cretaceous. Elsewhere, its relative abundance is even higher at localities in the Eastern Desert of Egypt (Tantawy, 2003), and Beloc, Haiti (Aguado et al., 2005). Singularly, at the Haitian site *Thoracosphaera* spp. has a relative abundance of 7% to 8% around 40 cm below the K/T boundary (Aguado et al., 2005; see also Section 7, above). In the Wadi Hamama section (Egypt) survivor species (mainly *Thoracosphaera* spp.) gently increased throughout the *M. prinsii* Subzone, while nannofossil absolute abundance decreased (Fig. 7 in Tantawy, 2003). This contrasting trend of the assemblages is not readily correlated with lithology, nor does it seem to be controlled by preservation, because species less resistant to dissolution are well represented (Tantawy, 2003). Hence, these recent findings further strengthen the role of *Thoracosphaera* as an ecological indicator of uppermost Maastrichtian planktonic ecosystems, which may have been presumably more unstable earlier than the record indicated at certain sites elsewhere.

Thus, the stratigraphic record at certain localities argues in support of certain changes in the nannofloral assemblages that may be related to temperature, nutrient or salinity variations that even predated the decrease of nannofossils recorded in the last 10 cm of the Maastrichtian (Fig. 2). Indeed, neither preser-

vation (see Section 6 on Taphonomy above), nor sedimentation rate seems to have a main role in those records, as percentages of CaCO₃ or soluble residues show minor changes (Fig. 2). Therefore, based on these data, changes observed at Caravaca are consistent with previous studies at Zumaya (Lamolda and Gorostidi, 1994), and at Bidart (Gorostidi and Lamolda, 1995) that implied some relation with the K/T boundary extinction events.

Lowermost Danian nannofloral assemblages at Caravaca include components attributable to low- and high-latitude realms, e.g., the survivor taxon *O. multiplus*, which is more related to low–mid latitude regions and became common in the lower Danian deposits of the section studied. *O. multiplus* blooms have also been reported at slightly younger levels of the Danian in the nearby Agost section (Pospichal, 1995), as well as in the section at Caravaca (Romein, 1977). We should also point out by comparison that *O. multiplus* has been found with lower frequency in samples of sections from northern Spain (Gorostidi and Lamolda, 1991; Lamolda and Gorostidi, 1992), and in southwestern France (Seyve, 1990; Gorostidi and Lamolda, 1995), which is a spatial distribution pattern in agreement with its known preferences for lower latitude sites.

The calcareous dinoflagellate *Thoracosphaera*, a taxon that is remarkably common to abundant at the base of the Tertiary in the Caravaca section, is commonly reported to be more confined to lower to middle latitude sites (Worsley and Martini, 1970; Worsley, 1974) and it flourished in warm-water similar to those recorded in present-day tropical environments. Also, other factors associated with its occurrence imply that its distribution pattern seems to reflect environmental changes and unusual marine conditions (Hildebrand-Habel et al., 1999; Gardin, 2002). *Thoracosphaera* blooms following the K/T event may thus parallel episodes of strong environmental stress as could be related to higher amount of CO₂, fluctuation in salinity and pH of marine waters, or considerable warming within a short interval. Such unusual blooms may also reflect a lack of competition with other planktonic organisms (e.g., coccoliths). Stressed in ecological conditions at that time may be further expressed by the *B. bigelowii* peak, which occurred shortly after the *Thoracosphaera* bloom (Fig. 7). Although its ecological stimuli are probably less well constrained, *B. bigelowii* bloom is believed

to indicate abrupt change in salinity (possibly brackish environment—after Tappan, 1980), low productivity, and lack of nutrients. Also, *B. bigelowii* seems to prefer marginal seas and eutrophic environments (Cunha and Shimabukuro, 1997).

M. inversus is considered to be common to abundant in lowermost Danian sites from northern latitudes (Worsley, 1974). We also identified this species as common in samples at the base of the Danian at Caravaca. Other nannofossils, listed by some authors as having boreal affinities, e.g., *C. reinhardtii*, *N. neocrassus* and *Z. sigmoides* (Romein, 1977; Perch-Nielsen et al., 1982; Pospichal and Wise, 1990), were identified as well in the lowermost Danian succession of Caravaca.

The nannofloral abundance patterns presented above for the Caravaca section argue for the presence at the base of the Danian of low–middle latitude nannofloral assemblages including components which occur preferentially in cold-water environments. This mix signal is similar to that found at Agost (Pospichal, 1994), and southwestern France (Gorostidi and Lamolda, 1995). The main difference between these sites is that at Caravaca the acme of *M. inversus* is recorded across the K/T boundary from –4 to +2 cm (Fig. 3). Also, this particular bio-event is less evident at Zumaya (Lamolda and Gorostidi, 1994), and so far had not been identified at Caravaca (Fig. 4 in Gardin and Monechi, 1998).

9. Conclusions

A qualitative and quantitative study of the calcareous nannofossil of the Caravaca section allowed us to clearly define a nannofloral mass extinction at the K/T boundary. In the Caravaca section this bio-event is closely synchronous with the planktonic foraminifera mass-extinction (Kaiho and Lamolda, 1999), as well as with other characteristic markers previously identified in the section (Arinobu et al., 1999; Kaiho et al., 1999), which are indicative of a catastrophic event.

Preservation of the nannofossils is usually moderate to good, although it is poor in the upper 20 cm of the studied section, but did not present a severe constraint in specific determination, and assessing assemblage composition with respect to original communities.

Reworking has a minor influence on nannofossils assemblages, except in the lowermost Danian interval between 2 and 3 cm above the K/T boundary, where a marked increase of Cretaceous specimens is caused by reworking. However, bioturbation does not seem to have caused perceivable mixing of lowermost Danian taxa into the uppermost Maastrichtian assemblages.

A gentle decline in absolute abundance of calcareous nannofloras is recorded prior to the K/T boundary until about 12 cm below the boundary. Then, the rate of decline is accentuated upsection, with a loss of 82.5% of absolute abundance in the transitional layer. Concurrently, taxa designated as survivors, which were always minor components of the assemblages, increased their occurrence by tenfold. Nonetheless, species richness showed only moderate changes, from an average of 56 to a minimum of 34 species in the transitional layer, and just below the fallout lamina there is a loss of 39% of taxa during the last 4 ky of the Maastrichtian. The characteristic decrease in absolute abundance found at Caravaca, which apparently has also been identified in sections from the central eastern desert of Egypt (Tantawy, 2003), should be tested in other localities by applying a similar sampling density, since its critical interval is only about several thousand years.

The Cretaceous nannofossil assemblages identified are typical of the Tethyan realm, but it is important to note that several species are more related to cold-water high latitude areas, thus providing the basis to argue that pulses of cold oceanic water apparently recurred in the area during the Maastrichtian, and continued into the early Danian. Furthermore, the tenfold increase in absolute abundance of survivor species, especially *Thoracosphaera* spp., in the top 10 cm of the Maastrichtian, which was preceded by the relative maxima of *C. ehrenbergii* and *Prediscosphaera* spp., can be interpreted to indicate instability of the calcareous nannofloral ecosystem prior to the K/T boundary event.

The main extinction event is recorded across the K/T boundary, although just above the boundary there are 12 survivor species representing 21.5% of the average assemblage in the lower part of the section, and 35% of the assemblage in the transitional layer. The absolute abundance of survivor species is about 0.4 s/FOV or 11.5% of the taxa in the transitional layer, where the main component is the calcareous

dinoflegellate “disaster species” *T. operculata*. The overlying Danian layers contain two successive blooms, the first consists of *Thoracosphaera*, followed by *B. bigelowii* (Fig. 7), both within the *B. sparsus* Zone.

In the Caravaca section studied, the interval of the early Danian that comprises approximately 30 ky includes a typical disaster assemblage. Most of the components belong to survivor species, and it is only within the uppermost 10 cm (or 30 cm above the assigned boundary) that the absolute abundance of incoming three species, *B. sparsus*, *C. alta* and *N. parvulum*, constitutes about half of the total assemblages.

Paleoecological and biogeographical characteristics of the calcareous nannofossils of the Caravaca section studied thus indicate important changes in the late Maastrichtian nannofloral assemblages that predated the K/T boundary mass extinction. These nannofloral changes are very close to the collapse of primary productivity associated with mass extinction of the planktonic foraminifera, and several lines of evidence that are consistent with a bolide impact. The combined effects of all these factors and complex phenomena most likely determined the characteristics of such an extraordinary event in the geological record.

Acknowledgements

The authors are grateful to Drs. Roque Aguado, Silvia Gardin and Florentin Maurrasse for their helpful reviews, suggestions and comments. Financial support for M.C. Melinte, provided by Grant No. 3/1037 (2001) of the Dirección de Política Científica, Gobierno Vasco, is gratefully acknowledged. This research has been partly financed by a grant-in-aid for scientific research from the Japanese Ministry of Education, Science and Culture.

Appendix A. Index of listed and selected figured nannofossil taxa

- Ahmuelerella octoradiata* (Górka, 1957); Reinhardt, 1966
Ahmuelerella regularis (Górka, 1957); Reinhardt and Górka, 1967
Amphizygus brooksii Bukry, 1969
Arkhangelskiella cymbiformis Vekshina, 1959 (Fig. 9.11B)
Biantholithus sparsus Bramlette and Martini, 1964
Biscutum constans (Górka, 1957) Black, in Black and Barnes, 1959
Biscutum melaniae (Górka, 1957) Burnett, 1997
Braarudosphaera alta Romein, 1979
Braarudosphaera bigelowii (Gran and Braarud, 1935); Deflandre, 1947 (Fig. 10.9)
Broinsonia enormis (Shumenko, 1968); Manivit, 1971
Calculites obscurus (Deflandre, 1959); Prins and Sissingh in Sissingh, 1977
Calculites ovalis (Stradner, 1963) Prins and Sissingh, in Sissingh, 1977
Ceratolithoides aculeus (Stradner, 1961); Prins and Sissingh, in Sissingh, 1977
Ceratolithoides kamptneri Bramlette and Martini, 1964
Chiastozygus amphipons (Bramlette and Martini, 1964); Gartner, 1968
Chiastozygus litterarius (Górka, 1957); Manivit, 1971
Chiastozygus ultimus Perch-Nielsen, 1981
Corollithion? madagaskarensis Perch-Nielsen, 1973
Corollithion signum Stradner, 1963
Cretarhabdus conicus Bramlette and Martini, 1964
Cribracorona gallica (Stradner, 1963); Perch-Nielsen, 1973
Cribrospheraella ehrenbergii (Arkhangelsky, 1912); Deflandre in Piveteau, 1952
Cyclagelosphaera alta Perch-Nielsen, 1979 (Fig. 10.3)
Cyclagelosphaera margerelii Noël, 1965
Cyclagelosphaera reinhardtii (Perch-Nielsen, 1968); Romein, 1977 (Fig. 10.4)
Cylindralithus biarcus Bukry, 1969
Cylindralithus nudus Bukry, 1969
Cylindralithus sculptus Bukry, 1969 (Figs. 9.9 and 9.10)
Discorhabdus ignotus (Górka, 1957); Perch-Nielsen, 1968
Eiffellithus gorkae Reinhardt, 1965
Eiffellithus parallelus Perch-Nielsen, 1973
Eiffellithus turriseiffelii (Deflandre in Deflandre and Fert, 1954); Reinhardt, 1965
Gartnerago segmentatum (Stover, 1966); Thierstein, 1974

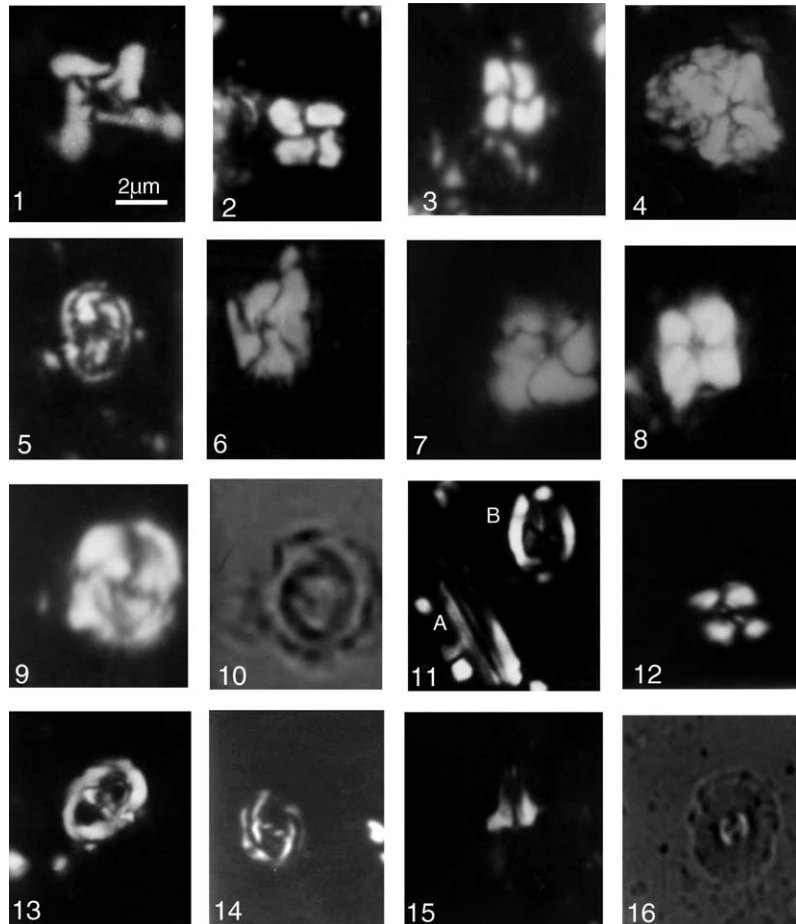


Fig. 9. (1) *Micula prinsii* Perch-Nielsen, 1979. Xpol; sample – 1/–0.3. (2, 3) *Micula murus* (Martini, 1961) Bukry, 1973. Xpol; 2: sample – 25/–23; 3: sample – 2/–1. (4, 8) *Micula decussata* Vekshina, 1959. Xpol; 4: sample – 4/–3; 8: sample – 0.3/0. (5) *Nephrolithus frequens* Górká, 1957. Xpol; sample – 9/–7. (6) *Micula swastica* Stradner and Steinmetz, 1984. Xpol; sample – 5/–4. (7) *Micula praemurus* (Bukry, 1973) Stradner and Steinmetz, 1984. Xpol; sample – 13/–11. (9, 10) *Cylindralithus sculptus* Bukry, 1969. 9: Xpol; 10: Ph; sample – 0.3/0. (11) A: *Lithraphidites quadratus* Bramlette and Martini, 1964, and B: *Arkhangelskiella cymbiformis* Vekshina, 1959. Xpol; sample – 19/–17. (12) *Watznaueria barnesae* (Black, 1959) Perch-Nielsen, 1968. Xpol; sample – 13/–11. (13) *Zeughrabdotos* cf. *sigmoides* (Bramlette and Sullivan, 1961) Bown and Young, 1997. Xpol; sample – 11/–9. (14) *Placozygus fibuliformis* (Reinhardt, 1964) Hoffmann, 1970. Xpol, sample – 23/–21. (15) *Semihololithus priscus* Perch-Nielsen, 1973. Xpol; sample – 25/–23. (16) *Markalius inversus* (Deflandre in Deflandre and Fert, 1954) Bramlette and Martini, 1964. Ph; sample – 1/–0.3. Xpol=cross-polarized light. Ph=phase contrast light. Scale bar=2 μ m.

Goniolithus fluckigeri Deflandre, 1957
Haqius circumradiatus (Stover, 1966); Roth, 1978
Helicolithus trabeculatus (Górká, 1957); Verbeek, 1977
Kamptnerius magnificus Deflandre, 1959
Lithraphidites carniolensis Deflandre, 1963
Lithraphidites praequadratus Roth, 1968
Lithraphidites quadratus Bramlette and Martini, 1964
 (Fig. 9.11A)

Manivitella pemmatoidea (Deflandre in Manivit, 1965); Thierstein, 1971
Markalius inversus (Deflandre, in Deflandre and Fert, 1954); Bramlette and Martini, 1964 (Figs. 9.16 and 10.1A)
Micula sp.1 (sensu Pospichal, 1996)
Micula concava (Stradner, in Manivit and Stradner, 1960); Verbeek, 1966
Micula cubiformis Forchheimer, 1972

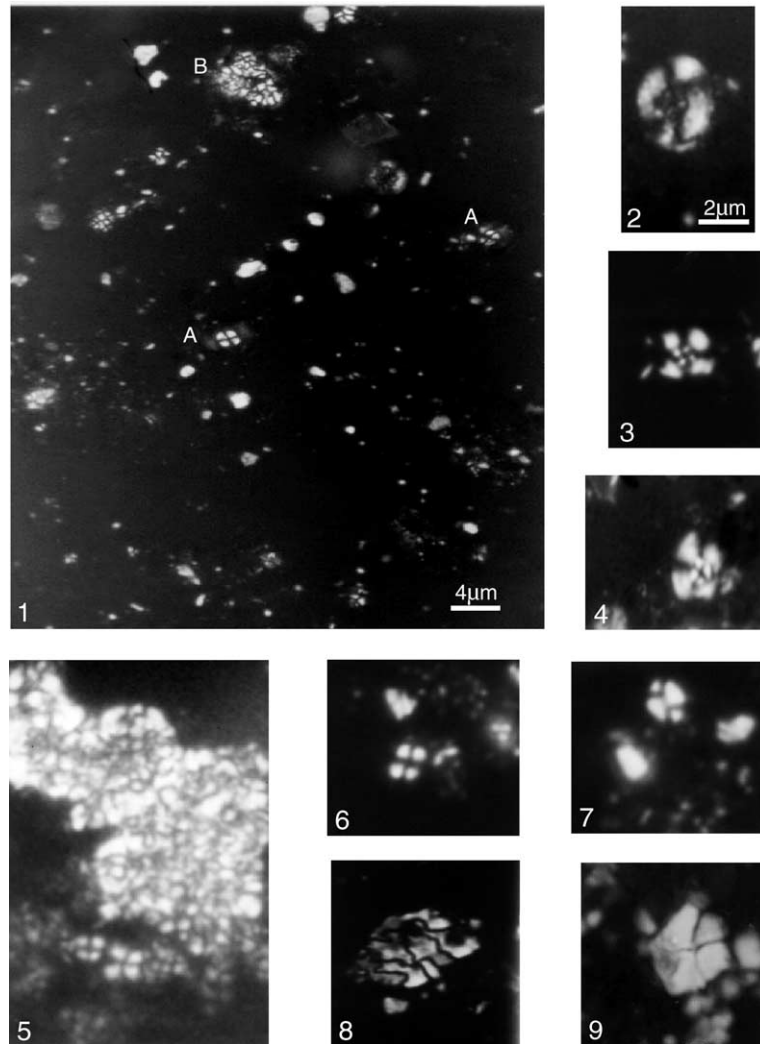


Fig. 10. (1) Nannofossil assemblage from the base of the Danian. Xpol; sample 0/+0.5. A: *Markalius inversus* (Deflandre in Deflandre and Fert, 1954) Bramlette and Martini, 1964; B: *Thoracosphaera* sp. (2) *Neocrepidolithus neocrassus* (Perch-Nielsen, 1968) Romein, 1979. Xpol; sample +1/+2. (3) *Cyclagelosphaera* cf. *alta*, Xpol; sample +34/+36. (4) *Cyclagelosphaera reinhardtii* (Perch-Nielsen, 1968) Romein, 1977. Xpol; sample +14/+16. (5) *Thoracosphaera* bloom, Xpol; sample +14/+16. (6, 7) *Octolithus multiplus* (Perch-Nielsen, 1974) Romein, 1979. Xpol; sample +18/+20; 7: rotated 45°. (8) *Thoracosphaera* sp. Xpol; sample +1/+2. (9) *Braarudosphaera bigelowii* (Gran and Braarud, 1935) Deflandre, 1947. Xpol=cross-polarized light. Ph=phase contrast light. (1) Scale bar=4 μm; (2–9) Scale bar=2 μm.

Micula murus (Martini, 1961); Bukry, 1973 (Figs. 9.2 and 9.3)

Micula praemurus (Bukry, 1973); Stradner and Steinmetz, 1984 (Fig. 9.7)

Micula prinsii Perch-Nielsen, 1979 (Fig. 9.1)

Micula decussata Vekshina, 1959 (Figs. 9.4 and 9.8)

Micula swastica Stradner and Steinmetz, 1984 (Fig. 9.6)

Microrhabdulus belgicus Haye and Towe, 1963

Microrhabdulus decoratus Deflandre, 1959

Microrhabdulus undosus Perch-Nielsen, 1973

Neobiscutum parvulum (Romein, 1979); Varol, 1989

Neocrepidolithus neocrassus (Perch-Nielsen, 1968); Romein, 1979 (Fig. 10.2)

Nephrolithus frequens Górká, 1957 (Fig. 9.5)

Octolithus multiplus (Perch-Nielsen, 1874); Romein, 1979 (Figs. 10.6 and 10.7)
Placozygus fibuliformis (Reinhardt, 1964) Hoffmann, 1970 (Fig. 9.14)
Prediscosphaera arkhangelskyi (Reinhardt, 1965); Perch-Nielsen, 1984
Prediscosphaera cretacea (Arkhangelsky, 1912); Gartner, 1968
Prediscosphaera ponticula (Bukry, 1969); Perch-Nielsen, 1984
Prediscosphaera spinosa (Bramlette and Martini, 1964); Gartner, 1968
Prediscosphaera stoveri (Perch-Nielsen, 1968); Shafik and Stradner, 1971
Quadrum gartneri Prins and Perch-Nielsen, in Manivit et al., 1977
Quadrum svabenickae Burnett, 1998
Reinhardtites levis Prins and Sissingh, in Sissingh, 1977
Retecapsa angustiforata Black, 1971
Retecapsa crenulata (Bramlette and Martini, 1964); Grün in Grün and Allemann, 1975
Rhagodiscus angustus (Stradner, 1963); Reinhardt, 1971
Rhagodiscus indistinctus Burnett, 1998
Rhagodiscus reniformis Perch-Nielsen, 1973
Rhagodiscus splendens (Deflandre, 1953); Verbeek, 1977
Rotelapillus crenulatus (Stover, 1966); Perch-Nielsen, 1984
Semihololithus bicornus Perch-Nielsen, 1973
Semihololithus priscus Perch-Nielsen, 1973 (Fig. 9.15)
Staurolithites crux (Deflandre and Fert, 1954); Caratini, 1963
Tegumentum stradneri Thierstein in Roth and Thierstein, 1972
Tetrapodorhabdus decorus (Deflandre in Deflandre and Fert, 1954); Wind and Wise in Wise and Wind, 1977
Thoracosphaera Kamptner, 1927 (Figs. 10.1, 10.5 and 10.8)
Thoracosphaera operculata Bramlette and Martini, 1964
Tranolithus minimus (Bukry, 1969); Perch-Nielsen, 1984
Watznaueria barnesae (Black, 1959); Perch-Nielsen, 1968 (Fig. 9.12)

Watznaueria ovata Bukry, 1969
Zeugrhabdotus embergeri (Noël, 1958); Perch-Nielsen, 1984
Zeugrhabdotus erectus (Deflandre in Deflandre and Fert, 1954); Reinhardt, 1965
Zeugrhabdotus sigmoides (Bramlette and Sullivan, 1961) Bown and Young, 1997 (Fig. 9.13)

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