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Integrated stratigraphy across the Paleocene/Eocene boundary at Caravaca, southern Spain

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Key words: Integrated stratigraphy, chronostratigraphy, biostratigraphy, geochemistry, Paleocene, Eocene, Betic cordillera, Spain

ABSTRACT

The Caravaca section is evaluated as a potential Paleocene/Eocene boundary stratotype based on a high resolution and integrated stratigraphical study. The P/E boundary event is characterized biostratigraphically and geochemically. The mass extinction horizon of the small benthic foraminifera coincides with a strong negative excursion in $\partial^{13}C$ and $\partial^{18}O$, a dark anoxic level, a carbonate dissolution interval and a major increase in the quartz content. It also coincides with major turnovers in other microfossil groups and significant changes in the concentration of TiO_2, MnO, Cr, Cu, Zn and REE. This horizon is considered to be the most suitable one to define the P/E boundary. A short hiatus present 2.5 m below the P/E boundary is evaluated to about 0.7 Ma. The Lower Ilerdian is missing and because of this hiatus the Caravaca section is not optimal as potential stratotype for the P/E boundary, but it constitutes a very good reference section.

RESUME

La coupe de Caravaca est évaluée comme stratotype potentiel de la limite Paléocène/Eocène à partir d'une étude stratigraphique intégrée et de haute résolution. L'événement de la limite P/E est caractérisé biostratigraphiquement et géochimiquement. L'horizon de l'extinction massive des petits foraminifères bentiques coïncide avec un grand changement négatif de $\partial^{13}C$ et $\partial^{18}O$, un niveau noir anoxique, un intervalle de dissolution de carbonates et une importante augmentation du contenu en quartz. Il coïncide aussi avec de grandes variations dans d'autres groupes de microfossiles et des changements significatifs dans la concentration de TiO_2, MnO, Cr, Cu, Zn et REE. Cet horizon est considéré comme le plus approprié pour définir la limite P/E. Un court hiatus qui est présent à 2.5 m en-dessous de la limite P/E est évalué à environ 0.7 Ma. Il manque l'Ilerdien Inférieur et du fait de ce hiatus la coupe de Caravaca n'est pas la meilleure comme stratotype potentiel pour la limite P/E, mais elle constitue une très bonne coupe de référence.

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 & Luterbacher 1992). Several sections have been proposed as candi-

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dates and are being evaluated as potential P/E boundary stratotype. The Caravaca section is evaluated in this paper since it 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, at 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. in press), 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.

The classical Caravaca section, very well known world wide because of the Cretaceous/Tertiary boundary, contains a nearly continuous marine record spanning from the Late Cretaceous to the Middle Eocene. The section was initially studied by Durand Delgá & Magné (1958) and later in more detail by Von Hillebrandt (1974) based on foraminifera and by Romein (1979) based on calcareous nannoplankton.

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. High resolution sample analysis across the Paleocene-Eocene transition at Caravaca based on integrated microfossil and geochemical data allow us to establish a high resolution stratigraphy. Our study reveals a series of events (extinctions, originations and geochemical shifts) that allow the establishment of a detailed chronostratigraphical framework.

Material and methods

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. 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 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

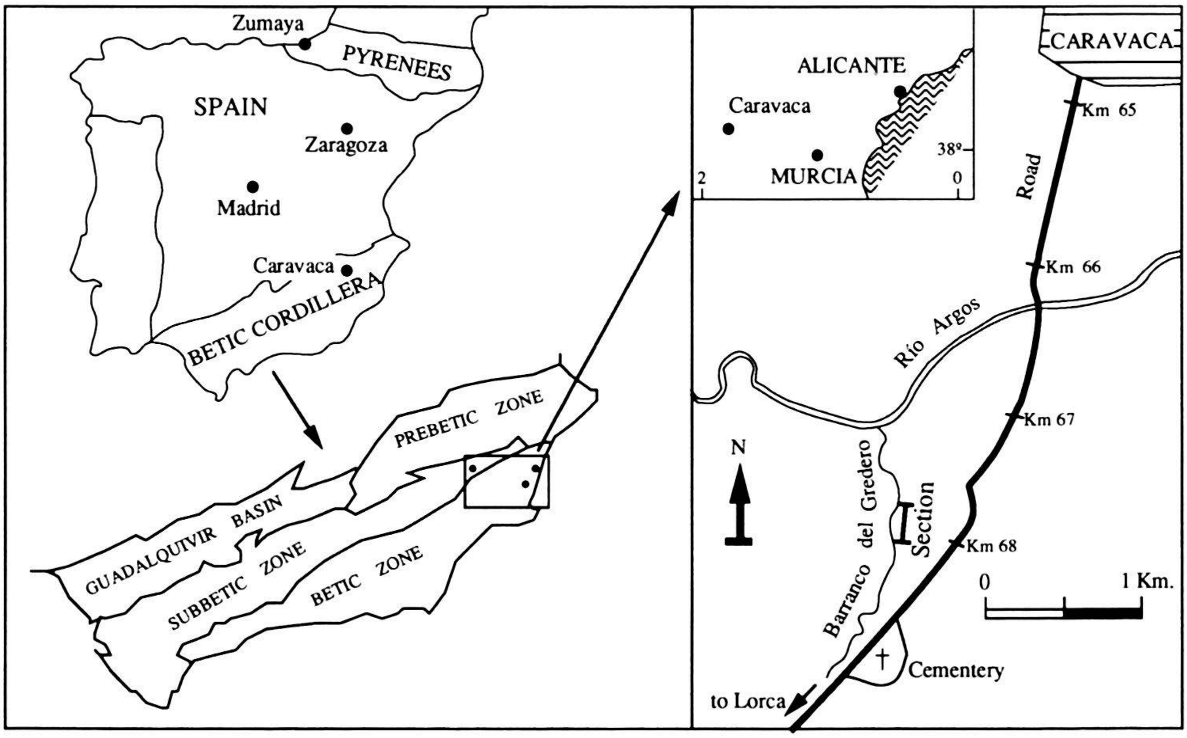

Fig. 1. Location map of the Caravaca section (Spain).

the sediment colour is dark gray 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 (Fig. 2) and calcareous nannoplankton are abundant and well preserved. Small benthic foraminifera (Fig. 3) 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 truempyi* except for the $\partial^{13}C$ shift interval where *N. truempyi* 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 Department of Mineralogy and Petrology of the University of Granada (Spain). Geochemical analyses

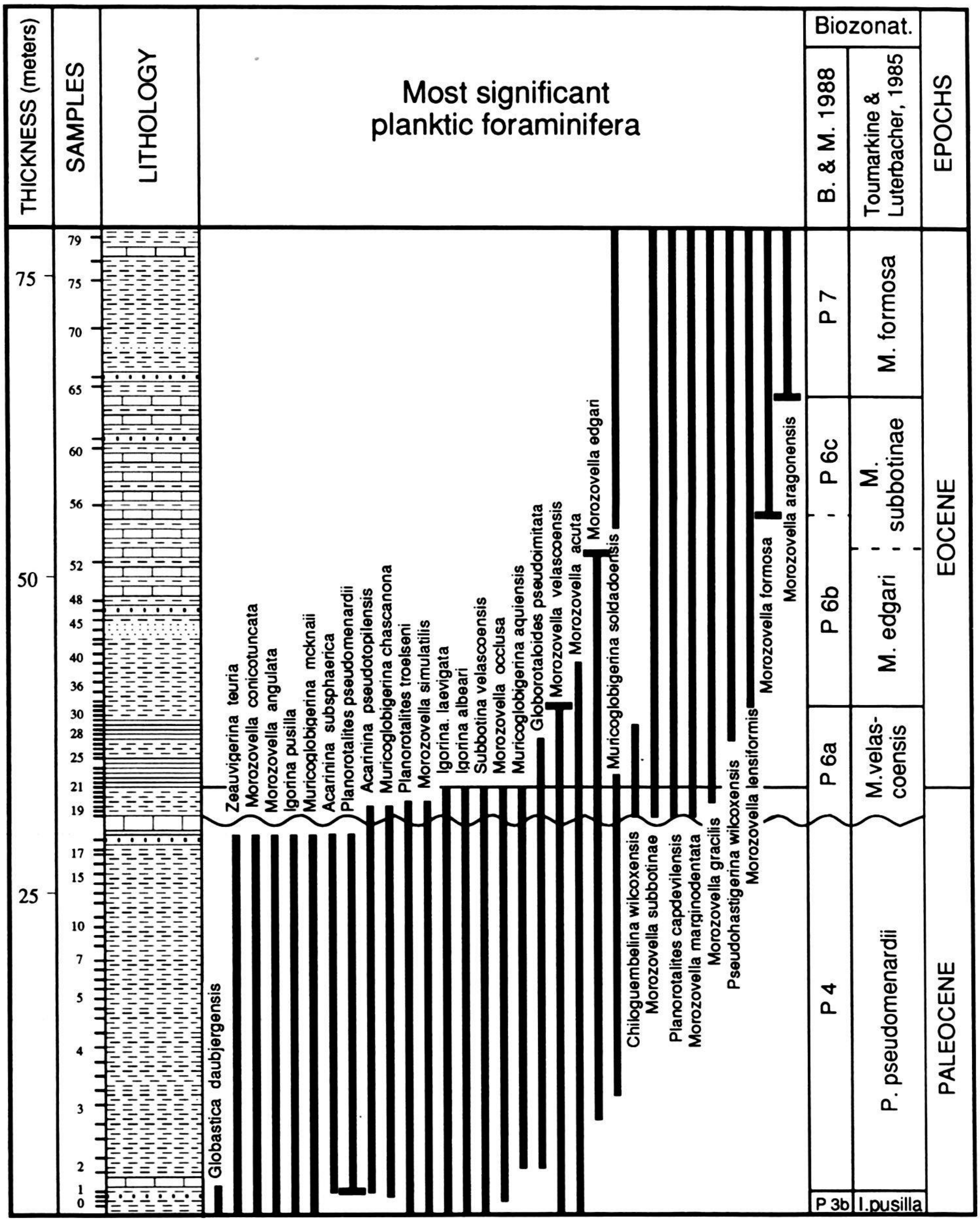

Fig. 2. Stratigraphical distribution of the most significant planktic foraminifera throughout the Paleocene-Eocene transition at Caravaca section. B. & M. 1988 means Berggren & Miller, 1988.

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 (Fig. 4 and 5).

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., in press), evaluating the planktic foraminiferal turnover across the Paleocene-Eocene transition. The following biozones have been recognized: *Igorina pusilla, Planorotalites pseudomenardii, Morozovella velascoensis, M. edgari, M. subbotinae and M. formosa,* according to the Toumarkine & Luterbacher (1985) biozonation (Fig. 2). These biozones correspond to P3b, P4, P6a, P6b, P6c and P7, according to the Berggren & Miller (1988) biozonation. The biozone P5 and the lower part of P6a were not identified, the reason is the presence of a hiatus, as it is shown by the simultaneous disappearance of seven species *(Zeauvigerina teuria, Morozovella conicotruncata, M. angulata, Igorina pusilla, M. mcknaii, Acarinina subspaerica and Planorotalites pseudomenardii)* and the subsequent appearance of four species *(Morozovella subbotinae, Chiloguembelina wilcoxensis, M. marginodentata* and *Planorotalites capdevilensis).* This hiatus is placed 2.5 m below the dissolution interval that marks the Paleocene/Eocene boundary. Nine species *(Acarinina pseudotopilensis, Muricoglobigerina chascanona, Planorotalites troelseni, Morozovella simulatilis, Igorina laevigata, I. 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 *(Igorina laevigata, I. albeari, Subbotina velascoensis, Morozovella occlusa and M. aquiensis)* seem to become extinct, but their distribution compared with other sections (Molina et al., 1992; Canudo et al., in press) 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., in press). 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 foloowing biozones have been recognized: *Pyramidina rudita, Stensioina beccariiformis, Haplophragmoides retrosepta, Bulimina tuxpamensis/Tappanina selmensis, Nuttallides truempyi,* and *Cibicidoides subspiratus* (Fig. 3). This new biozonation is correlated with the Berggren & 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 domi-

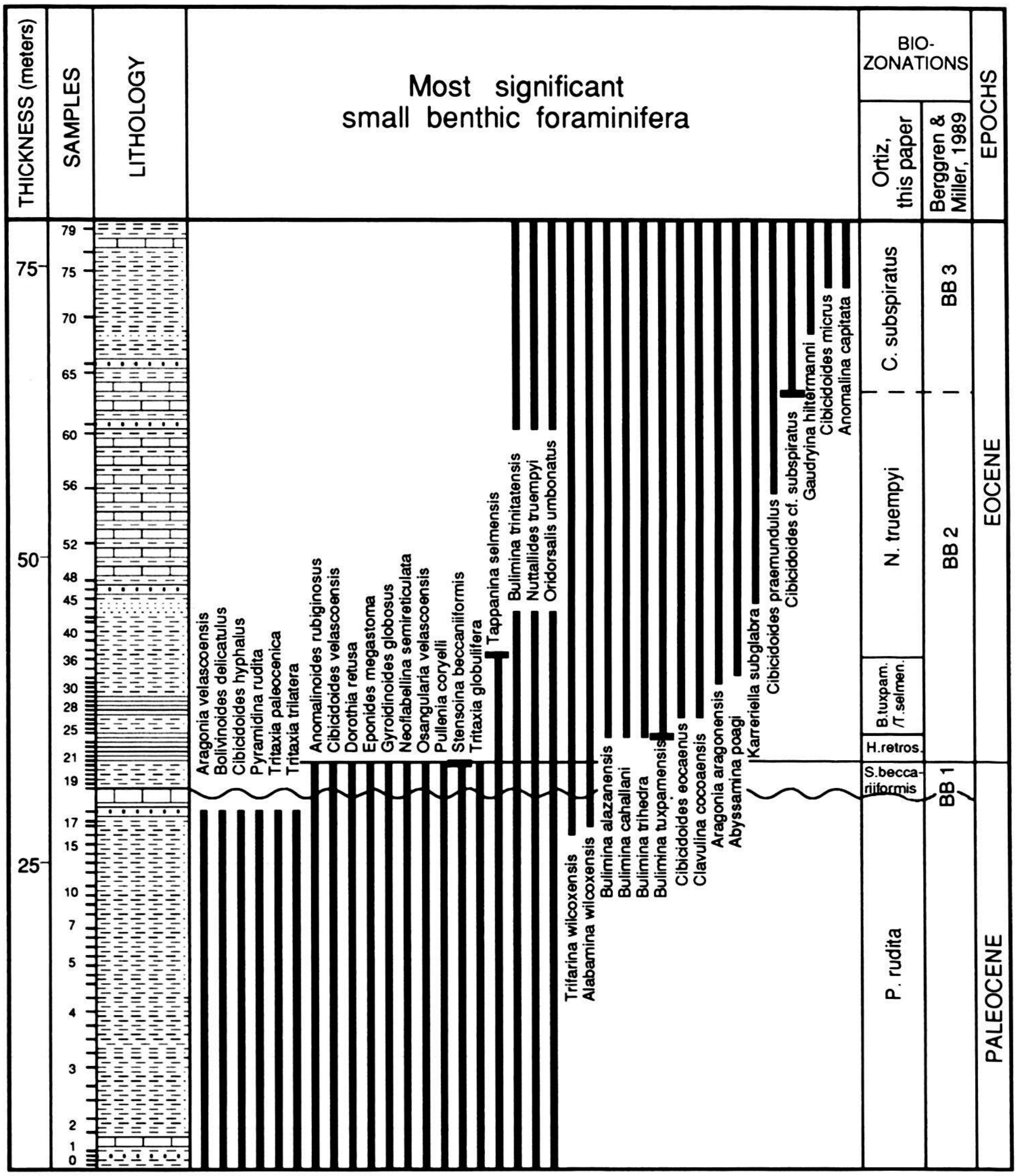

Fig. 3. Stratigraphical distribution of the most significant small benthic foraminifera throughout the Paleocene-Eocene transition at Caravaca section.

nated fauna including *N. truempyi, 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 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 (Fig. 6). 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* (Fig. 6). 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.*

Geochemistry

Some aspects of the carbon and oxygen isotopes have been previously discussed by Canudo et al., (in press) 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 (Fig. 4), the trace and major elements and the biostratigraphy, in order to clearly characterized the P/E boundary event.

The $\partial^{13}C$ isotope measured on *Nuttallides 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 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. truempyi* values gradually increase by 2.5 permil (Fig. 4).

The $\partial^{18}C$ isotope has also been measured on *N. truempyi* and where it was absent *Lenticulina* was analysed. In P4 Biozone there is a small shift that coincides with a shift in $\partial^{13}C$ and just above the hiatus another small shift is observed. Furthermore, at the transi-

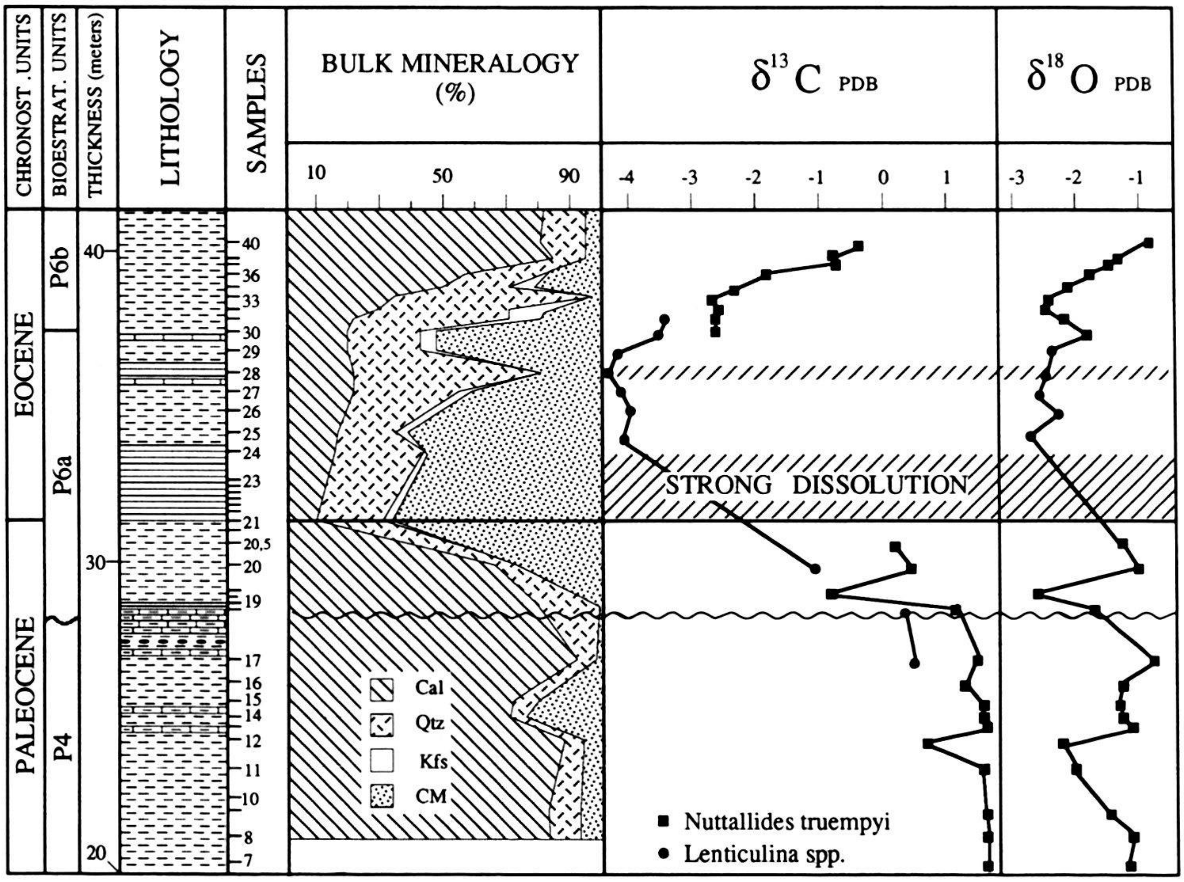

Fig. 4. $\partial^{13}C$ and $\partial^{18}O$ isotopes and bulk sample mineralogy across the Paleocene/Eocene boundary at Caravaca section.

tion 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 (Fig. 4).

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. 5).

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

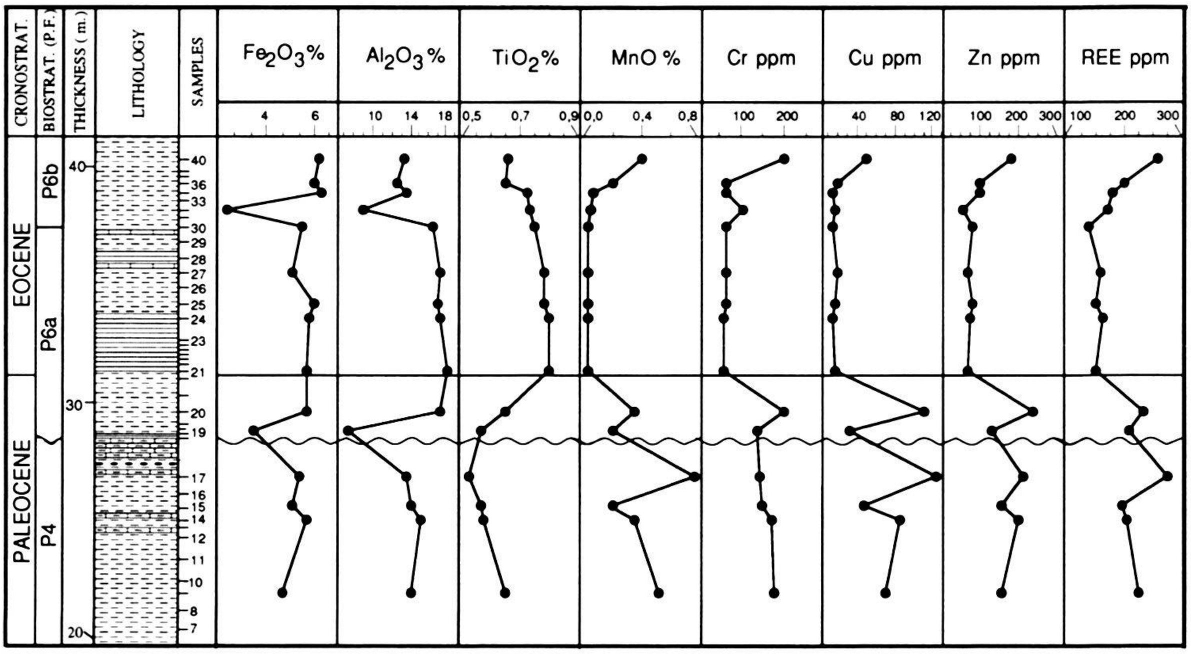

Fig. 5. Geochemical analyses across the Paleocene/Eocene boundary at Caravaca section.

quite clearly. Based in the study of this section, as well as in regional observations, several depositional sequences have been recognized (Fig. 6). 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 sequence 1 and 2 is clearly placed in the lower part of P4 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. 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 & Magné 1958; Von Hillebrandt 1974; Romein 1979) none of them found the hiatus that has been recently discovered by means of planktic foraminifera (Canudo

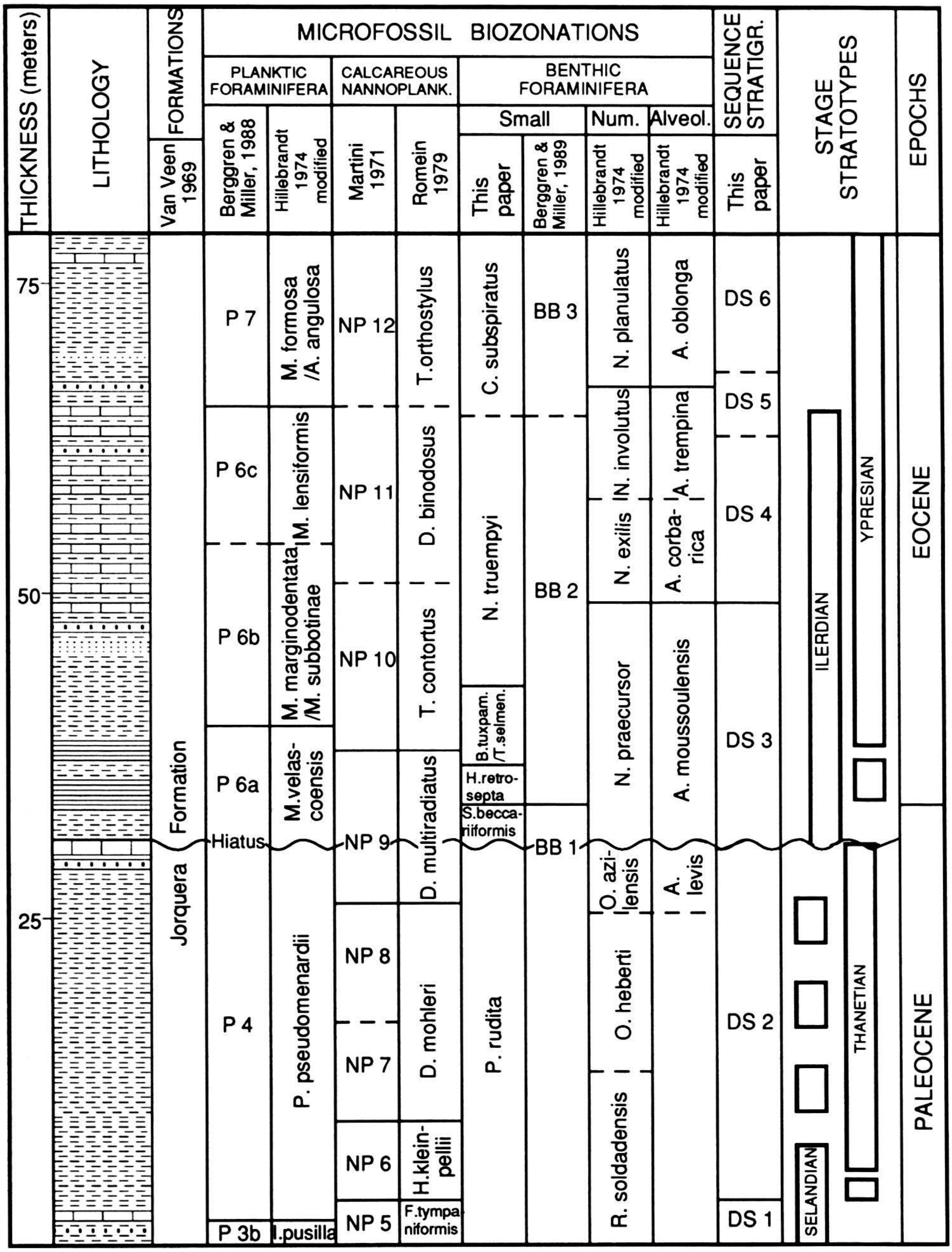

Fig. 6. Integrated stratigraphy throughout the Paleocene-Eocene transition at Caravaca section.

et al., in press) and it is also documented in this paper by the simultaneous disappearance of at least six small benthic foraminifiera *(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 & 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 $\partial^{13}C$ excursion at 58.0 Ma by Pak & 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 *Operculina azilensis* Biozone (Late Thanetian) (Fig. 6). About 17 m above Von Hillebrandt (1974) found another level with nummulitids of the *Nummulites 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 *Alveolina cucumiformis* and *A. ellipsoidalis* Biozones (Early Ilerdian). When this section is compared with the Zumaya section (Canudo & 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.

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., in press), but at this interval no evidence of a hiatus exists, consequently the sedimentation has to be condensed at this interval at Caravaca where the $\partial^{13}C$ 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 concidence 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 $\partial^{13}C$ excursion, which has been determined to be globally synchronous (Thomas 1990; Kaiho 1991; Kennett & Stott 1991; Pak & Miller 1992; Lu & 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 *Morozovella 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 *Planorotalites 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 & Molina 1992a, b; Pardo et al., in press). 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., in press). 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 (1990) and Kennett & Stott (1991). In the Caravaca section we have found two slight shifts 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 & 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., in press).

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 (Fig. 5), suggests an important increase in the detrital accumulation around this boundary, which is also indicated by the increase in the quartz content (Fig. 4). 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 paleonviromental conditions. The main source for this element is volcano-hydrothermal activity (Klinkhammer 1980; Andrianiazy & 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 & MacKenzie 1984) and, as a consequence, an increase in the hydrothermal activity (Olivarez & Owen 1989). Therefore an enrichment in Mn can be expected in the area of the oceanic ridges due to hydrothermal input (Lyle 1976). 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 under which Mn would be in its soluble reduced state.

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 seems to be related to a strong sea level rise. According to Leinfelder & 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 depletion. 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 depletion in the deep sea, causing partial collapse of the benthic bathyal and abyssal marine ecosystems.

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 has been detected between the P4 and P6a biozones and is evaluated at about 0.7 Ma, missing the Early Ilerdian (*Nummulites fraasi* Biozone and *Alveolina cucumiformis* and *A. ellipsoidalis* Biozones). Above the hiatus we have 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 *(Morozovella velascoensis)* Biozone, the upper part of NP9 (*Discoaster multiradiatus*) Biozone, the top of BB1 *(Stensioina 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 vey good reference section and it allows the integration of geochemistry and biostratigraphy based on different groups of microfossils.

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