

Original article

Correlation between the Paleocene/Eocene boundary and the Ilerdian at Campo, Spain

Corrélation de la limite Paléocène/Éocène et l'Ilerdien dans la coupe de Campo, Espagne

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Abstract

The Ilerdian is a well-established Tethyan marine stage, which corresponds to an important phase in the evolution of larger foraminifera not represented in the type-area of the classical Northwest-European stages. This biostratigraphic restudy of its parastratotype in the Campo Section (northeastern Spain) based on planktic foraminifera, calcareous nannofossils, dinoflagellate cysts and the distribution of the stable isotopes $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ is an attempt to correlate the Paleocene/Eocene boundary based on a characteristic carbon isotope excursion (CIE) marking the onset of the Initial Eocene Thermal Maximum (IETM) and the Ilerdian stage. The base of this $\delta^{13}\text{C}$ excursion has been chosen as the criterion for the recent proposal of the Global Stratotype Section and Point (GSSP) of the base of the Eocene (= base of the Ypresian) in the Dababiya Section (Egypt) to which an age of 54.9 Ma has been attributed. This level is also characterized by a marked extinction among the deep-water benthic foraminifera (Benthic Foraminifera Extinction Event, BFEE), a flood of representatives of the planktic foraminiferal genus *Acarinina* and the acme of dinoflagellate cysts of the genus *Apectodinium*. In the Campo Section, detailed biozonations (planktic foraminifera, calcareous nannofossils, dinoflagellate cysts) are recognized in the Lower and Middle Ilerdian. The correlation with the Ypresian stratotype is based on dinoflagellate cysts and calcareous nannofossils. The base of the Ilerdian is poor in planktic microfossils and its precise correlation with the redefined Paleocene/Eocene boundary remains uncertain.

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Résumé

L'Ilerdien est un étage téthysien bien défini, correspondant à un moment important de l'évolution des grands Foraminifères qui manquent dans les stratotypes des étages classiques du Nord-Ouest européen. La révision biostratigraphique du parastratotype de Campo (Espagne NE), prenant en compte les Foraminifères planctoniques, les nannofossiles calcaires, les dinokystes et la distribution des isotopes stables $\delta^{13}\text{C}$ et $\delta^{18}\text{O}$, est une tentative de corrélation de l'étage ilerdien avec la limite Paléocène/Éocène fondée sur l'Excursion des Isotopes du Carbone (CIE), marquant le début du Maximum Thermique du Début de l'Éocène (IETM). Le début de l'excursion du $\delta^{13}\text{C}$ a été adopté comme critère dans la récente proposition du GSSP (Global Stratotype Section and Point) de la base de l'Éocène (= base de l'Yprésien) dans la section de Dababiya (Égypte), dont l'âge attribué est de 54.9 Ma. Ce niveau est aussi caractérisé par une extinction importante des Foraminifères benthiques d'eaux profondes (BFEE = Benthic Foraminifera Extinction Event), par un afflux de représentants de Foraminifères planctoniques du genre *Acarinina*, et par l'acmé des dinokystes du genre *Apectodinium*. Dans la coupe de Campo, des biozonations détaillées (Foraminifères planctoniques, nannofossiles calcaires, dinokystes) ont été établies dans l'Ilerdien inférieur et moyen. La corrélation avec le stratotype de l'Yprésien est fondée sur les dinokystes et les nannofossiles calcaires. La base de l'Ilerdien étant pauvre en microfossiles planctoniques, sa corrélation précise avec la limite Paléocène/Éocène reste incertaine.

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1. Introduction

The Paleocene/Eocene Boundary Working Group of the International Subcommission on Paleogene Stratigraphy (ISPS) has recently proposed to locate the Global Stratotype Section and Point (GSSP) for the base of the Eocene (= base of the Ypresian) in the Dababiya Section (near Luxor, Upper Egypt) at the base of a thin dark gray clayey layer underlying a 2 m-thick phosphatic laminite. The start of the Carbon Isotope Excursion (CIE) which has been selected by the ISPS as the criterion for the definition of the GSSP is firmly located in the lowest part of this clay layer. This CIE corresponds to the Initial Eocene Thermal Maximum (IETM). Based on astronomically tuned cyclostratigraphy (Röhl et al., 2000), the CIE is thought to span a time interval of only 0.015 million years and to have an age of 54.9 Ma. In nearby sections, the lithostratigraphic level corresponding to the GSSP of the base of the Eocene is also corresponding to the so-called Benthic Foraminifera Extinction Event (BFEE) and associated with a sudden increase in representatives of the planktic foraminiferal genus *Acarinina* as well as an acme of the dinoflagellate cysts attributed to the genus *Apectodinium*. In northern Spain, these Paleocene/Eocene boundary events have been recognized in the Zumaya section (Canudo and Molina, 1992; Canudo et al., 1995; Schmitz et al., 1997; Molina et al., 1999; Arenillas and Molina, 2000) and in the Ermua and Trabakua sections (Orue-Etxebarria et al., 1996; Schmitz et al., 2001).

The Ilerdian has been proposed as a new stage by Hottinger and Schaub (1960) to cover an important interval in the evolution of the Paleogene larger foraminifera (mainly belonging to the genera *Nummulites*, *Assilina*, *Alveolina*, *Orbitolites*) which is well characterized and widespread in the Tethyan realm, but which is not represented in northwestern Europe where most of the stratotypes of the classical stages of the Paleogene have been defined. The Ilerdian is a well-defined stratigraphic unit, which is recognized and widely used from the Eastern Mediterranean to the Indo-Pacific area. The stratotype of the Ilerdian is the so-called Tremp section (Schaub, 1969; Luterbacher, 1969). The Campo section includes the parastratotype of the Ilerdian (Schaub, 1969, 1973). Within the marine Paleogene of the Tremp-Graus Basin, the well-exposed Campo section is located in a more distal position than the Tremp section. Therefore, it is more expanded and contains more intervals with planktic microfossils than the stratotype of the Ilerdian. In the Campo section, biozonations based on various groups of microfossils have been established: larger foraminifera (Hottinger, 1960; Schaub, 1966, 1981, 1992; Kapellos and Schaub, 1973), planktic foraminifera (von Hillebrandt, 1965), calcareous nannofossils (Wilcoxon, 1973), dinoflagellate cysts

(Caro, 1973) and ostracoda (Ducasse, 1972). A synthesis on the biostratigraphy of the Paleogene of the Campo section has been published by Schaub (1973) at the occasion of the XIII European Colloquium of Micropaleontology. The present discussion is restricted to the lower part of the section along the road from Campo to Ainsa (Fig. 1).

More recently, several authors studied and revised the planktic microfossil biostratigraphy of the Campo section (Molina et al., 1992), but also including smaller benthic foraminifera (Ortiz, 1993), larger foraminifera (Sansó et al., 1990; Tosquella et al., 1990; Serra-Kiel et al., 1994, 1998) and ostracoda (Guernet in Molina et al., 1992). Furthermore, the magnetostratigraphy has been established by Pascual and Pares (in Molina et al., 1992).

According to the biostratigraphic synthesis of the Campo section published by Schaub (1973, 1992), the lower Ilerdian is placed into the *Globorotalia velascoensis* Biozone *sensu* von Hillebrandt (1965), the NP9 Biozone *sensu* Wilcoxon (1973) and the *Wetzeliella hyperacantha* Biozone *sensu* Caro (1973). The biozones based on larger foraminifera and ostracods are less useful for correlations with pelagic environments. This traditional correlation implies that the CIE used to define the base of the Eocene should be found near the boundary between the lower and the middle Ilerdian. In two preliminary papers presented in meetings in Tremp (Arenillas and Molina, 1995) and in Göteborg (Molina et al., 2000), this traditional correlation has been maintained, but it has been questioned by Pujalte et al. (2000), Payros et al. (2000) and by Orue-Etxebarria et al. (2001). In order to resolve this controversy, which is mainly caused by the absence or scarcity of planktic microfossils in the lower Ilerdian, we have revised our data on planktic foraminifera and calcareous nannofossils and undertaken a new study of the dinoflagellate cysts. The results of this revision are discussed in the present paper.

2. Materials and methods

The studied section is located 2 km south of the village of Campo (Huesca Province, Aragon, Spain) (Fig. 1). The UTM coordinates of the sampled section are E285756, N4696466 (base) and E285166, N4696486 (top). We sampled in detail 270 m, from the uppermost Thanetian to the lower part of the middle Ilerdian, which are perfectly exposed on the north side of the road to Ainsa.

The Thanetian consists of 80 m of limestones attributed to the *Alveolina primaeva*, *Alveolina levis*, *Deflandrea speciosa* and the lower part of the *W. hyperacantha* Biozones. Within the same interval, the magnetochrones C26n and C25r have been recognized (Serra-Kiel et al., 1994).

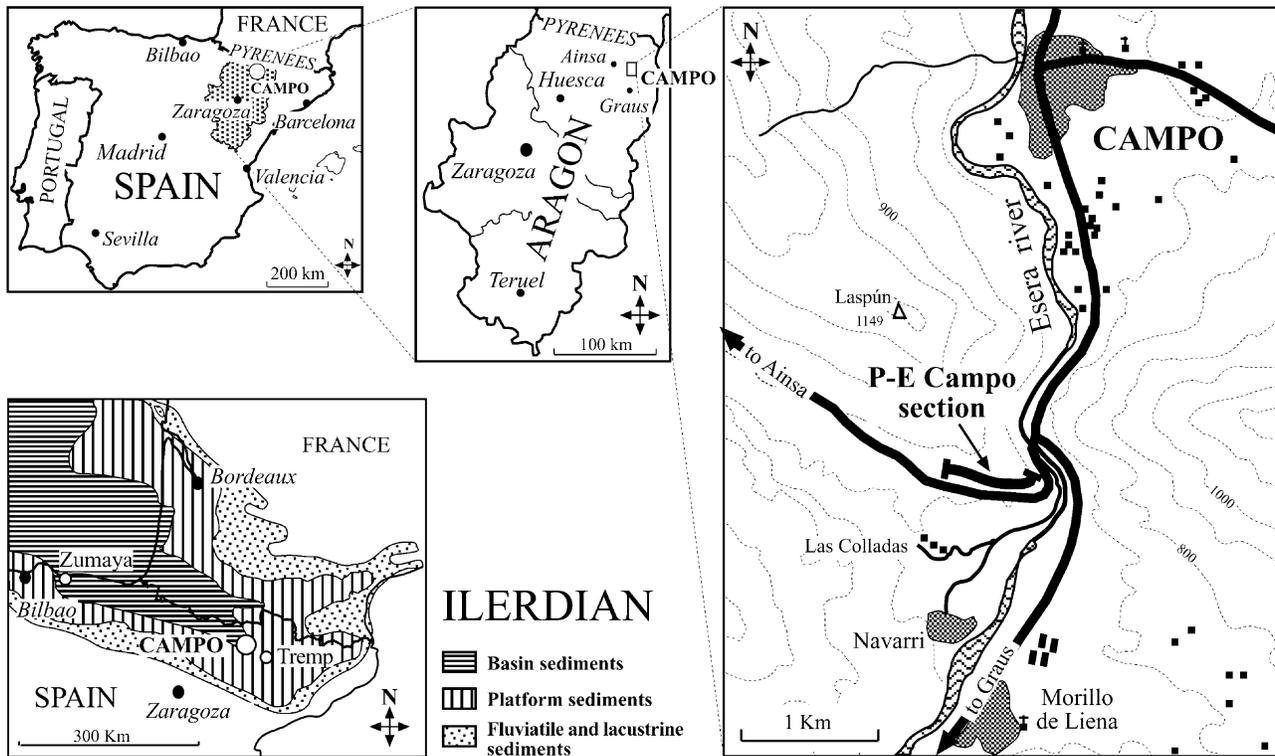


Fig. 1. Geographical and geological location of the Campo section.
 Fig. 1. Localisation géographique et géologique de la coupe de Campo.

The uppermost Thanetian (Fig. 2) contains a 6 m thick interval of terrestrial lutites, 1 m of sandstones and 4 m of bioturbated marly limestones. It is attributed to the Navarri Formation because of the presence of several terrestrial intervals. This predominantly terrestrial interval has been attributed to the Ilerdian by Payros et al. (2000) and Orue-Etxebarria et al. (2001), but the lutites contain charophyte oogonia of the *Sphaerochara edda* Biozone (Tambareau and Villatte, 1974; Massieux and Tambareau, 1978), and therefore, belong to the Thanetian.

The Ilerdian section studied consists of 80 m of bioclastic limestones, 60 m of bioclastic limestones with marls and sandstones interbedded, 10 m of sandstones, 90 m of marls with sandstones interbedded and more than 100 m of dark gray marls. These lithologies are attributed to the *Alveolina* Limestones (*Alveolina cucumiformis* and *Alveolina ellipsoidalis* Biozones) and the Riguala Marls (*Alveolina moussoulsensis* Biozone and lower part of the *Alveolina corbarica* Biozone). The *Alveolina* Limestones and the Riguala Marls constitute the Serraduy Formation, which characterize the lower and middle Ilerdian.

A total of 95 samples were analyzed for planktic foraminifera studies, being disaggregated in tap water and diluted H_2O_2 , then washed through a 100 μm sieve and dried at 50 °C. The same samples studied for planktic foraminifera have been processed for calcareous nannofossil analyses. Smear slides were prepared with the standard technique without centrifuging in order to minimize modifications of the original composition of the nannofloral assemblages. The

samples were also processed for dinoflagellate cysts, using standard palynological techniques at the LPP Utrecht University. The slides were analyzed following the methodology described by Brinkhuis and Biffi (1993). The dinocyst taxonomy is according to that cited in Williams et al. (1998). The present paper reports on selected, stratigraphically important dinocyst events only. Stable oxygen and carbon isotope analyses were performed on whole-rock samples following procedures described in Schmitz et al. (1997, 2001).

3. Planktic foraminifera

Planktic foraminifera are absent in the basal 70 m because of the shallow and restricted environment of deposition of the uppermost Thanetian and the lowermost Ilerdian. In the lower Ilerdian planktic foraminifera are scarce and poorly preserved. Their abundance increases and their preservation improves from the base of the middle Ilerdian upward. Planktic foraminifera are frequent in the overlying 200 m and become very abundant toward the top of the Riguala Marls (Fig. 3).

The planktic foraminiferal assemblages are dominated by the genera *Subbotina*, *Morozovella*, *Acarinina* and *Muricoglobigerina*. In addition, scarce "*Chiloguembelina*" specimens have been identified by Canudo (1991) and Orue-Etxebarria et al. (2001). The most abundant species in the Campo section are *Subbotina eocaenica* (= *S. linaperta*), *S. triangularis*, *S. hornibrooki*, *Muricoglobigerina aquiensis*, *Mg. soldadoensis*, *Morozovella subbotinae*, *M. lacerti*

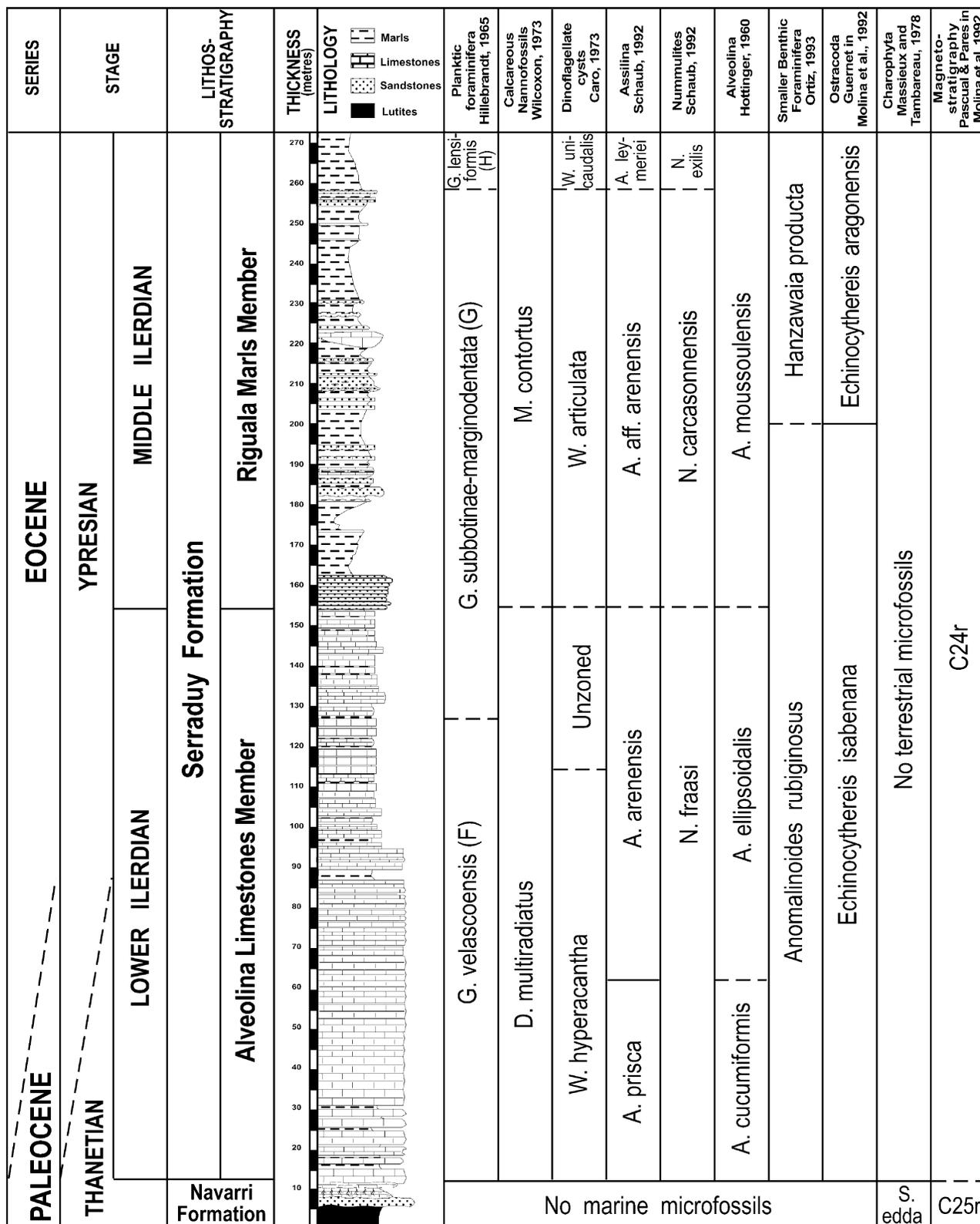


Fig. 2. Integrated stratigraphy of the Campo section (modified from Schaub, 1992).

Fig. 2. Stratigraphie intégrée de la coupe de Campo (modifié de Schaub, 1992).

(= *M. tholiformis*), *M. aequa*, *M. gracilis*, *Acarinina acarinata*, *A. pseudotopilensis*, *A. wilcoxensis* and *A. strabocella*. Species of the genus *Subbotina* are very abundant (50–80%)

in the uppermost Lower Ilerdian, decreasing in abundance to 10–40% in the Middle Ilerdian. The decrease in abundance of representatives of the genus *Subbotina* is parallel to a rise in

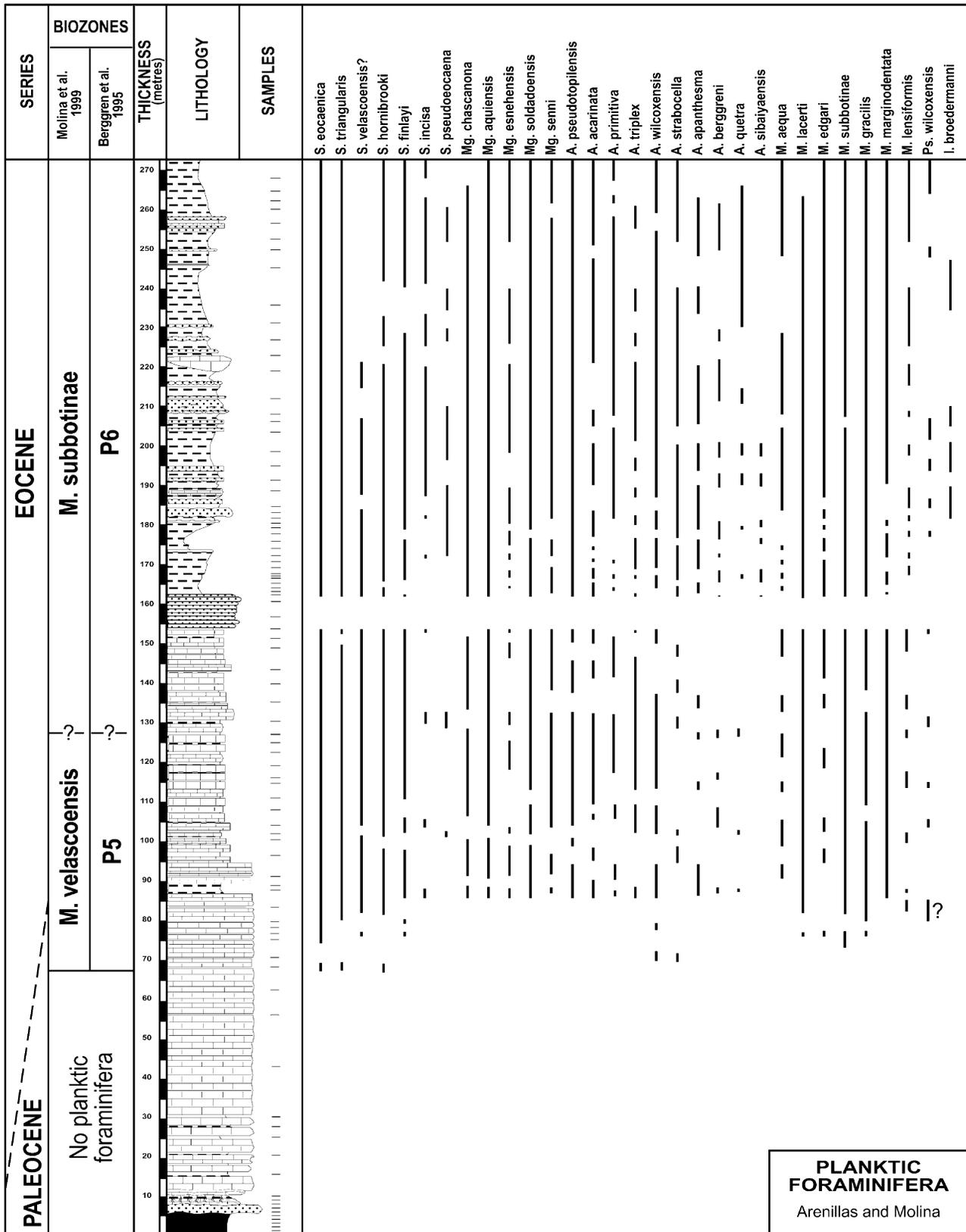


Fig. 3. Revised planktic foraminiferal biostratigraphy of the Campo section.
 Fig. 3. Biostratigraphie révisée de foraminifères planctoniques de la coupe de Campo.

the numbers of specimens belonging to the genera *Acarinina* and *Morozovella*. This slight increase in the frequency of *Acarinina* and the apparent last occurrence (LO) of *Igorina laevigata* were used by Arenillas and Molina (1995) to place the Paleocene/Eocene boundary.

The group of “large” morozovellids, which include *Morozovella velascoensis*, *M. acuta*, *M. parva*, *M. occlusa* and *M. crosswicksensis*, is absent in the Ilerdian. This could be due to the shallow water depth and the restricted connection with the open marine realm. The absence of the prominent index species *M. velascoensis* prevents a reliable planktic foraminiferal biozonation of the Lower Ilerdian. The impoverished planktonic foraminiferal faunules found in the Lower Ilerdian of the Campo section are tentatively attributed to the *M. subbotinae* Biozone (*M. edgari* Subzone).

Hillebrandt (1965) identified the following biozones in the Campo section: *G. velascoensis* (“Zone F”), *Globorotalia marginodentata-subbotinae* (“Zone G”) and *Globorotalia lensiformis* (“Zone H”), which correlate with the *A. cucumiformis*, *A. ellipsoidalis* and *A. moussoulensis*. von Hillebrandt (1965) tentatively equated the *G. velascoensis* (F) Biozone with the Lower Ilerdian *A. cucumiformis* Biozone and the lower part of the *A. ellipsoidalis* Biozone. He recognized the first occurrence (FO) of *Pseudohastigerina eocænica* (= *P. wilcoxensis*) near the boundary between the *A. cucumiformis* and the *A. ellipsoidalis* Biozones. However, poorly preserved benthic foraminiferal specimens belonging to the genera *Valvulineria* or *Anomalinoidea* species may be confused with representatives of the genus *Pseudohastigerina*. Nevertheless, Canudo et al. (1989), Canudo (1991) and Molina et al. (1992) identified typical *P. wilcoxensis* in the Middle Ilerdian (Rigualá Marls), which suggests the presence of the *M. aequa-subbotinae* and *P. wilcoxensis* biozones, which are equivalent to the *M. velascoensis*, *M. edgari* and *M. subbotinae* biozones of Toumarkine and Luterbacher (1985).

Molina et al. (2000) suggested that the Paleocene/Eocene boundary approximately coincides with the boundary between the Lower and the Middle Ilerdian boundary, based on the traditional correlation, the presence of *Acarinina berggreni*, *Acarinina sibaiyaensis*, *P. wilcoxensis* and the presence of the nannofossil *Rhombaster bramlettei* within a CIE close to 165 m. The same index species were used in Molina et al. (1999) for the subdivision of the Paleocene–Eocene transition. In their preliminary study, Molina et al. (2000) provisionally placed the base of the *A. berggreni*, *A. sibaiyaensis* and *P. wilcoxensis* subzones between 150 and 175 m of the studied section. However, according to new biostratigraphical data published by Orue-Etxebarria et al. (2001) and our own revision, this tentative biozonation must be abandoned mainly because *A. berggreni* and *P. wilcoxensis* have been found in older levels. The FO of *Igorina broedermanni* at 180 m which in other sections is observed close to the LO of *M. velascoensis* (Molina et al., 1999) could be used to draw approximately the top of the *M. velascoensis* Biozone in the Campo section.

Orue-Etxebarria et al. (2001) identified *M. occlusa*, *P. wilcoxensis*, *I. laevigata* (= *Igorina albeari*) and *Igorina pusilla* and other index species in their Member 2c of the lower Alveolina Limestone. If the LOs of *I. pusilla* and *I. laevigata* really occur in the Member 2c, the Paleocene/Eocene boundary should be placed above 85 m in accordance with the ranges of these species published by Canudo et al. (1995), Arenillas and Molina (1996), Berggren and Norris (1997), Molina et al. (1999) and Olsson et al. (1999). However, we could not confirm the presence of these species. *Igorina lodoensis* could be present in the lower Ilerdian. Specimens identified as “*I. laevigata*” by Arenillas and Molina (1995) in the basal part of the *A. moussoulensis* Biozone are now included in *I. broedermanni*.

Orue-Etxebarria et al. (2001) indicate the presence of *M. occlusa* in the Member 2c suggesting that the planktic foraminifera found in this member belong to the upper part of Zone P5 of Berggren et al. (1995). In this case, the Paleocene/Eocene boundary based on the CIE would have to be placed below the base of the Ilerdian, since *M. occlusa* disappears approximately at the same time as *M. velascoensis*. However, specimens illustrated by Orue-Etxebarria et al. (2001: Pl. 1, Figs. 8–11) as “*M. occlusa*” are in so far atypical since they have a completely muricate wall, whereas the specimens illustrated by Berggren and Norris (1997) and Olsson et al. (1999) as *M. occlusa* have a finely perforate wall which is nearly free of muricae, except in the muricocarinat and the circum-umbilical rim.

Hillebrandt (1965) and Orue-Etxebarria et al. (2001) reported the presence of *P. wilcoxensis* above 85 m. The FO of this species is generally above the Paleocene/Eocene boundary (Molina et al., 1999) and may be very useful to clarify the biostratigraphic position of the Ilerdian. Nevertheless, the very rare and doubtful specimens similar to *P. wilcoxensis* recovered by us from the same interval cannot be reliably attributed to any species.

4. Calcareous nannofossils

Calcareous nannofossils are present throughout the Campo section even though they are very rare and poorly preserved in the lower part of the section and improve upwards both in abundance and preservation. Reworked Cretaceous species are also present throughout the section and become particularly abundant above 165 m. Nevertheless, the ranges and succession of the most important markers in the rare “autochthonous” Paleogene assemblages of the Campo section are the same as observed in other sections covering the same interval of the Paleogene (Fig. 4).

The first studies of calcareous nannofossils of the Campo section are those by Wilcoxon (1973) and Kapellos and Schaub (1973, 1975). The latter two authors stressed the correlation between the zonations based on larger foraminifera and on calcareous nannofossils. Recently, a more detailed biostratigraphic study has been completed by Angori

and Monechi in Molina et al. (2000) across the Paleocene/Eocene boundary. Orue-Etxebarria et al. (2001) reexamined the planktic microfossils of the upper Thanetian-middle Ilerdian interval and reached a somewhat different correlation of the zonations based on larger foraminifera with those based on planktic microfossils.

The age assignment of the very poor and badly preserved assemblages of the samples collected in the lower part of the section (Navarri and Serraduy Formations) is very difficult. The occurrence of *Discoster multiradiatus* at 20 m allows to assign this interval to Zone NP9 of Martini (1971), which is defined by its first occurrence. Samples collected above 20 m are either barren of calcareous nannofossils or are characterized by poorly preserved assemblages including specimens of *D. multiradiatus*, *Coccolithus pelagicus* and *Toweius pertusus*.

The richness of the assemblages increases upward (mainly from 60 m upward). They are mainly composed of *C. pelagicus*, *Sphenolithus moriformis*, *S. primus*, *Campylosphaera eodela*, *Zygrabliothus bijugatus*, *T. pertusus*, *Chiasmolithus* spp., pentoliths and discoasters. Specimens of *Fasciculithus* are absent. So, according to the previous recognized nannofossil assemblage this interval can be confidently assigned to Zone NP 9. Bernaola (in Orue-Etxebarria et al., 2001) studied the same section and reported for this interval the same assemblages, but minor differences concern the occurrence of *Rhomboaster* and *Discoaster diastypus*. Nannofossil workers generally agree that the FO of *R. bramlettei* defines the base of Zone NP10 of Martini (1971), but the concept of this species is controversial (Aubry et al., in press; Von Salis et al., 2000). According to the usage of Bybell and Self-Trail (1995) and Angori and Monechi (1996) followed in this paper the FO of *Rhomboaster* (*R. bramlettei* “with short arms” of Angori and Monechi in Molina et al., 2000 = *R. cuspis* of several authors) defines the base of Zone NP10.

In Molina et al. (2000), we reported that the base of Zone NP10 approximately coincides with the boundary between the lower and the middle Ilerdian. According to the present new revision of the calcareous nannofossils, the lowermost very rare specimens of *Rhomboaster* cf. *R. bramlettei* “with short arms” have been found around 90 m and few scattered specimens of *R. bramlettei* “with short arms” around 100 m. This species is consistently present above 130 m together with rare specimens of *R. bramlettei* var. T (= *R. bramlettei* according to Aubry et al., in press). Representatives of the so-called “cubic forms”, that usually precede the FO of *R. bramlettei* “with short arms”, have been found from 70 m upward. Orue-Etxebarria et al. (2001) observed the FO of *Rhomboaster* a few meters above the level indicated in the present paper. In the Campo section, the very small number of specimens of *Rhomboaster* renders difficult the unambiguous placement of the boundary between zones NP9 and NP10. In addition, few specimens related to *D. diastypus*, a species that defines the base of Zone CP9 of Okada and Bukry (1980), were observed at 100 m. Literature data indi-

cate that the boundary between zones NP9 and NP10 is usually somewhat older than the boundary between zones CP8 and CP9. Since the calcareous nannofossils assemblages in the lower part of the section are very poor, the base of Zone NP10 is not clear-cut. Following the previous data it should be placed below 90 m, where very rare specimens of *Rhomboaster* cf. *bramlettei* “with short arms” have been found.

Preservation and abundance of nannofossils improve above 165 m. Starting with this level, reworked Upper Cretaceous specimens greatly increase. From the same level upward, the *Rhomboaster*–*Tribrachiatulus* lineage is documented by the successive FOs of *Tribrachiatulus digitalis*, *Rhomboaster contortus* and *Tribrachiatulus orthostylus*. The LO of *R. contortus* defines the base of Zone NP11 at 210 m. The FO of *Sphenolithus radians* is observed close to the FO of *T. orthostylus*, in agreement with the data reported by Pospichal and Wise (1990) and Bralower and Mutterlose (1995). Rare specimens of *Sphenolithus editus* have been observed prior to the FO of *T. orthostylus*.

5. Dinoflagellate cysts

Recent studies involving organic walled dinoflagellate cysts (dinocysts) from the Northern and Southern Hemispheres have indicated that the IETM is associated with a massive acme of *Apectodinium* spp. (Crouch et al., 2001). Moreover, additional dinocyst events in global Late Paleocene–Early Eocene sedimentary records have now become well established and calibrated (see e.g. overviews in Bujak and Brinkhuis, 1998; Crouch et al., in press). Several other papers have indicated that dinocysts are particularly well suited for correlations between proximal and distal marine sites (e.g. Brinkhuis, 1994). This plankton group is, therefore, of importance in correlating the predominantly marginal marine Paleogene stages of NW Europe to the often deeper marine settings of the GSSPs (cf. Brinkhuis and Visscher, 1995). In the frame of the multi-disciplinary search for a suitable Paleocene/Eocene GSSP, we analyzed a closely spaced set of samples from the Campo section for its dinocyst content. Earlier studies (e.g. Caro, 1973; Nuñez-Betelu et al., 2000) demonstrated the presence of dinocysts in this section, and prompted us to investigate potential Paleocene–Eocene transitions in the Campo section in more detail.

Although most samples contain abundant acid resistant organic remains (palynodebris), preservation is usually poor at best, and identifiable palynomorphs, including dinocysts are relatively scarce. In general, samples are dominated by sporomorphs. Dinocysts are the next most abundant palynomorph group. Only about 30 dinocyst taxa are recognized in the material. Meaningful quantification of the dinocyst portion is not possible in view of the above. Moreover, unfortunately, only few index taxa may be recognized with certainty. Most occurring taxa are long-ranging forms (e.g. *Glaphrocysta*, *Cordosphaeridium*, *Spiniferites*, *Operculodinium* and *Fibrocysta* spp.).

Detailed literature-based evaluation of the few significant FO/LO of taxa in the Campo section resulted in the recognition of the following important stratigraphic events (Fig. 5), viz. the FOs of *Apectodinium* spp., *Homotryblium* spp., *Deflandrea oebisfeldensis*, *Wetzeliella meckelfeldensis*, and *D. phosphoritica*. These findings do allow recognition of several NW European dinocyst zones; here we apply the zonal scheme of Bujak and Mudge (1994) Mudge and Bujak (1996), as it provides the highest resolution. Unequivocal is the recognition of the base of their E2 biozone, by the FO of *W. meckelfeldensis*, around 165 m. Recognition of their P5/P6 zonal boundary, defined by the FO of *Apectodinium margarita*, is not possible. Still, the lower portion of the Campo section may tentatively be assigned to biozone P6 of Bujak and Mudge, as *Apectodinium* spp., a common constituent of P6 assemblages are present above 65 m. Moreover, despite the apparent absence of the index species *Apectodinium augustum*, and absence of truly *Apectodinium*-dominated assemblages, tentatively the boundary between subzones P6a and P6b—and hence the Paleocene/Eocene boundary—may occur around 85 m. Around this level, *Apectodinium* spp. reach their highest relative abundance (up to an estimated 20% of the assemblage). The interval around 165 m is also characterized by relatively common *Apectodinium*, but here, this aspect coincides with the FO of *W. meckelfeldensis*. This second phase of *Apectodinium*-influx may represent a subsequent acme, recently identified to occur in association with the base of zone NP10 in the North Sea Basin and elsewhere (e.g. Powell et al., 1996; Crouch et al., in press). The FOs of *D. oebisfeldensis* and notably *D. phosphoritica* are in-line with such an age assessment (compare e.g. Powell et al., 1996; Bujak and Brinkhuis, 1998). In addition, the finding of early *Homotryblium* spp. in the lower part of the Campo section matches recent findings elsewhere (e.g. in Tunisian and Kazakhstani sections, Crouch et al., in press; Iakovleva et al., 2001), that representatives of this genus may occur as early as in Late Paleocene times.

6. Stable isotopes

Previous isotopic studies of the Paleocene and earliest Eocene part of the Zumaya section have shown that whole-rock samples of limestone and calcite-rich marls from this section give reliable $\delta^{13}\text{C}$ results. These sediments were indurated or compacted during early diagenesis and represent relatively closed systems with respect to carbon isotopes. The $\delta^{13}\text{C}$ signal of the abundant marine calcite in the sediments also overprints signals from any carbonate that possibly has precipitated in pores during diagenesis. In the Campo section, however, lithology is different from that at Zumaya and isotopic results are much more unreliable. In the lower part of the section, dominated by Alveolina limestones, $\delta^{13}\text{C}$ values are relatively positive, typically in the range 1–1.5‰ (Fig. 6). Considering that limestones show reliable $\delta^{13}\text{C}$ signals in other lower Paleogene sections in northern

Spain (Schmitz et al., 1997, 2001) also these Alveolina limestone signatures may be original.

The $\delta^{13}\text{C}$ values in the Alveolina limestones are similar to those in upper Paleocene–lower Eocene limestones both in the Ermua and Zumaya sections. The gradual decline in $\delta^{13}\text{C}$ from the top of the Alveolina limestone and upwards through the Campo section correlates with a decline in $\delta^{18}\text{O}$. This strongly indicates a diagenetic effect. The very low values of –2 to –4‰ in $\delta^{13}\text{C}$ in the sandy sediments in the upper NP10 and NP11 Zones very likely reflect diagenetic alteration. Coarse-grained siliciclastic sediments are generally not suitable for isotope studies, since calcite content is low and pore space large, providing ample possibilities for diagenetic overprinting. Considering the unstable trend in stable isotopes throughout the Campo section, and the clear evidence of diagenetic overprinting at some levels, it is not possible to say whether the small negative excursion around meter 85 reflects the CIE or not. Isotopic analyses on organic matter extracted from the sediments could give a more reliable $\delta^{13}\text{C}$ curve.

7. Discussion

The Ilerdian has been introduced by Hottinger and Schaub in 1960 based on larger foraminifera, which are of prime importance for the classic Paleogene stratigraphy of the Eastern Hemisphere. The Campo section has been selected by Schaub (1969) as parastratotype since it is located in a more distal position than the stratotype defined in the Tremp section. The lower part of the Ilerdian is mainly represented by the shallow marine Alveolina limestones, which contain only very poor and poorly preserved planktonic foraminifera and calcareous nannofossils, which generally defy unequivocal age attributions. A few levels have yielded dinoflagellate cysts, which allow to recognize a series of events, which can be used for correlations. From the middle Ilerdian onward, the site of the Campo section becomes part of the eastern margin and slope of the narrow trough extending from the Basque Country to the Alto Aragón area. Depositional environments deepen rather abruptly and planktic microorganisms become richer and more diversified, but a large part of the sediments and microfossils is redeposited. Nevertheless it is possible to recognize a coherent succession of the calcareous nannofossils and planktonic foraminiferal zones as recognized elsewhere.

In their subdivision of the Paleogene based on larger foraminifera, Hottinger and Schaub (1960) considered the Ilerdian as the youngest stage of the Paleocene and started the Eocene with the Cuisian (base of the *Nummulites planulatus* Zone). According to Aubry (2000) and Aubry et al. (in press) the base of the Ypresian stratotype coincides with the FO of *T. digitalis*. The redefinition of the Paleocene/Eocene boundary based on the proposed GSSP with the CIE as main correlative criterion raises the question of the position of the Ilerdian in relation to this boundary. The Paleocene/Eocene boundary corresponds to the BFEE. It is placed in the middle

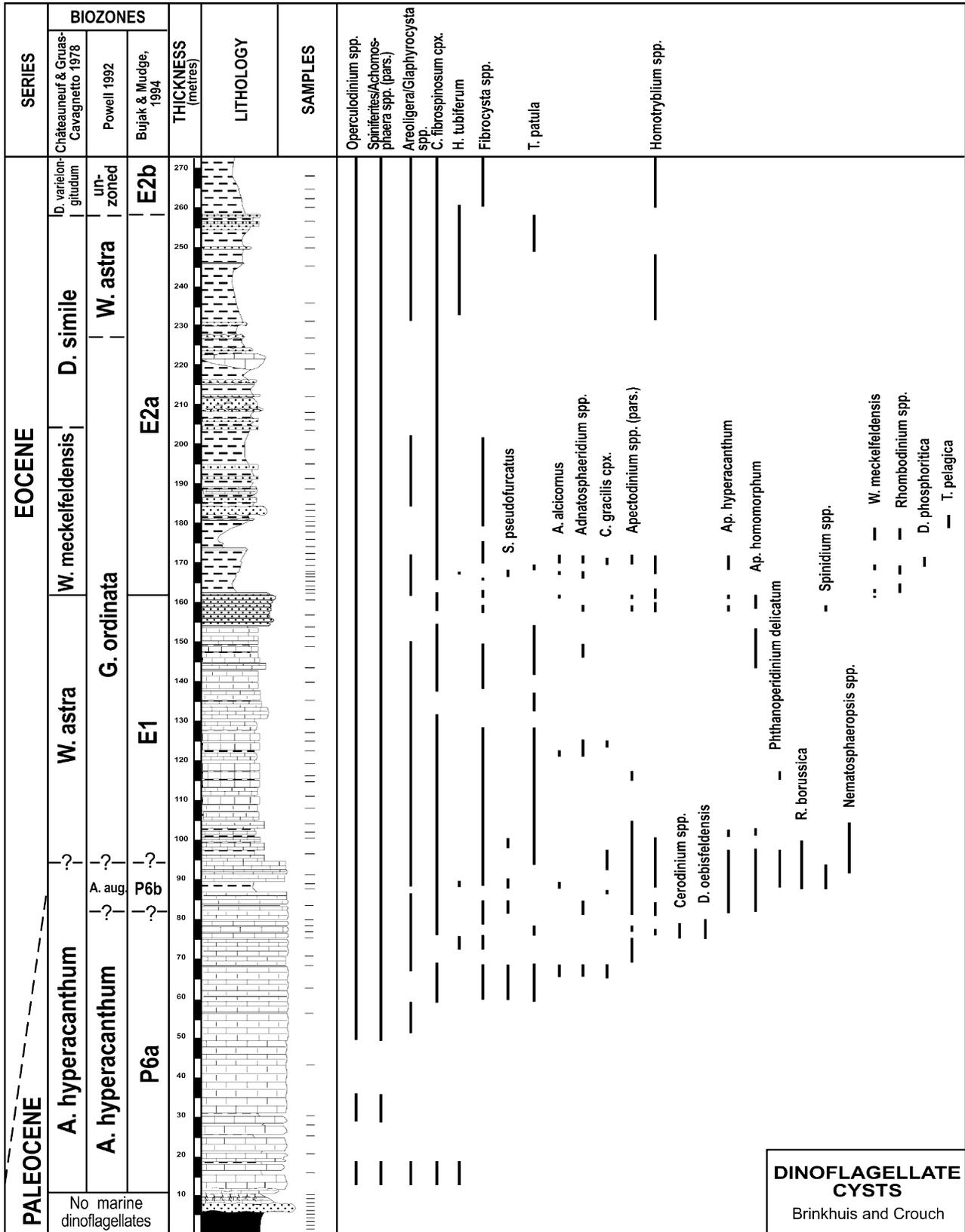


Fig. 5. Revised Dinoflagellate cyst biostratigraphy of the Campo section.

Fig. 5. Biostratigraphie révisée de dinoflagellés de la coupe de Campo.

part of the planktic foraminiferal *M. velascoensis* Zone (P5) of Berggren et al. (1995) and the boundary between the calcareous nannofossils zones NP9 and NP10 (Monechi and Von Salis in Schmitz et al., 1997).

Whereas these criteria for the Paleocene/Eocene boundary are easily recognized in the pelagic sections of the Western Pyrenees (Ermua, Trabakua and Zumaya; see Canudo and Molina, 1992; Canudo et al., 1995; Schmitz et al., 1997; Orue-Etxebarria et al., 1996; Molina et al., 1999; Arenillas and Molina, 2000; Schmitz et al., 2001), they cannot be readily located in the shallow neritic facies as found e.g. in the Campo section.

Based on planktic foraminifera, von Hillebrandt (1965) correlated the base of the Ilerdian with the base of his Zone F or *G. velascoensis* Zone. Although he did not find *M. velascoensis* in the Campo section, he based this correlation on the abundant occurrence of this species in the Zumaya section. Consequently, von Hillebrandt (1965) placed the base of the Ilerdian at Zumaya 40 m below the Paleocene/Eocene boundary as defined by the CIE. This traditional correlation was mainly followed by Canudo and Molina (1992), Canudo et al. (1995), Schmitz et al. (1997), Molina et al. (1999) and Arenillas and Molina (2000).

Wilcoxon (1973) attributed the lower Ilerdian in the Campo section to the *D. multiradiatus* Zone. Kapellos and Schaub (1975) correlated the base of the Ilerdian in the same section with middle part of the *D. multiradiatus* Zone (= Zone NP9 of Martini, 1971) and placed the *D. multiradiatus*/*Marthasterites contortus* (= NP9/NP10) zonal boundary in the *A. ellipsoidalis* and *A. arenensis* zones. In the Zumaya section, Kapellos (1974) located the base of the Ilerdian in the *D. multiradiatus* Zone at the same level as von Hillebrandt (1965). Caro (1973) placed the base of the Ilerdian in the middle part of the *W. hyperacantha* Zone and correlated the top of this zone with the top of the *D. multiradiatus* Zone and the *G. velascoensis* Zone (sensu von Hillebrandt, 1965), i.e. approximately at the lower/middle Ilerdian boundary.

According to von Hillebrandt (1965), Wilcoxon (1973), Caro (1973) and Kapellos and Schaub (1975), the lower Ilerdian of the Campo section belongs to the *G. velascoensis* Zone (sensu von Hillebrandt 1965), the Zone NP9 and the *W. hyperacantha* Zone. This traditional correlation implies that the recently proposed Paleocene/Eocene boundary based on the CIE has to be placed within the lower Ilerdian. Most of the authors that studied the Ilerdian of the Campo section accepted this correlation (Canudo et al., 1989; Canudo, 1991; Molina et al., 1992; Serra-Kiel et al., 1994). In preliminary studies published at meetings in Treppe and Göteborg, Arenillas and Molina (1995) and Molina et al. (2000) thought to have found the CIE marking the Paleocene/Eocene boundary close to the boundary between the lower and the middle Ilerdian boundary, since a negative $\delta^{13}\text{C}$ excursion had been recorded at 165 m. In the Göteborg meeting, Pujalte et al. (2000) questioned this correlation mainly because in the Ermua section (northern Spain) an assemblage of the basal

Ilerdian *A. cucumiformis* Zone (SBZ5) had been found associated with the CIE marking the Paleocene/Eocene (Orue-Etxebarria et al., 1996). In a restudy of the calcareous nannofossils of the Campo section, Orue-Etxebarria et al. (2001) reached the conclusion that the larger foraminiferal turnover, which marks the base of the Ilerdian would be coeval or nearly coeval with the CIE and the BFEE which mark the Paleocene/Eocene boundary.

Our revision of the calcareous plankton undertaken in view of these discrepancies has convinced us that the poor and badly preserved assemblages obtained in the lower Ilerdian are not conclusive. Therefore, we have complemented our revision by a restudy of the dinoflagellate cysts, because considerable progress has been made since the pioneering study of Caro (1973). Dinoflagellate data indicate that the $\delta^{13}\text{C}$ excursion present at 165 m does not correspond to the CIE marking the Paleocene/Eocene boundary as indicated by Molina et al. (2000), because this level corresponds to the *W. meckelfeldensis* Zone. The turbiditic interval at 160 m, that corresponds to the *Wetzeliella astra* Zone is well below the FO of *T. digitalis*, and therefore, could correspond to the base of the Ypresian stage.

According to the correlation of our revised data on the calcareous plankton, the dinoflagellate cysts and the $\delta^{13}\text{C}$ and the $\delta^{18}\text{O}$ values (Fig. 6), the Paleocene/Eocene boundary could be placed either at the negative excursion of the $\delta^{13}\text{C}$ and the $\delta^{18}\text{O}$ at 85 m or at the base of the Ilerdian. The scarcity or absence of calcareous and palynomorph plankton in the lowermost Ilerdian does not allow to discriminate between these two possibilities.

Planktic foraminifera are very rare or absent below 85 m. The index species *M. velascoensis* has not been found, but *Acarinina quetra*, *Muricoglobigerina senni*, *Morozovella lensiformis* and *P. wilcoxensis* have been found at this level. These species are known to appear after the Paleocene/Eocene boundary as observed in the Zumaya section (Arenillas and Molina, 2000), thus indicating that the CIE observed at 85 m is unlikely to be the Paleocene/Eocene boundary event. The presence of rare specimens of *Rhombaster* cf. *R. bramlettei* "with short arms" (= *R. cuspis*) at 90 m and of *D. diastypus* at 100 m suggests that the boundary between zones NP9 and NP10 could be below this level. Representatives of the dinoflagellate cyst genus *Apectodinium* reach their highest relative abundance (<20% of the total assemblage) around 85 m. Consequently, based on dinoflagellate cysts the P/E boundary could be placed around 85 m. An ambiguous CIE is present in a 2 m thick marly layer, which is the thickest marly intercalation in the Alveolina Limestone.

Pujalte et al. (2000), Payros et al. (2000) and Orue-Etxebarria et al. (2001) suggest to place the Paleocene/Eocene boundary below the base of the Ilerdian at the base of the terrestrial interval underlying the lower Ilerdian Alveolina Limestone. However, these 6 m thick lutites contain charophytes attributed by Massieux and Tambareau (1978) to the uppermost Thanetian *S. edda* Zone. In the continental deposits of the Paris Basin, the CIE indicating the

Paleocene/Eocene boundary has been identified by Sinha et al. (1996) in the lower part of the Sparnacian attributed to the *Peckichara disermas* Zone. According to Rivelino et al. (1996), the *S. edda* Zone is placed in the upper Thanetian and is thought to correlate with the upper part of the planktic foraminiferal Zone P4. The terrestrial interval underlying the Alveolina Limestone cannot be attributed to the Ilerdian as suggested by Payros et al. (2000) and Orue-Etxebarria et al. (2001). Furthermore, the Ilerdian stage was defined as a marine stage having its base at the *A. cucumiformis* Zone. Later, a hiatus was identified by Molina et al. (1992) below the base of the Ilerdian at Campo. Another hiatus could exist between the terrestrial interval and the limestones in the upper Navarri Formation and in one of these hiatuses is missing C25n.

The proposition to place the Paleocene/Eocene boundary below the base of the Ilerdian would be in contradiction with correlations between larger foraminiferal zones and calcareous plankton zonations, in which the base of the Ilerdian, marked by a significant radiation within the larger foraminifera (Zone SBZ5), is found within the *M. velascoensis* Zone (Zone P5) and the *D. multiradiatus* Zone (Zone NP9), see e.g. Kapellos and Schaub (1973, 1975), Luterbacher (1998), Serra-Kiel et al. (1998). The time-equivalence of the radiation event among the larger foraminifera with the IETM (Orue-Etxebarria et al., 2001) cannot be confirmed at Campo section.

8. Conclusions

The Paleocene/Eocene boundary defined by the CIE as main correlative event corresponds in open marine sections to the BFEE (benthic foraminiferal extinction event), the acme of representatives of the planktic foraminiferal genus *Acarinina* in the middle part of the *M. velascoensis* Zone, the boundary between the calcareous nannofossils zones NP9 and NP10 marked by the FO of *R. bramlettei* (= *R. cuspis* of several authors) and the acme of specimens attributed to the dinoflagellate cyst genus *Apectodinium* in the *A. augustum* Zone. These events mark the IETM and are dated at 54.9 Ma. All these events cannot be recognized unambiguously in the Campo section, because the critical interval is represented in marginally marine to terrestrial facies and may contain one to several hiatus. The very poor and badly preserved calcareous plankton in the lower Ilerdian Alveolina Limestone do not allow reliable correlations with the successions in open marine sections. The occurrence of a few species known to start at or above the base of the Eocene close to the 80 m level of the section suggests to look for the Paleocene/Eocene boundary between the 85 m level and the hiatus at the base of the Alveolina Limestone. Likewise, the very poorly preserved calcareous nannofossil assemblages in the lower part of the section prevent to trace reliably the base of Zone NP10, but imply that it is probably below the 90 m level. In spite of the generally poor preservation of the palynomorphs, a few potentially important dinocyst events have been recognized.

The succession of the events, and notably the oldest relative increase in numbers of *Apectodinium* spp. around 85 m may reflect the Paleocene–Eocene transition, and in particular the onset of the IETM.

The arguments to place the Paleocene/Eocene boundary at the 85 m level of the Campo section are not conclusive. The small $\delta^{13}\text{C}$ excursion could correspond to the CIE, but data on stable C and O isotopes are strongly affected by diagenesis, and therefore, unreliable in the present lithologies. Another possibility would be to draw the Paleocene/Eocene boundary below the lower Ilerdian Alveolina Limestone as favored by Pujalte et al. (2000) and Orue-Etxebarria et al. (2001). However, the lack of conclusive planktic and palynomorph microfossils as well as of reliable data on the stable isotopes prevent to prove or disprove this proposal.

Finally, the interval containing the Paleocene/Eocene boundary may not be represented in the Campo section as indicated by the hiatus separating the base of the lower Ilerdian Alveolina Limestone and the underlying terrestrial lutites with charophytes attributed to the uppermost Thanetian.

At present, the problem of the position of the Paleocene/Eocene boundary in the Campo section and the correlation of this boundary with the base of the Ilerdian remains questionable, since the present data does not allow to determine the exact level of the P/E boundary in the Campo section. Further studies concentrating on the correlation of the zonations based on larger foraminifera and planktic microfossils in better-suited sections are needed to solve this problem.

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