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Integrated stratigraphy and chronostratigraphy across the Ypresian-Lutetian transition in the Fortuna Section (Betic Cordillera, Spain)

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with 6 figures

Abstract. This integrated study across the Ypresian/Lutetian boundary in the Fortuna Section (Spain) allowed us to recognize a bundle of events in the transitional interval between the Ypresian and Lutetian stages. Planktic foraminifera show an apparently continuous succession spanning the planktic foraminiferal zones P9, P10 and P11. Calcareous nannofossils allowed the recognition of the nannofossil subzones NP14b, NP15a, NP15b and of zone NP16. Small benthic foraminiferal assemblages may indicate a hyperthermal event as evidenced by a bloom of *Aragonia aragonensis*, which is coeval with a major change in clay mineralogy. This event coincides with the first occurrence of *Hantkenina* specimens at the base of planktonic foraminiferal zone P10 in the uppermost part of nannofossil subzone NP14b, which could be used to define the Ypresian/Lutetian boundary.

Zusammenfassung. Im Profil von Fortuna (SE Spanien) weisen die planktonischen Foraminiferen im Übergangsbereich vom Yprésien zum Lutétien eine kontinuierliche Abfolge auf, welche die Planktonforaminiferen-Zonen P9, P10 und P11 umfasst, während die kalkigen Nannofossilien die Nannofossil-Subzonen NP14b, NP15a, NP15b und die Nannofossil-Zone NP16 anzeigen. Bei den benthonischen Kleinforaminiferen wurde möglicherweise eine von einem bedeutenden Wechsel im Spektrum der Tonmineralien begleitete Blüte von *Aragonia aragonensis* durch ein hyperthermales Ereignis verursacht. Dieses fällt mit dem ersten Vorkommen von Individuen der Gattung *Hantkenina* an der Basis der Planktonforaminiferen-Zone P10 und im obersten Teil der Nannofossil-Subzone NP14b zusammen und kann damit der Festlegung der Yprésien/Lutétien-Grenze dienen.

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Introduction

An international working group of the International Subcommission on Paleogene Stratigraphy is searching for a suitable section to define the Global Stratotype Section and Point (GSSP) for the Ypresian/Lutetian (Y/L) boundary. The Y/L boundary corresponds to the lower/middle Eocene boundary and must be defined near the base of the Lutetian stratotype, preferably outside the Paris Basin where a suitable continuous section is found. Such a section does not exist in the epeiric Paris Basin. A chronostratigraphic boundary is defined by its GSSP, which is a point in a rock sequence. A good boundary level will usually be marked by one marker event, such as the phyletic first appearance or the extinction of a taxon, a magnetic reversal, or a mineralogical or isotopic signal. The boundary level should be chosen within a "bundle" of successive events, enabling reliable good approximate correlation in the absence of the primary marker (Remane et al. 1996).

Several countries (France, Italy, Morocco, Tunisia, Israel, Cuba and Spain) have been visited by the working group searching for a suitable section, and many sections have been studied in order to delineate a bundle of successive events across the Y/L boundary. In Spain, many sections have been sampled and studied, and several have been selected for a more detailed study (Agost, Alamedilla and Fortuna). These sections are the best exposed ones, with the most continuous and best preserved pelagic sediments rich in calcareous nannofossils and foraminifera (Gonzalvo 1997, 1999, Gonzalvo & Molina 1998, Molina et al. 2000). At present, one of the best sections may be the Fortuna Section, which in preliminary studies (Gonzalvo et al. 2001, Gonzalvo & Molina 2003, Ortiz & Molina 2003, Mancheño et al. 2003) showed potential to be a suitable candidate for the definition of the Y/L boundary. The present integrated study, based on planktic foraminifera, benthic smaller foraminifera, calcareous nannofossils, stable isotopes and clay mineralogy, recognizes a bundle of successive events, allowing a detailed stratigraphy across the Y/L boundary.

Materials and methods

The Fortuna Section is located in the Murcia Region (southeastern Spain), 10 km North of the village of Fortuna, along the northern slope of road A-17, between Fuente Blanca and Peña de la Zafra, 200 m NE from La Rauda ravine (Fig. 1).

The geological setting of this section is in the meridional Prebetic realm of the Betic Cordillera, developed in a transitional facies between the external Subbetic and the internal Prebetic. The section is located exactly in the periclinal closure of the La Garapacha Anticline.

The lithology consists of marls in the lower 20 m, limestones from m 20 to 30 and marls in the upper part. Some marly limestones and calcarenite layers are interbedded in the marls, and conglomerates are interbedded in the limestone interval. The lower 20 m of marls were sampled in more detail since they correspond to the critical interval spanning the Y/L transition. A total of 33 samples was collected for an integrated study, including planktic and benthic foraminifera, calcareous nannofossils, mineralogy and stable isotopes.

For the study of planktic foraminifera samples were disaggregated in water and washed through a 100 µm sieve. Each sample was cleaned using ultrasonic agitation, with wash-

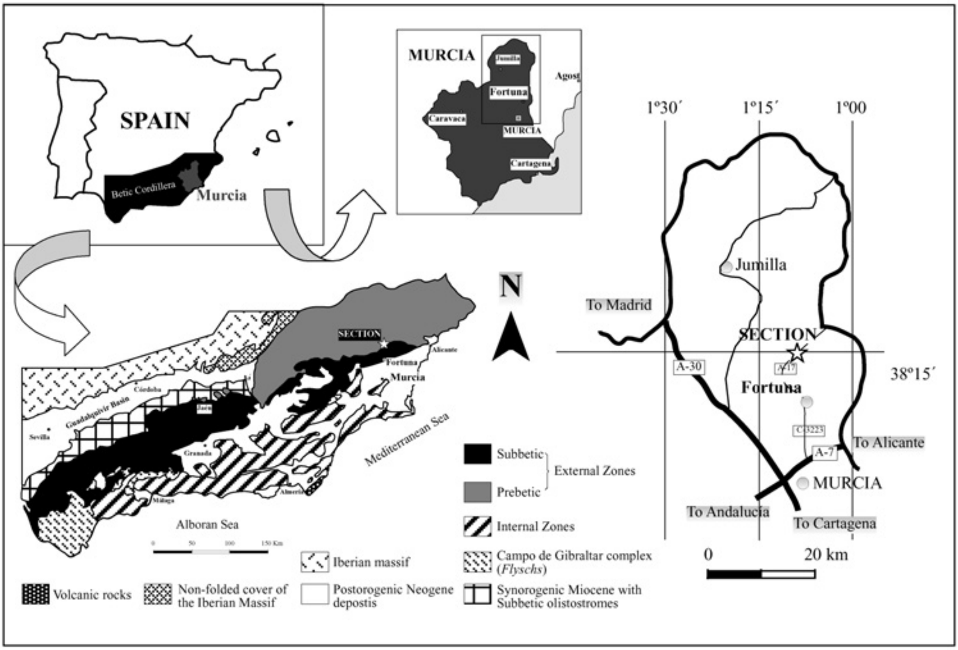

Fig. 1. Location of the Fortuna Section.

ing repeated until a clean foraminiferal residue was recovered. The final residue was dried in an oven at a temperature below 50 °C. Quantitative analyses of planktic foraminifera are based on representative random splits (using an Otto microsplitter) of more than 300 specimens; the remaining sample was searched for rare species.

For smaller benthic foraminifera we used the same residue as in the study of planktic foraminifera. About 300 specimens were picked and counted from a split of the > 100 μm size fraction. All samples except sample For 31 contained sufficient specimens for the study. The preservation of the benthic foraminifera is fairly good, less so in samples For 13 and For 13.5.

For the study of calcareous nannofossils, smear slides were prepared and studied by light microscope at a magnification of 1,000 ×. The calcareous nannofossil content varies from very rare to few/common, and the preservation ranges from poor to moderate.

Stable carbon and oxygen isotope analyses were performed on whole-rock samples and on specific benthic foraminifera, *Cibicidoides hadjibulakensis* and *Lenticulina* spp. Between two and six foraminiferal tests were used for each analysis. The analyses were performed with a VG Prism Series II mass spectrometer attached to an Isocarb automated carbonate preparation system (Schmitz et al. 2001). All values are expressed as per mil differences with respect to the PDB standard. The mean values and standard deviations of 24 analyzed NBS-19 standards are 1.98 ± 0.02 ‰ for $\delta^{13}C$ and –2.25 ± 0.04 ‰ for $\delta^{18}O$.

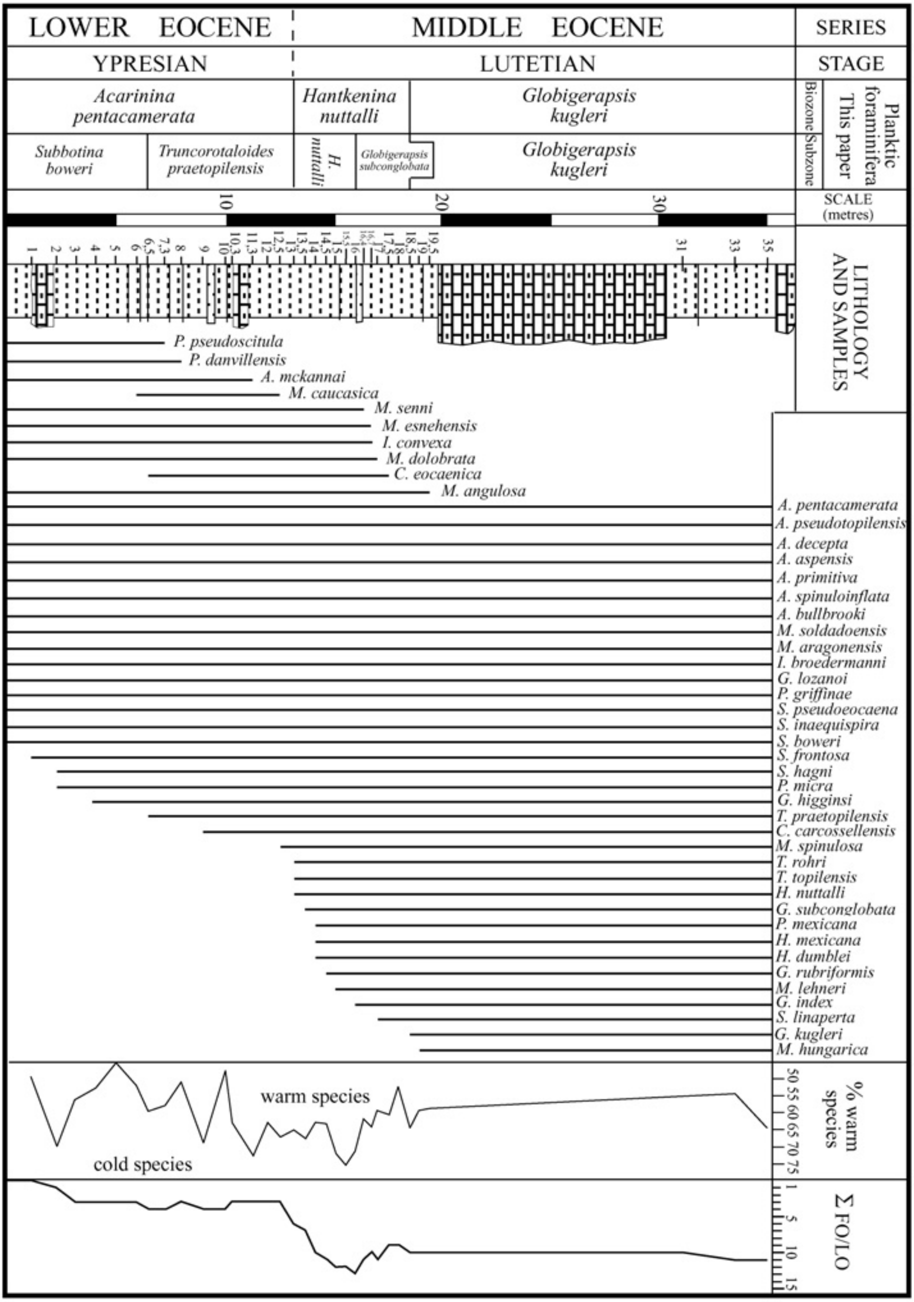

Fig. 2. Planktic foraminifera: biozonation, stratigraphical distribution, warm/cold index and appearance/extinction index.

A total of 30 whole-rock marl samples were analyzed by X-Ray Diffraction (XRD) in order to identify the mineral components and to conduct a semi-quantitative analysis of those minerals. Subsequently, clay extractions were made from all samples. These were studied using the oriented aggregates method and prepared for an estimate of their mineralogical properties by several procedures.

Planktic foraminifera

Planktic foraminifera are abundant and generally well preserved from the base of the section to 19.5 m, and in the upper 12 m of the section, although the tests are filled with sediment and the original calcite seems to be slightly recrystalized. The limestone interval and sample For 31 just above the limestone are barren and contain only few reworked specimens, probably due to the shallow environment of deposition.

The planktic foraminiferal biostratigraphy of the Fortuna section is based on the first and last occurrences of the species, which allows us to recognize the biozonation established by Gonzalvo & Molina (1998) for the lower-middle Eocene transition. The following biozones and subzones have been recognized: the upper part of the *Acarinina pentacamerata* Biozone, with the *Subbotina boweri* and *Truncorotaloides praetopilensis* Subzones (late Ypresian, early Eocene), the *Hantkenina nuttalli* Biozone (Lutetian, middle Eocene), with the *H. nuttalli* Subzone and the *Globigerapsis subconglobata* Subzone, and in the uppermost part of the section the *Globigerapsis kugleri* Biozone (Lutetian, middle Eocene) (Fig. 2).

The *Acarinina pentacamerata* Biozone is defined by Gonzalvo & Molina (1998) as the interval between the last occurrence (LO) of *Morozovella formosa* and the first occurrence (FO) of *Hantkenina nuttalli*, and is divided in three subzones: the *Acarinina pentacamerata* Subzone, the *Subbotina boweri* Subzone and the *Truncorotaloides praetopilensis* Subzone. This biozone is represented in the Fortuna section by 13 m of sediments of the *S. boweri* and *T. praetopilensis* subzones, which can be considered to be of early Eocene age. Dominant in this biozone is the nominate species *A. pentacamerata*; other common constituents include *M. soldadoensis*, *M. aragonensis*, *I. broedermanni*, *G. lozanoi*, *G. higginsi*, *S. boweri* and *S. inaequispira*.

In the early Eocene a faunal turnover started, which accelerated at the base of the middle Eocene. In the *S. boweri* Subzone three species first appeared (*S. frontosa*, *S. hagni* and *P. micra*), and in the *T. praetopilensis* Subzone additional three species first appeared (*T. praetopilensis*, *C. carcossellensis* and *Morozovella spinulosa*). In these two subzones four species (*P. pseudoscitula*, *P. danvillensis*, *A. mckannai* and *M. caucasica*) have their LO. The result is an increase in the species diversity in this subzone.

The *Subbotina boweri* Subzone is easy to recognize because *S. boweri* is frequent. In addition, some species of *Subbotina* first appear within this interval, i. e., *S. frontosa* and *S. hagni*. Furthermore, *G. higginsi* first appear in this subzone. No extinctions occur, but some characteristic and dominant species present from the middle early Eocene, *A. pentacamerata* and *M. soldadoensis*, decreased in abundance at the same time when others species appear for the first time.

The *Truncorotaloides praetopilensis* Subzone is characterized by the presence of the nominate taxon, which is the oldest species of the genus *Truncorotaloides*. *A. pentacamerata* and *M. soldadoensis* continued to decrease in abundance, and *P. pseudoscitula*, *A. mckannai*, *P. danvillensis* and the characteristic *M. caucasica* have their LO. There are three FOs in this subzone, those of *C. carcossellensis*, *M. spinulosa* and *C. eocaenica*. *Clavigerinella eocaenica* is the only clavigerinillid species found in this section. The FO of *M. spinulosa*, the species that dominated the middle Eocene assemblages, occurs at the top of this Subzone, below the FO of hantkeninids.

The *Hantkenina nuttalli* Biozone, a partial range zone between the FO of *Hantkenina nuttalli* and the FO of *Globigerapsis kugleri* (Gonzalvo & Molina 1998), is divided into the *H. nuttalli* and *Globigerapsis subconglobata* subzones. This biozone is recorded from 13 m to 18.5 m.

Within the *H. nuttalli* Biozone eleven species first appeared. An important first occurrence event is the FO of the genus *Hantkenina*. Representatives of this genus are good markers for the middle and upper Eocene, due to their distinctive morphology and thus easy identification. This bioevent coincides with the Ypresian/Lutetian boundary. The other FOs are the diversification of *"Globigerinatheka"*, including *Globigerapsis* and *Porticulasphaera*, and the genus *Truncorotaloides*. These FOs are coeval with several LOs, including those of three species in the genus *Muricoglobigerina*. The result is an increase of species diversity at the base of the middle Eocene, where 6 species have their LOs, whereas 11 have their FOs.

The *Hantkenina nuttalli* Subzone is characterized by the FO of the genus *Hantkenina*, in this section represented by the species *H. nuttalli*, which coincides with the FO of *T. rohri* and *T. topilensis*. Other species of *Hantkenina*, *H. mexicana* and *H. dumblei*, have a later FO. *G. subconglobata*, *P. mexicana*, *G. rubriformis* and *M. lehneri* have their FOs in this subzone. The FO of *G. index* is near the boundary with the next subzone. In the *H. nuttalli* Subzone no species have a LO, whereas 9 have a FO, so that the diversity increased by about 25 %. The assemblage is dominated by *A. bullbrooki*, *I. broedermanni*, *G. lozanoi*, *G. higginsi*, *S. inaequispira*, and *S. boweri*. Truncorotaloidids are constantly present, whereas hantkeninids are rare.

The *Globigerapsis subconglobata* Subzone represents the interval between the FO of *Globigerapsis index* and the FO of *G. kugleri*. Within this subzone there are only two FOs, that of *G. index* and that of *S. linaperta*, whereas there are 5 LOs, those of *I. convexa*, *M. senni*, *M. dolobrata*, *M. esnehensis*, and *C. eocaenica*. Overall, the species diversity thus declined in this subzone. The faunal assemblage is similar to that in the underlying subzone, and is characterized by the presence of abundant *A. bullbrooki*, *I. broedermanni*, *G. lozanoi*, *G. higginsi*, *S. pseudoeocaena*, and *S. boweri*. Truncorotaloidids are common and specimens of the *"Globigerinatheka"* group are constantly present.

The *Globigerapsis kugleri* Biozone was not defined by Gonzalvo & Molina (1998), and we also do not define it in this paper, because the Fortuna Section has a stratigraphic interval of about 10 m, which is not suitable for the study of planktic foraminifera. Only the base of this biozone is present, and its lower boundary is placed at the FO of *G. kugleri*. Close to this level, *Morozovella hungarica* also has its FO, whereas *Muricoglobigerina angulosa* has its LO. In the upper part of the section the faunal assemblage is characterized by a high abundance of *G. higginsi*, *G. lozanoi*, *S. inaequispira*, *M. spinulosa* and *Pseudohastigerina micra*, while truncorotaloidids, hantkeninids and specimens of the "globigerinathekid" group are common.

Overall, from the top of the *S. boweri* Subzone to the top of *H. nuttalli* Subzone, the diversity increased from 28 to 37 species. Nineteen FOs and 10 LOs occur across the transition from the lower to the middle Eocene, which represents a significant increase in the species diversity of the planktic foraminifera.

Benthic foraminifera

The benthic foraminiferal species have generally a more limited stratigraphic value than planktic species. Several long-ranging species, such as *Nuttallides truempyi*, *Oridorsalis umbonatus*, *Nonion havanense* and *Bulimina trinitatensis* (compare Tjalsma & Lohmann 1983) are present at low relative abundances. Other species, with a shorter range, such as *Aragonia aragonensis*, *Cibicidoides grimsdalei*, *Cibicidoides eocaenus*, *Hanzawaia ammophila*, and *Uvigerina rippensis* (compare van Morkhoven et al. 1986) are more abundant. The benthic foraminiferal assemblages do not allow us to derive an age more precise than early through middle Eocene.

The assemblages are generally highly diverse, with 50 to 75 species present in most samples. Generally, the assemblages contain a few dominant species and many are rare species. These species richness values are similar to those observed for bathyal to abyssal faunas of the same age at other locations (e. g., Thomas 1990). The exceptions are samples For 12 and 12.5, which contain only 34 and 44 species respectively. The most common calcareous taxa include various *Globobulimina* species (with *Globobulimina ovata* as most abundant taxon), *A. aragonensis*, various *Cibicidoides* species (including *C. eocaenus*), *Osangularia dominicana*, and various *Lenticulina* species (including *L. cultrata*). The most common agglutinated taxa include *Clavulinoides angularis*, *Thalmannammina subturbinata*, *Gaudryina arenata*, and *Dorothia cylindracea*. In most samples calcareous species dominate with a relative abundance of about 50–95 %. Infaunal species usually dominate over epifaunal species, with the latter varying between 10–45 %. Planktic foraminifera constitute about 65–95 % of the total foraminiferal assemblages.

Benthic foraminifera are widely used for paleobathymetric estimates (e. g., Tjalsma & Lohman 1983, van Morkhoven et al. 1986, Murray 1991). Samples For 1 through For 19.5 contain species commonly described as having an upper depth limit of 500–700 m (e. g., *N. truempyi*, *B. trinitatensis*, van Morkhoven et al. 1986), but they never reach more than a few percent. Various *Lenticulina* species are common, suggesting upper-middle bathyal depths (200–1,000 m) (e. g., Murray 1991, Bignot 1998). Neritic to upper bathyal taxa such as *Anomalinoides acutus* and *Osangularia plummerae* are present (Alegret & Thomas 2001). In the lower samples hispid species of *Uvigerina* are common, indicating an upper depth limit of ~ 600 m in the present oceans (Frerichs 1970, Pflum & Frerichs 1971).

Among the most abundant taxa in the Fortuna Section are species of *Globobulimina*, which in the present oceans occur over very large depth range, from neritic through abyssal depths (e. g., Murray 1991). *Aragonia aragonensis* is very abundant in samples

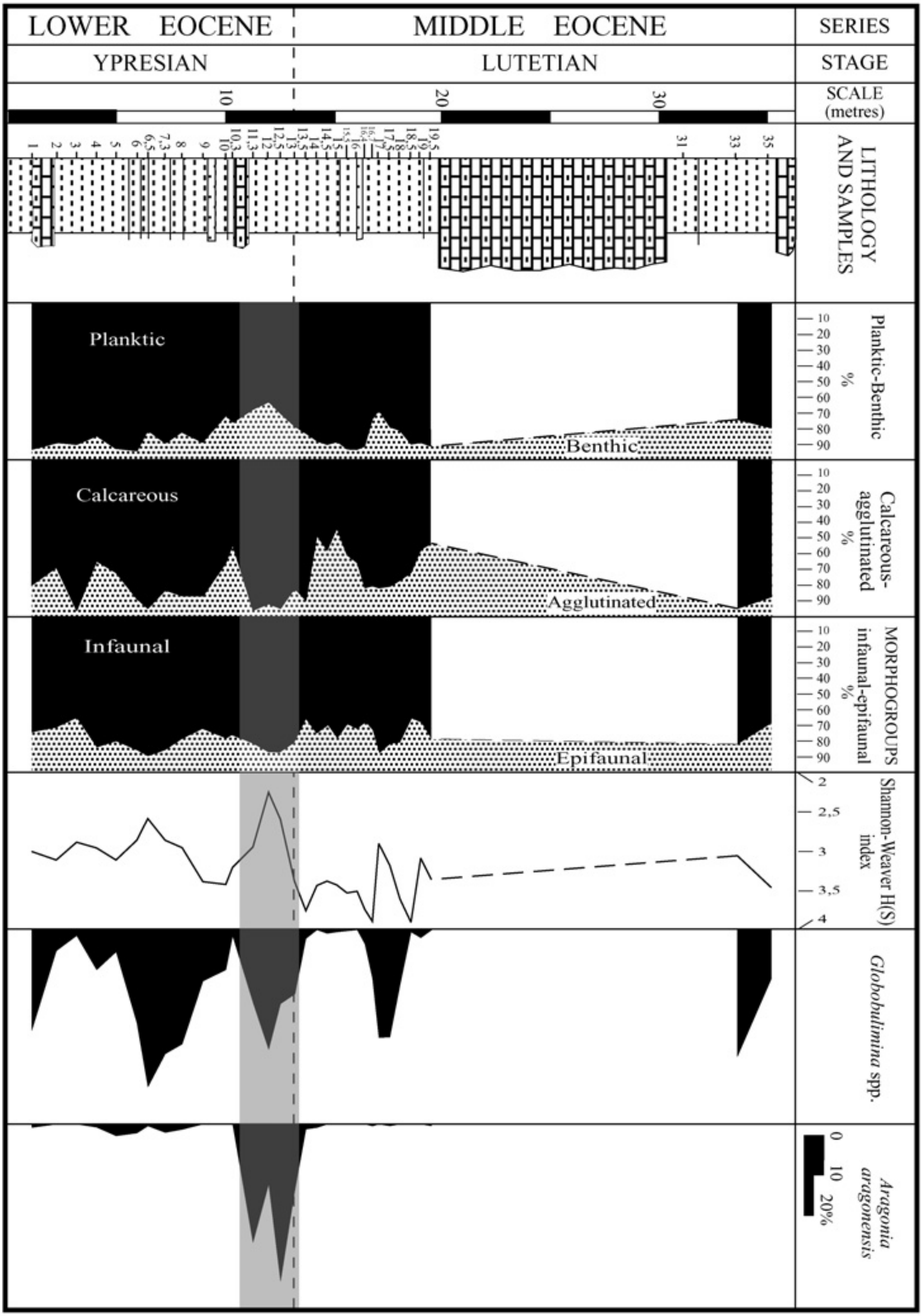

Fig. 3. Smaller benthic foraminiferal data and the hyperthermal event.

For 11.3 through For 13. Van Morkhoven et al. (1986) assigned an upper depth limit of 1,000–1,500 m to this species; however, Grünig & Herb (1980) interpreted water depths of about 600–1,000 m for an ecologic zone in the Possagno area (Italy), in which *Aragonia* was dominant. *Aragonia aragonensis* has also been quoted at upper bathyal depths by Bignot (1998), Speijer (1994) and Browning et al. (1997). We therefore suggest that samples For 1 through For 19.5 were deposited at depths close to the upper-middle bathyal boundary (~ 600 m). Such a paleodepth interpretation is in agreement with the observed planktic foraminiferal percentages (e. g., van der Zwaan et al. 1990).

Samples For 12.5–13.5 contain rare and abraded specimens of *Pararotalia audouini*, an inner neritic species (Murray 1991), which we consider to have been transported downslope. Samples For 33 and For 35 contain more and better preserved *P. audouini*, and these samples thus may have been deposited at neritic depths (< 200 m). They are separated from samples For 1–19.5 by several meters of limestones with macrofauna.

Benthic foraminiferal assemblages in samples For 1–19.5 show major fluctuations in relative abundances of the most common taxa, in particular those of *Globobulimina* species. In samples with high percentages of *Globobulimina*, the species richness is low, as shown by the relative abundance of *Osangularia* spp., *Cibicidoides* spp., various agglutinant taxa, and planktic foraminifera. In the present oceans, high relative abundances of *Globobulimina* species (deep infaunal taxa) are typical for areas with a high flux of organic matter to the sea floor, thus high productivity, and associated to low oxygen conditions in bottom or pore waters (e. g., van der Zwaan et al. 1999, Sen Gupta 1999, Gooday & Rathburn 1999, Schmiedl et al. 2003).

We do not interpret the environment of deposition of the samples with high percentages of *Globobulimina* spp. here as being indicative of shallower water, as might be thought from the lower percentages of planktic foraminifera. Planktic/benthic foraminiferal ratios are influenced by productivity (e. g., Berger & Diester-Haass 1988), and in the absence of important signs of dissolution in these intervals we interpret them as indicative of high primary productivity (Herguera & Berger 1991).

Overall, we thus interpret the observed variations in benthic foraminiferal assemblages as representing fluctuations in productivity.

The Ypresian/Lutetian boundary lies within one of the intervals (samples For 11.3–13) characterized by a high relative abundance of *Globobulimina* spp. (Fig. 3). This interval is unusual because it is the only one of such intervals where there is also a high relative abundance of *A. aragonensis*, and in which the bulk $\delta^{13}C$ values show a negative excursion.

Aragonia aragonensis has peaks in relative abundance at several deep-ocean sites in the lowermost Eocene, just after the benthic foraminiferal extinction at the end of the Paleocene and during the unusually warm interval called the Paleocene-Eocene Thermal Maximum (PETM) (Thomas 1990, Thomas et al. 2000, Thomas 2003). It has been interpreted as an opportunistic species, by comparison of its abundance patterns with that of ostracods (Steineck & Thomas 1996).

Thomas & Zachos (2000) and Thomas (2003) suggested that there may have been several events similar to the PETM, which they called hyperthermals, in the late Paleocene through early Eocene, with the latest of these events at the Y/L boundary (about 49 Ma, Berggren et al. 1995). Such hyperthermal events were defined as intervals of extremely

1,0	2,0	3,0	4,0	5,0	6,0	6,5	7,5	8,0	9,0	10,0	10,3	11,3	12,0	12,5	13,0	13,5	14,0	15,0	15,5	16,0	16,4	17,0	17,5	18,0	18,5	19,0	19,5	31,0	33,0	**FORTUNA (SPAIN) Samples, KvS**
C	Rf	R	Fr	R	F	R	Cf	Fc	vR	Fc	Fc	R	R	F	F	R	F	F	F	Rf	F	Rf	F	Fc	F	Fc	Rf	F	Rf	Abundance
M	Pm	P	Pm	P	Pm	P	M	Mp	P	Mp	M	P	P	MF	Mp	P	Pm	PM	Pm	Pm	Pm	Pm	Pm	Pm	Pm	Pm	vP	Pm	P	Preservation
1	1						1	1		1	1		1	1		1	1	1		1	1			1		1		1		Braarudosphaera bigelowii
1	1																													Birkelundia staurion
		1	1		1		1			1	1			1		1	1	1		1	1			1	1		1	?	1	**Campylosphaera dela**
1											1						1			1	1					1				Chiasmolithus grandis
1	1		1					1	?	1	1				1		1	1	1	1	1	1	1	1	1	1			1	**Chiasmolithus solitus**
			1																											Clausicoccus vanheckae
1			1	1	1		1	1		1	1			1	1	1		1	1	1	1					1	1	1		Clausicoccus sp.
											?																?			Coccolithus crassus
1			1		1	1	1	1		1	1			1	1		1	1	1	1	1		1	1	1	1	1	1		Coccolithus eopelagicus
1	1	1	1	1	1	1	1	1		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	Coccolithus pelagicus
1		1	1		1		1	1			1			1		1		1		1				1		1				Coronocyclus prionion
1			1																		1									Cruciplacolithus sp.
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1	1	1	1	1	1	1	1	1		1	1		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1		Discoaster barbadiensis
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1							1	1		1	1			1	1		1			1										Discoaster binodosus
1							1	1		1																				Discoaster gemmeus
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					1			1			1			1	1															Discoaster saipanensis
1					1		1	1		1	1		1	1	1	0	0													**Discoaster sublodoensis**
1											?			1	1	1	1						1	1				?		Discoaster wemmelensis
							1	1			1																			Discoaster cf. D. wemmelensis 6µ
							1	1		1																				Discoaster 9 arms
							1			1																				Discoaster 8 arms
							1				1						1			1										Discoaster sp. 7 arms
							1	1		1	1			1	1		1			1	1					1				Discoaster sp. 6 arms
										1				1	1															Discoaster sp. 5 arms
1	1		1		1	1	1	1		1	1			1	1	1	1	1	1	1	1	1	1	1	1	1		1	1	Ericsonia formosa
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1				1				1			1			1	1		1			1	1			1						Helicosphaera lophota
			?												1					1			1						1	Helicosphaera salebrosa
1							1	1		1	1			1	1															Helicosphaera seminulum
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1											?			?					1					1					1	Lanternithus minutus
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1	1		1	1			1	1						1	1			1	1		1			1						Micrantolithus sp.
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											1			1	1					1										Neococcolithes dubius
															1															Neococclithes minutus
								1																						Pedinocyclus larvalis
											1							1	1											Pemma sp.
1			1				1	1			2					1	1			1			1	1					1	Pontosphaera sp.
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	Prinsiaceae < ca. 6µ
1	1	1	1	1	1		1	1		1	1			1	1	1	1	1	1	1			1					?		**Pseudolithraphidites inversus**
1							1																							**Rhabdolithus gladius**
1	1						1	1		1	1			1	?															**Rhabdolithus inflatus**
					1			1																						**Rhabdoliths rudis**
1				1		1	1											1												Rhabdolithus perlongus/tenuis
1			1		1		1	1		1				1	1		1													Rhabdolithus sp.
1	1	1	1		1		1	1			1			1	1	1	1	1		1	1	1	1	1		1				Reticulofenestra dictyoda (<11µ)
								?			1						1		1		?		1			1		1	1	**Reticulofenestra umbilicus > 11µ**
					?													?												Sphenolithus editus
			1																1	1	1			1		1			1	**Sphenolithus furcatolithoides**
1	1				1	1	1	1		1	1		1	1	1	1	1	1	1	1	1		1	1	1	1	1	1	1	Sphenolithus moriformis
			1																											Sphenolithus obtusus
1							1	1		1	1	1		1	1				1				1		1			1		Sphenolithus radians
1	1	1	1		1	1	1	1		1	1			1	1	1	1	1	1	1	1	1		1	1	1			1	Sphenolithus spiniger
1	1	1	1	1	1	1	1	1		1	1		1	1	1	1	1	1	1	1	1	1	1	1		1	1		1	Sphenolithus sp.
																					?									Striatococcus pacificanus
1			1	1			1				1			1	1	1				1	1				1	1				Sullivania consueta
																		1	1					1			1			**Sullivania gigas**
1															1	1		?	?		?						1			Sullivania nitida
1																														Sullivania titus
1	1	1			1	1	1	1	1	1	1			1	1	1	1			1	1		1			1			1	Thoracosphaera sp.
							?	?																						Toweius magnicrassus
							1	1							1			1						1					1	Transversopontis sp.
1	1		1		1	1	1	1		1	1			1	1		1	1	1	1	1			1					1	Zygrhablithus bijugatus
38	16	10	23	10	20	11	35	37	2	28	37	3	8	31	32	18	25	21	19	30	23	8	17	23	12	22	11	11	17	TOTAL TERTIARY SPECIES
12b																	13a	13b										14a		**CP, Okada & Bukry, 1980**
14b																	15a	15b										16?		**NP, Martini, 1971**

Fig. 4. Calcareous nannofossil stratigraphical distribution and biozonation.

high global temperatures and low latitudinal sea surface temperature gradients, during which the deep to intermediate oceans were dominated by waters derived from subtropical latitudes. The extreme warm climates were supposedly caused by high atmospheric greenhouse gas levels, resulting from dissociation of methane hydrates at the sea floor, as indicated by negative carbon isotope excursions. THOMAS (2003) speculated that methane dissociation in the oceans may have triggered increased chemosynthetic activity, and that high abundances of “bloom species” such as *A. aragonensis* could indicate presence of a chemosynthetic bacterial food supply.

Our data from the Fortuna Section thus tentatively support that there might have been a hyperthermal event at the Y/L boundary: a high relative abundance of *A. aragonensis* occurred at a time of low species richness, and a negative shift in bulk carbon isotopes. However, because diagenetic processes may have affected the isotopic values, more evidence is needed to make a convincing case for the occurrence of a hyperthermal at this time.

Calcareous nannofossils

As in other Ypresian/Lutetian Mediterranean sections, the use of the classical calcareous nannofossil zonations is similarly difficult as in the Fortuna Section. The markers used by MARTINI (1971) and OKADA & BUKRY (1980) were not found or were too rare to be used confidently. The ranges given by other authors for additional possible markers from mainly Northern Europe seem to be only partly useful for the subdivision of the section and the age assignment by the calcareous nannofossil assemblages of the Fortuna section (Fig. 4).

The marker for the lower boundary of NP14 of MARTINI (1971), *Discoaster sublodoensis*, was found from the lowermost sample on upwards to sample 13.0. *Nannotetrina fulgens* and *Rhabdolithus gladius*, the zonal markers for NP15, were not found. The NP14/15 boundary is thus placed in the interval above the FO of *Nannotetrina cristata*, a form related to *Nannotetrina fulgens*. It does, however, only occur in two more samples above that level. *Sphenolithus furcatolithoides*, the other marker used occasionally for this boundary, first appears in Sample 15 just above, where the FO of *Sullivania gigas* and thus the base of NP15b was found. The attempt to locate the position of the NP15/16 boundary was without success due to the absence of the marker *Rhabdolithus gladius* above the FO of *N. cristata*. Therefore, its LO cannot be used for the recognition of the NP15/16 boundary. This boundary may, however, be approximated by the LO of *S. gigas* in Sample 19.5. Its total range defines NP15b. The presence of *Chiasmolithus solitus* in all the samples up to the uppermost sample assigns the top of the section to NP16.

Whereas some of the zonal markers of OKADA & BUKRY (1980), such as *Rhabdosphaera inflata*, *Sullivania gigas* and *Reticulofenestra umbilicus*, were observed, others, namely *N. fulgens* and *Discoaster bifax*, were not found. The total range of *R. inflata* defines Subzone CP12b and the total range of *S. gigas* defines Subzone CP13b. The FO’s of *R. umbilicus* and *D. bifax* should mark the base of CP14a. The FO of *R. umbilicus* larger than 11 μm seems to be lower than usual, namely below the FO of *N. cristata*, and, therefore, this is not a useful event in the Fortuna Section. *C. solitus* is still present in the uppermost sample and thus the uppermost two samples are assigned to CP14a. The presence of *Campylosphaera dela*, a species that usually disappears in CP14a, supports this assignment.

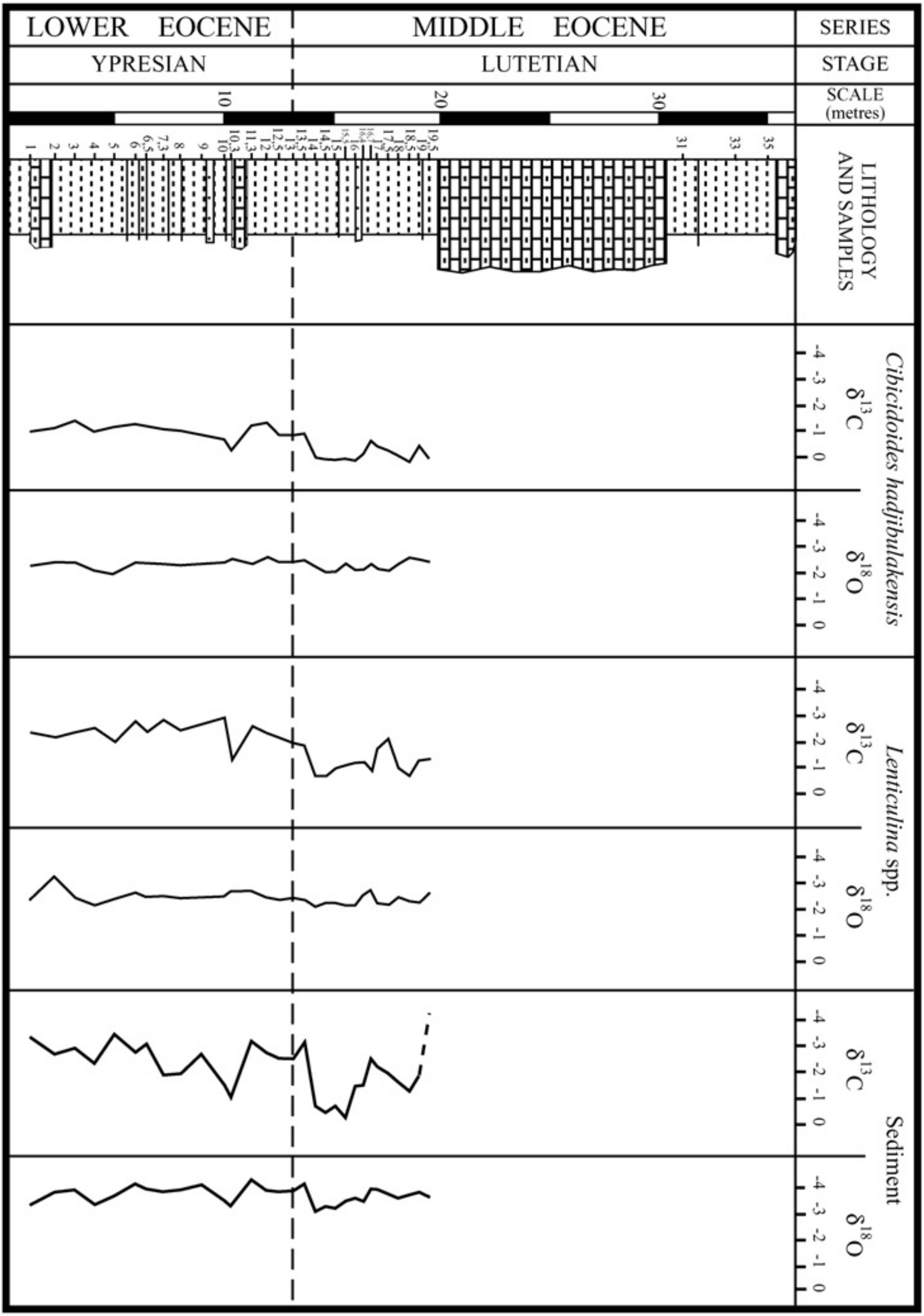

Fig. 5. Stable isotope data on benthic foraminifera and whole rock samples.

Reworked Cretaceous coccoliths are present in all samples, and Cretaceous coccoliths can outnumber the Eocene ones. *Watznaueria barnesae*, a species ranging through the whole of the Cretaceous, is the most commonly reworked form. Various species of *Nannoconus*, a genus not restricted to, but most commonly found in Lower Cretaceous sediments, are also present in all samples. Reworking from certainly Upper Cretaceous sediments is rare and such floras are mainly represented by *Micula decussata* (Coniacian through Maastrichtian). Other species, such as *Prediscosphaera cretacea* and *Eiffellithus turriseiffelii*, could be derived from Albian and younger sediments.

The number of species determined varies greatly from sample to sample and is partly depending on the state of preservation of the assemblage and partly on the time spent for the search for rare species. Fig. 4 shows the number of probably *in situ* Eocene species and reworked Cretaceous species.

Stable isotopes

The whole-rock isotopic values appear to be strongly affected by diagenetic processes (Fig. 5), as shown by the low $\delta^{13}C$ values, mostly in the range of −1 ‰ to −3.5 ‰, which is a few per mil lower than typical $\delta^{13}C$ values in isotopically well preserved marine limestones of early Paleogene age (see Schmitz et al. 1997, 2001). Other features indicating significant diagenetic overprinting of original values are the large scatter in the isotopic results, the negative $\delta^{18}O$ values, typically around −4 ‰, and the apparent correlation between whole-rock $\delta^{13}C$ and $\delta^{18}O$ values (see Corfield et al. 1991).

The isotopic results for the benthic foraminifera show a less prominent scatter, more positive $\delta^{13}C$ and $\delta^{18}O$ values, and no correlation between the two isotope ratios. Both records show consistent trends of increasing $\delta^{13}C$ values from the lower to the upper part of the section. All these features suggest that the benthic isotopic records are dominantly representing original ambient water trends in a marine environment. However, minor diagenetic equilibration has occurred and the foraminiferal tests were not searched for infillings, which can partially distort original signatures (Charisi & Schmitz 1995). The slightly more negative $\delta^{13}C$ and $\delta^{18}O$ values in the *Lenticulina* tests compared to the *Cibicidoides* tests may reflect larger chambers in the former and more infilling calcite in relation to foraminifera calcite, but microhabitat and vital effects may also have played a role. Because of these uncertainties the small wiggles in the isotopic records should be treated with caution. Most likely these reflect diagenetic artefacts and cannot be used for stratigraphic correlation. On the other hand, the general trend seen in all three records, with increasing $\delta^{13}C$ values throughout the section, most likely represents an original trend. Deep-sea $\delta^{13}C$ records measured on well preserved tests of foraminifera tests show a gradual long-term increase in $\delta^{13}C$ in the NP12 to NP14 interval (Charisi & Schmitz 1996).

Mineralogy

Calcite is the most common mineral as it accounts for an average 45 % of the whole rock samples, followed in abundance by phyllosilicates (40 %) and quartz (15 %). The concen-

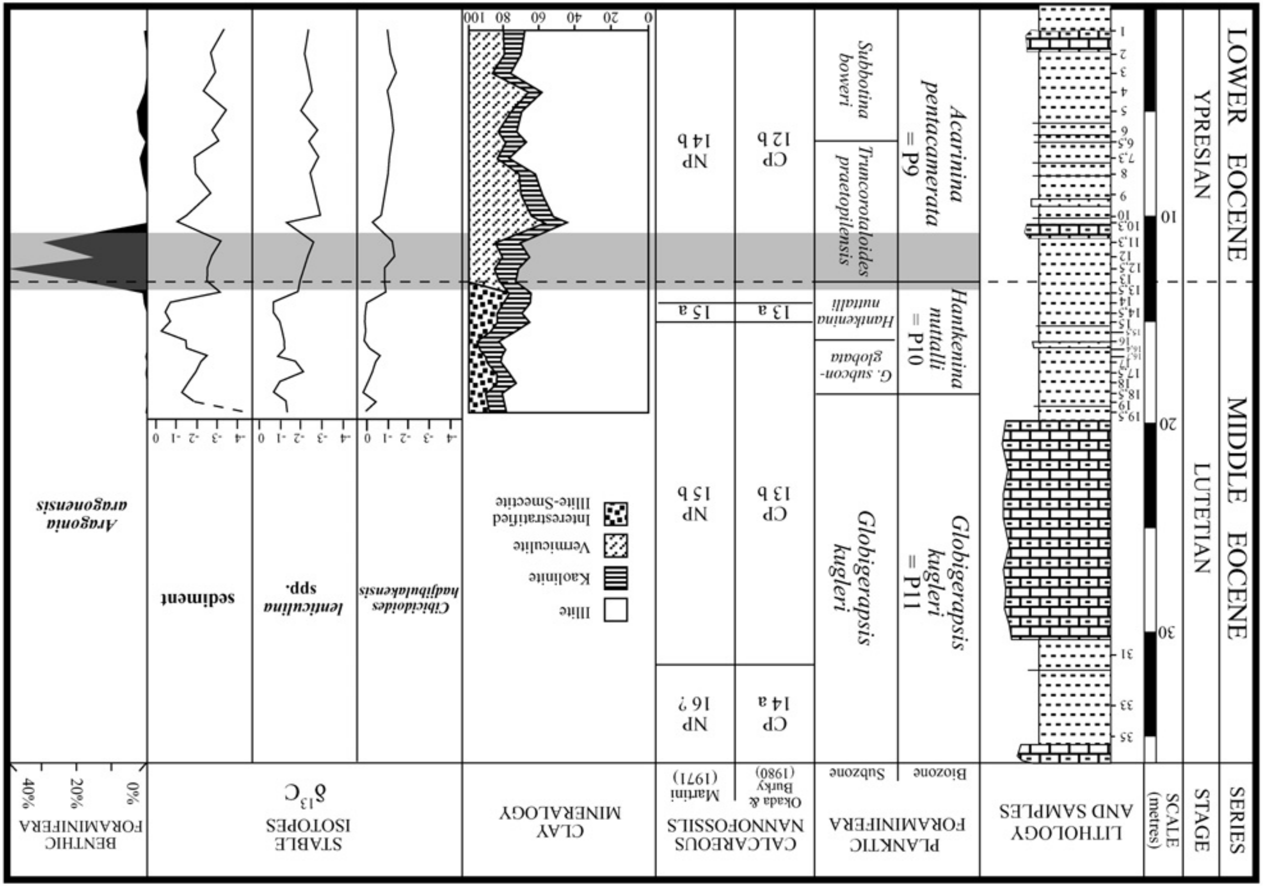

Fig. 6. Integrated stratigraphy of planktic foraminifera, calcareous nannofossils, clay mineralogy, stable isotopes and smaller benthic foraminifera.

tration of calcite and quartz increases towards the top of the section, whereas the concentration of phyllosilicates decreases (Fig. 6).

The dominant component of the clay mineral assemblage is illite (70 %), which thus is much more abundant than kaolinite (10 %), vermiculite (13 %) and illite-smectite mixed-layer clays (7 %). When vermiculite is present, there are no illite-smectite mixed-layer clays and vice versa. Vermiculite was found in the lowest seventeen samples and illite-smectite mixed-layer in the upper thirteen. Vermiculite reaches its highest abundance from the base to 14 m. The content of illite together with illite-smectite mixed-layer clays is higher than in the samples which contain vermiculite (76 % for the first mineral and 67 % for the second); the same happens with kaolinite (11 % to 9 %). Scanning electron micrographs of the clay samples shows the presence of nontronite in the *Hantkenina nutalli* Biozone.

Coinciding in time with the paleontological changes described by GONZALVO et al. (2001), there are important changes in mineralogy at 13.5 m. These variations document the beginning of a transgressive phase (previously documented by GONZALVO & MOLINA 2003, based on paleontological criteria) and significant paleoclimatical and paleoenviromental changes.

The occurrence of a transgression is indicated by an increase in carbonates and a decrease in clay minerals. Paleoclimatical and paleoenviromental variations can be detected in the mineralogy of the clays in that the trend of detrital clay minerals changes into alteration and neoformation processes.

Most of the clay minerals such as illite and kaolinite are detrital and arrived in the basin almost without undergoing chemical weathering in the source area. The presence of vermiculite in the lowermost seventeen samples indicates that there was a significant change in the source sediments resulting in a considerable number of cations. Vermiculite can be the result of chemical weathering of illite and chlorite with an enrichment in alumina, iron and magnesium in a not very acid medium.

The change in the clay mineral assemblage from an assemblage with vermiculite to an assemblage with illite-smectite mixed-layer clays points to a change to a more humid and warm climate which favours wash out and oxidation processes. The increasing abundance of smectites towards the top of the section explains the presence of nontronite in some samples; in these samples, magnesium was removed whereas iron and aluminium were not affected. The increase in iron towards the top of the section shows a more oxidizing paleoenvironment.

Chronostratigraphy and conclusions

The GSSP for the Ypresian/Lutetian boundary must be defined by an event near the base of the Lutetian stratotype. The Lutetian stage was defined by DE LAPPARENT (1883) in the Paris Basin (from Lutetia, the Roman name for Paris), but he did not indicate a stratotype section. The coarse limestone representing the Lutetian stage is only rarely visible in Paris in old underground quarries, in the Catacombs and in the Trocadéro gardens. A new stratotype for the Lutetian was thus proposed by BLONDEAU (1981) some 50 km North of Paris. The neostratotype is located on the right bank of the river Oise at St Leu d'Esserent and the large quarry at St Vaast-les-Mello (Oise). The lower part of the Lutetian is characterised by the occurrence of *Nummulites laevigatus* and the upper part by *Nummulites variolarius*. The lower boundary is sandy and glauconitic at the base and lies on Cuisian formations. The sedimentation took place on a marine continental shelf, a transgression allowed the development of *Nummulites laevigatus* in the lower and middle Lutetian, but the presence of *Alveolina boscii* and *Orbitolites complanatus* indicates that the environment gradually became restricted since the middle Lutetian (Blondeau 1981).

According to Blondeau (1981) planktic foraminifera are present but are infrequent and not typical in the Lutetian. The lower Lutetian could be indirectly correlated with the *Hantkenina aragonensis* (P10) Zone of Blow, with the Bruxellian of Belgium, and in term of calcareous nannofossils with part of the *Discoaster sublodoensis* (NP14) Zone of Martini. According to Aubry (1985) the Lutetian can be correlated to zones NP14 (upper part), NP15 and the base of NP16. In the Paris Basin there is a known unconformity (Hottinger & Schaub 1960, Aubry 1985), due to a major sea-level drop, between the Sables de Cuise (*Nummulites planulatus* beds, Cuisian, upper Zone NP12) and the Calcaire grossier (*Nummulites laevigatus* beds, Lutetian, upper Zone NP14). According to Berggren et al. (1995) the Cuisian/Lutetian unconformable contact reflects a stratigraphic gap, which encompasses the upper part of Zone NP12, Zone NP13 and Subzone NP14a. Consequently, the base of the Lutetian stratotype is within Subzone NP14b.

In the Fortuna section we could recognize the calcareous nannofossil subzones NP14b, NP15a, NP15b and possibly NP16, and the planktic foraminiferal zones P9, P10 and P11. The presence of these biozones thus indicates that the studied interval of the Fortuna Section includes the Y/L boundary, which is generally placed at the base of P10 and in NP14b. The first appearance of representatives of the genus *Hantkenina* has been used to recognize the Y/L boundary in pelagic sequences from low and middle latitudes. In the Fortuna Section, this event occurs at m 13.5, where *Hantkenina nuttalli* first appears. This section seems to be continuous, but the boundary interval is very condensed as compared to the Agost Section (Molina et al. 2000).

The first appearance of *Hantkenina* coincides with a bloom of the benthic foraminifers *Globobulimina* spp. and *A. aragonensis*, which may indicate a hyperthermal event (Thomas 2003, Ortiz & Molina 2003). At this level a major change in clay mineralogy is also observed; vermiculite is replaced by interstratified illite-smectite, indicating that the climate became warmer and more humid. The stable isotopes do not show a significant shift, probably due to diagenetic alteration (Fig. 6).

In conclusion, the Fortuna Section can be considered a candidate to define the GSSP for the Ypresian/Lutetian boundary, since the base of P10 in NP14b has been recognized in an apparently continuous hemipelagic section. Furthermore, a bundle of events in planktic and benthic foraminifera, calcareous nannofossils, stable isotopes and mineralogy could be recognized straddling the Y/L transition. We found no evidence for a major sea-level fall which has been reported to be coeval with the first appearance of *Hantkenina*. Nevertheless, a sea level drop or a local regression occurs above the Y/L boundary in Zone P11, where larger foraminifera are frequent in the Fortuna Section, but this seems to be a younger event. Prior to the definition of the GSSP a more expanded section, such as Agost, with possible evidence of a major sea level drop, should be studied in more detail.

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