

Reassessment of the Early–Middle Eocene biomagnetostratigraphy based on evidence from the Gorrondatxe section (Basque Country, western Pyrenees)

AITOR PAYROS, GILEN BERNAOLA, XABIER ORUE-ETXEBARRIA, JAUME DINARÈS-TURELL, JOSEP TOSQUELLA AND ESTIBALIZ APELLANIZ

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Thirteen Lower–Middle Eocene (Ypresian–Lutetian) successions, including the Gorrondatxe section in the western Pyrenees, show biomagnetostratigraphic correlation schemes that do not agree with the current standard framework. The main discrepancy concerns the position of the boundary between planktonic foraminiferal Zones P9 (=E7, approximately) and P10 (=E8, approximately), which was thought to occur within calcareous nannofossil Subzone CP12a and at the boundary between magnetic polarity Chrons C22n and C21r. However, in the differing correlation scheme the boundary between Zones P9 (=E7) and P10 (=E8) occurs close to the base of Subzone CP13a and to the boundary between Chrons C21n and C20r. An attempt at a new Ypresian–Lutetian boundary biomagnetostratigraphy is made based on data from the Gorrondatxe section, which shows that the boundary between Zones P9 (=E7) and P10 (=E8) is 3.1 Myr younger than hitherto considered. Therefore, the duration of the Early Eocene, most commonly defined according to this planktonic foraminiferal zonal boundary, has generally been underestimated over the last four decades. □ *Calcareous nannofossil, Eocene, Lutetian, magnetostratigraphy, planktonic foraminifer, Ypresian.*

Aitor Payros [a.payros@ehu.es], Gilen Bernaola [gilen.bernaola@ehu.es], Xabier Orue-etxebarria [xabi.orueetxebarria@ehu.es] and Estibaliz Apellaniz [estibaliz.apellaniz@ehu.es], Department of Stratigraphy and Palaeontology, Faculty of Science and Technology, University of the Basque Country, PO Box 644, E-48080 Bilbao, Spain; Jaume Dinarès-Turell [dinares@ingv.it], Istituto Nazionale di Geofisica e Vulcanologia, Laboratorio Di Paleomagnetismo, Via di Vigna Murata, 605, I-00143 Rome, Italy; Josep Tosquella [josep@uhu.es], Department of Geodynamics and Palaeontology, Faculty of Experimental Sciences, University of Huelva, Campus del Carmen, Avenida de las Fuerzas Armadas s/n, E-21071 Huelva, Spain. Received 4th December 2006; revised 30th January 2007.

The International Commission on Stratigraphy aims to define Global Boundary Stratotype Sections and Points of all Stages. To this end, appropriate boundary marker events must first be defined (Gradstein *et al.* 2003; Ogg 2004; Walsh *et al.* 2004). One of the boundaries still needing definition is the Ypresian–Lutetian (Early–Middle Eocene) boundary. However, the calibration of geomagnetic polarity and calcareous plankton biostratigraphic scales around the Ypresian–Lutetian boundary has long been recognized as a difficult task, as shown by the variable correlation schemes presented over the last four decades (see Berggren 1969, 1972; Martini 1970; Hardenbol & Berggren 1978; Berggren *et al.* 1985, 1995; Cavalier & Pomerol 1986; Aubry *et al.* 1988; Odin & Luterbacher 1992; Gradstein & Ogg 2004; Luterbacher *et al.* 2004).

Planktonic foraminifera, calcareous nannofossil and magnetic polarity results from some recently described successions (Erbacher *et al.* 2004; Pearson *et al.* 2004; Zachos *et al.* 2004; Bernaola *et al.* 2006) suggest that

the currently accepted biomagnetostratigraphic correlation scheme around the Ypresian–Lutetian boundary might need revision. In this light, this paper evaluates the robustness of the evidence on which the standard Ypresian–Lutetian biomagnetostratigraphy was based, and compiles published data that support an alternative correlation framework. Furthermore, the most reliable differing data are selected in order to attempt a new biomagnetostratigraphy.

Background

The currently most accepted biomagnetostratigraphic correlation scheme for the Ypresian–Lutetian boundary is shown in Figure 1 (Berggren *et al.* 1995; Luterbacher *et al.* 2004). This standard scheme is largely based on data from stratigraphic sections near Gubbio (Berggren *et al.* 1995), although it has long been recognized that some levels of these

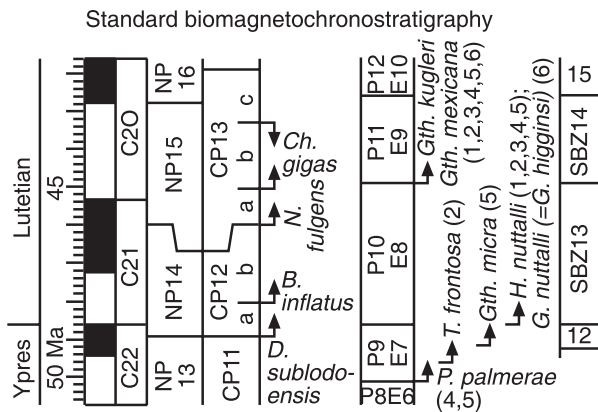


Fig. 1. Ypresian–Lutetian standard biomagnetostratigraphic framework. Absolute ages and correlation between magnetic polarity Chrons, calcareous nannofossil Zones and planktonic foraminiferal Zones are from Luterbacher *et al.* (2004). NP and CP scales are calcareous nannofossil biostratigraphic scales by Martini (1971) and Okada & Bukry (1980), respectively, as defined by first and last occurrences indicated to the right of the biostratigraphic scales; the higher (younger) position of the boundary between Zones NP14 (=CP12) and NP15 (=CP13), marked by the first occurrence of *Nannotetrina fulgens*, is according to Agnini *et al.* (2006). P and E scales are planktonic foraminiferal biostratigraphic scales by Berggren *et al.* (1995) and Berggren & Pearson (2005), respectively. Definition of planktonic foraminiferal events is as follows: (1) Stainforth *et al.* (1975); (2) Blow (1979); (3) Toumarkine & Luterbacher (1985); (4) Berggren *et al.* (1995); (5) Premoli Silva *et al.* (2003); (6) Berggren & Pearson (2005); correlation of events by (1), (2) and (3) with magnetic polarity Chrons are based on Berggren & Miller (1988). Larger foraminiferal biostratigraphy (SBZ scale), as presented and correlated by Serra-Kiel *et al.* (1998), is also shown.

sections present problems for biostratigraphic studies due to poor fossil preservation (Lowrie *et al.* 1982; Napoleone *et al.* 1983; Monechi & Thierstein 1985). Nevertheless, the standard biomagnetostratigraphic framework around the Ypresian–Lutetian boundary has seldom been checked until recently. This is so because most successions containing Lower and Middle Eocene strata present one or more of the following problems: (1) many outcrop and deep-sea sections include unconformities (e.g. Atlantic Ocean and North European sections; Aubry 1991, 1995); (2)

others contain condensed intervals (e.g. ODP 208, Site 1265; Zachos *et al.* 2004), a situation that hampers reliable correlations; (3) some important fossil groups do not occur or are poorly represented (e.g. planktonic foraminifera in many North European sections; Aubry 1986), or key species are missing (e.g. calcareous nannofossils at the Agost and Fortuna sections by Molina *et al.* 2000, 2006, respectively); and/or (4) palaeomagnetic response is not optimal (e.g. Tanzanian sections by Pearson *et al.* 2004).

Interestingly, a number of recently described successions have shown biomagnetostratigraphic schemes that are at odds with the standard time-scale (Fig. 2A–C and Tables 1–3; Erbacher *et al.* 2004; Zachos *et al.* 2004; Pearson *et al.* 2004). The boundary between planktonic foraminiferal Zones P9 (=E7, approximately) and P10 (=E8, approximately) actually occurs close to the boundary between calcareous nannofossil Zones NP14 (=CP12) and NP15 (=CP13), and not within Subzone CP12a as depicted in the standard chart. Furthermore, when palaeomagnetic data are available, the boundary between planktonic foraminiferal Zones P9 (=E7) and P10 (=E8) occurs close to the boundary between magnetic polarity Chrons C21n and C20r, and not C22n and C21r. However, such discrepancies were generally overlooked and/or no one thought to question the long-established biomagnetostratigraphic framework. Only Pearson *et al.* (2004, p. 49) suggested that the correlation of planktonic foraminiferal and nannofossil zonal schemes might need revision, although this was restricted to shelf deposits. Recently, Bernaola *et al.* (2006) presented new biostratigraphic and magnetostratigraphic data from the Gorrondatxe beach section in the western Pyrenees, which shows a zonal correlation scheme similar to the differing examples (Fig. 3). In addition, Molina *et al.* (2006) also obtained a roughly similar correlation framework in the Fortuna section; unfortunately the marker taxon of Zone CP13 was not identified there and, therefore, further refinements were not possible.

Table 1. Datum levels used in Fig. 2A (ODP 207, Hole 1258A by Erbacher *et al.* 2004).

Event	Marker	Location	Resolution	Source
Base of P10 / E8	FO of <i>G. nuttalli</i>	Sample 3R-5, 50–54 at 20.7 mbsf	1.5 m to underlying Sample 3R-6, 50–54	Erbacher <i>et al.</i> (2004), Chapter 5, p. 15 and tables T4 and T5
Base of NP15	FO of <i>N. fulgens</i>	Sample 4R-CC, 7–12 at 30.33 mbsf	8.25 to underlying Sample 5R-CC, 14–20	Erbacher <i>et al.</i> (2004), Chapter 5, p. 12 and table T6
Base of NP14	FO of <i>D. subloboensis</i>	Sample 6R-CC, 0–6 at 52.5 mbsf	7.84 m to underlying Sample 7R-CC, 14–19	Erbacher <i>et al.</i> (2004), Chapter 5, p. 12 and table T6
Base of C20r	Polarity reversal	Sample 3R-5, 64 at 20.84 m	0.58 m to underlying Sample 3R-5, 122	Erbacher <i>et al.</i> (2004), Chapter 5, p. 20 and table T10
Base of C21n	Polarity reversal	Sample 5R-3, 18 at 40.88 mcd	1.1 m to underlying Sample 5R-3, 128	Erbacher <i>et al.</i> (2004), Chapter 5, p. 20 and table T10
Base of C21r	Polarity reversal	Sample 6R-5, 12 at 49.44 mcd	1.18 m to underlying Sample 6R-5, 130	Erbacher <i>et al.</i> (2004), Chapter 5, p. 20 and table T10

Table 2. Datum levels used in Fig. 2B (ODP 208, Site 1263 by Zachos *et al.* 2004).

Event	Marker	Location	Resolution	Source
Base of P10 / E8 (certain)	FO of Hantkeninids and <i>G. higginsii</i> (= <i>G. nutalli</i>)	Sample 1263A-17H-CC at 177.02 mcd	6.12 m to underlying Sample 1263B-12H-CC	Zachos <i>et al.</i> (2004), Chapter 4, table T8
Base of P10 / E8 (probable)	Downhole reduction in globigerinathekid diversity and concomitant increases in the relative abundances of <i>M. caucasica</i> , <i>S. higginsii</i> , and 'Gth' <i>senni</i>	Sample 1263A-19H-CC at 198.72 mcd	5.92 m to underlying Sample 1263B-14H-CC	Zachos <i>et al.</i> (2004), Chapter 4, p. 13 and table T8
Base of CP13a	FO of <i>Nannotetrina fulgens</i> FO of <i>Nannotetrina</i> spp.	Sample 1263B-14H-3, 40 at 199.02 mcd Sample 1263A-21H-1, 40 at 213.54 mcd	0.8 m to underlying Sample 1263B-14H-3, 120 1 m to underlying Sample 1263A-21H-1, 140	Zachos <i>et al.</i> (2004), Chapter 4, table T5 Zachos <i>et al.</i> (2004), Chapter 4, table T5
Base of CP12b	FO of <i>R. inflata</i> (= <i>B. inflatus</i>)	Sample 1263A-21H-7, 55 at 222.69 mcd	0.05 m to underlying Sample 1263A-21H-CC	Zachos <i>et al.</i> (2004), Chapter 4, table T5
Base of CP12a	FO of <i>D. sublodoensis</i>	Sample 1263A-22H-3, 130 at 228.68 mcd	0.6 m to underlying Sample 1263A-22H-4, 40	Zachos <i>et al.</i> (2004), Chapter 4, table T5

Table 3. Datum levels used in Fig. 2C (Kilwa Masoko 2 by Pearson *et al.* 2004).

Event	Marker	Location	Resolution	Source
Base of P9-P10 transition zone	FO of hantkeninids transitional between <i>C. caucasica</i> and <i>H. mexicana</i>	Sample 23-1, 0-10 at 55.15 m	1.1 m to underlying Sample 23-2, 10-20	Pearson <i>et al.</i> (2004), p. 46
Base of CP13c	LO of <i>Ch. gigas</i>	Sample 10-1, 6 at 18.96 m; questionable specimens in Core 2, which extends from 2.3 to 3.15 m	Not specified	Pearson <i>et al.</i> (2004), p. 47
Base of CP13b	FO of <i>Ch. gigas</i>	Sample 34-2, 7 at 59.37 m	Not specified	Pearson <i>et al.</i> (2004), p. 47
Base of CP13a	Due to the absence of the index taxon <i>N. fulgens</i> , alternative markers (LO of <i>B. inflatus</i> , FO of <i>N. cristata</i> and LO of <i>D. sublodoensis</i>) were used to define the interval including the upper part of CP12b and CP13a	The alternative markers occur in Core 6, which extends from 63.4 to 66.7 m	Not specified	Pearson <i>et al.</i> (2004), pp. 46–47

Here we compile additional data from six deep-sea Sites (DSDP Sites 363, 366, 384, 549, 612 and 613) and two long-known Pyrenean successions (the Zumaia–Getaria section and a composite section based on directly correlatable successions of the Hecho Group) (Fig. 2D–K). The zonal correlations obtained from these deep-sea and outcrop successions do not agree with the standard scheme, being more similar to the aforementioned differing correlation scheme. Thus, thirteen Lower–Middle Eocene successions show data that suggest that the differing zonal correlations might not be local or regional anomalies, but in fact reflect the true correlation scheme. Among these thirteen successions, the Gorrondatxe section of Bernaola *et al.* (2006) is the one that best combines a good quality of exposure along a very thick, almost continuous Lower–Middle Eocene succession. In addition, a highly diversified set of data was provided.

Given this situation, we elaborate on the data from the Gorrondatxe section with the aim of evaluating the need to correct the biomagnetostratigraphic scheme around the Early–Middle Eocene boundary and the feasibility of designing a new correlation framework.

The Gorrondatxe section: setting and stratigraphy

Located just northwest of Bilbao (43°23'N 3°01'50"W), the Gorrondatxe section is part of a 2300-m-thick lower Ypresian to upper Lutetian succession, well exposed in coastal cliffs (Fig. 3A). During Eocene times the area formed part of the bottom of a 1500-m-deep marine gulf that opened into the Atlantic Ocean at approximately 35°N latitude. This area

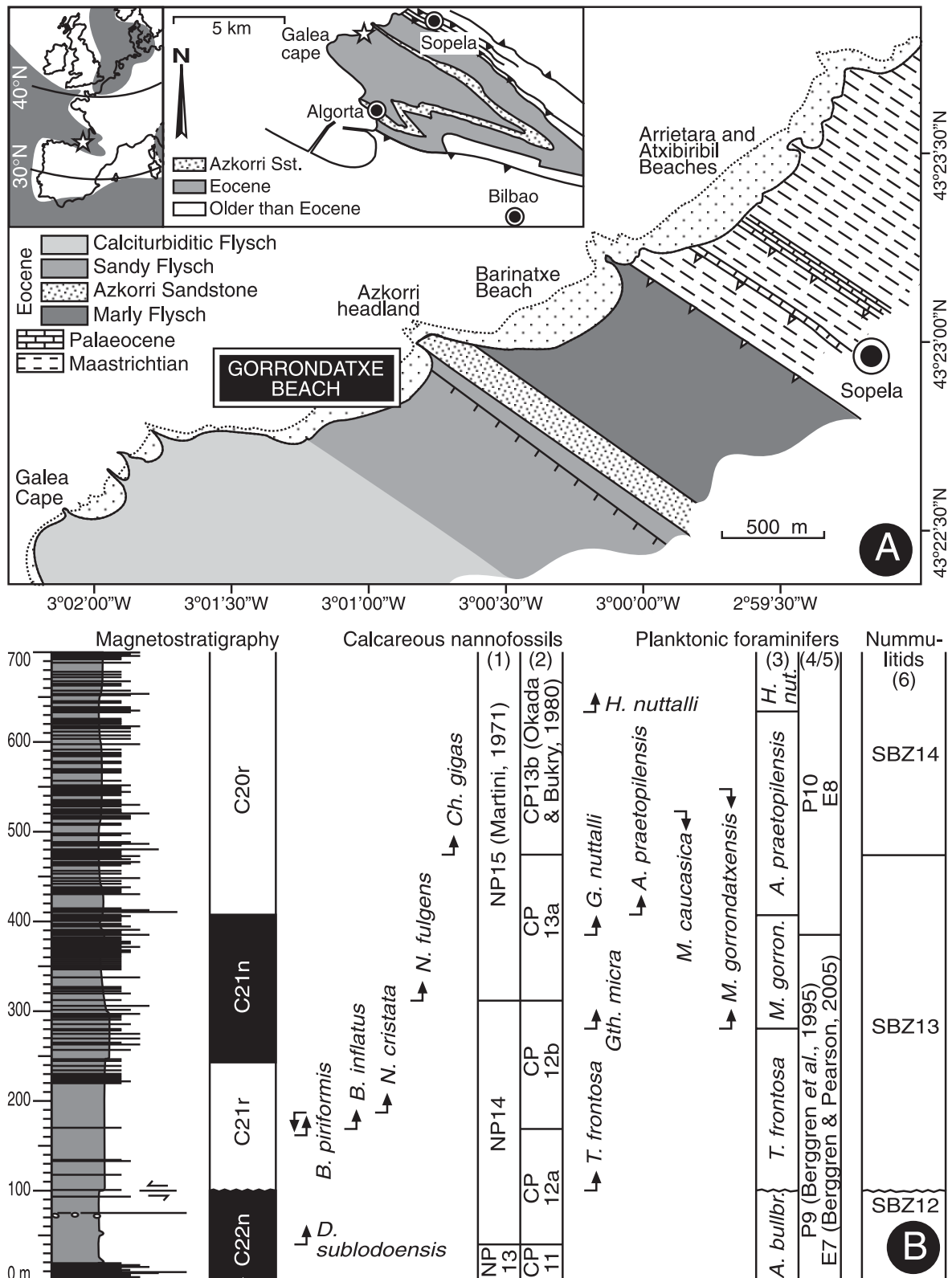


Fig. 3. □A. Palaeogeographical (left-hand inset) and present day (right-hand inset) location of the Gorrondatxe section (white star). Simplified geological map of the study area, showing lithostratigraphic units as used by Bernaola et al. (2006). The Gorrondatxe beach section extends from the uppermost Azkorri Sandstone to the lowermost Calciturbiditic Flysch. □B. Stratigraphic log of the Gorrondatxe beach section (based on Bernaola et al. 2006), showing magnetic polarity Chrons and the summary of the most important calcareous nannofossil, planktonic foraminiferal and nummulitid events and biostratigraphy: (1) Martini (1971); (2) Okada & Bukry (1980); (3) local scale by Bernaola et al. (2006); (4) Berggren et al. (1995); (5) Berggren & Pearson (2005); (6) Serra-Kiel et al. (1998).

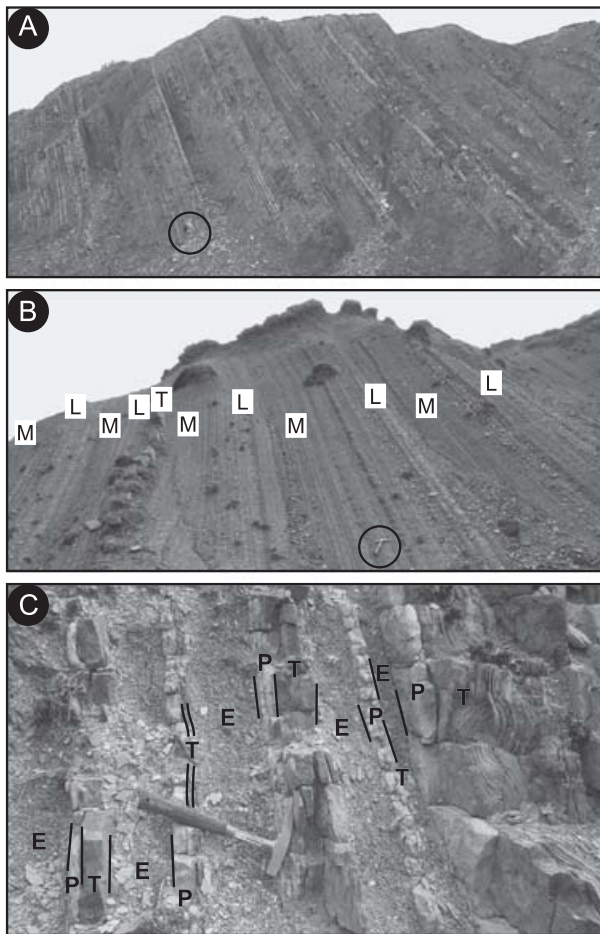


Fig. 4. Outcrop photographs of the Gorrondatxe section (stratigraphic top is to the right in all pictures). □A. General view of the succession extending from 540 m to 615 m (encircled geologist for scale), which is composed of grainy turbidites (prominent grey beds), their capping lutites (recessive grey beds) and limy pelagic deposits (prominent whitish beds). □B. Close-up of the interval from 115 m to 124 m (encircled hammer is 32 cm long), showing a 20-cm-thick turbidite (T) embedded in background deposits composed of thin-bedded turbidites (dark grey), their capping lutites (clear grey) and limy pelagic deposits (whitish). When pelagic deposits are composed of hard limestone (L) weather-resistant intervals occur, whereas pelagic deposits composed of soft marly limestone (M) result in recessive intervals. □C. Repetitive sequences of thin-bedded turbidites (T, dark grey), their capping lutites (turbiditic Bouma E interval, clear grey), and pelagic limy deposits (P, whitish). A thick-bedded turbidite with convolute lamination caps the succession. Hammer is 32 cm long.

received sediments from several sources, notably pelagic carbonates, calciclastic turbidites and debrites derived from northern sources, and siliciclastic turbidites coming from northern and eastern sources (Payros *et al.* 2006). Thus, the 700-m-thick Gorrondatxe section is composed of alternating pelagic limestones and marls, interspersed with thin-bedded (< 15 cm) siliciclastic turbidites and thick-bedded (up to 240 cm) mixed calciclastic–siliciclastic turbidites (Fig. 4). Bernaola *et al.* (2006) presented the results

of an integrated high-resolution stratigraphic study in which planktonic foraminiferal biostratigraphy, calcareous nannofossil biostratigraphy, nummulitid biostratigraphy and magnetic polarity stratigraphy were undertaken (Fig. 3B). Bernaola *et al.* (2006) provided details on the number, location and quality of samples studied, methods, taxonomy and interpretations. Therefore, only a summary of the most significant biomagnetostratigraphic features is presented here.

The lowermost 100 m of the succession present a planktonic foraminiferal assemblage typified by *Subbotina linaperta*, '*Guembeltrioides*' *lozanoi*, *Globanomalina planoconica*, *Pseudohastigerina micra*, *Morozovella caucasica*, *Morozovella aragonensis*, *Igorina broedermanni* and *Acarinina bullbrooki*, among others, which indicate Zone P9 of Berggren *et al.* (1995), an interpretation supported by the occurrence of *Planorotalites palmerae*, marker taxon of Zone P9, 250 m lower in the succession (see Orue-Etxebarria *et al.* 1984; Orue-Etxebarria & Apellaniz 1985; Payros *et al.* 2006). Calcareous nannofossil assemblages are characterized by *Coccolithus pelagicus*, *Reticulofenestra dyctioda*, *Discoaster lodoensis*, *Discoaster barbadiensis*, *Chiasmolithus solitus*, *Chiasmolithus grandis* and *Zygrhablithus bijugatus*, among others. The first occurrence of *Discoaster sublodoensis*, which marks the base of Zones NP14 of Martini (1971) and CP12 of Okada & Bukry (1980) was found 40 m above the base of the succession. The lower 100-m-thick interval of the Gorrondatxe section is characterized by normal magnetic polarity and here is interpreted as the lower part of Chron C22n based on planktonic foraminiferal and calcareous nannofossil biostratigraphic data (see Fig. 1).

The Gorrondatxe section is affected by a normal fault at 100 m, and consequently an unknown thickness of the succession is missing. The succeeding 142 m above the fault are characterized by reverse magnetic polarity and are considered to belong to the lower part of Chron C21r due to the stratigraphic position above the interval interpreted as Chron C22n and on the basis of calcareous nannofossil biostratigraphic data. In fact, the first occurrence of *Blackites piriformis* is recorded at 161 m, that of *Blackites inflatus*, which marks the base of Subzone CP12b of Okada & Bukry (1980), at 169 m, and that of *Nannotetrina cristata* at 187 m. Planktonic foraminiferal assemblages contain *A. bullbrooki*, *I. broedermanni*, *Turborotalia frontosa*, *P. micra*, *S. linaperta*, *Subbotina senni*, *Globanomalina indiscriminata*, *G. planoconica*, *M. caucasica*, *Morozovella crater* and *M. aragonensis*, which indicate the upper part of Zone P9 of Berggren *et al.* (1995).

The interval from 242 m to 408 m shows normal magnetic polarity. On the basis of its stratigraphic

position and calcareous nannofossil content, it is attributed to Chron C21n. The most significant calcareous nannofossil biohorizon is the first occurrence of *Nannotetrina fulgens*, which marks the base of Zones NP15 and CP13, at 311 m. Planktonic foraminiferal assemblages are similar to those in the underlying interval, but show the addition of *Globigerinatheka micra* and *Morozovella gorrondatxensis* (a species defined in the Gorrondatxe beach section; Orue-Etxebarria 1985) from 283 m upwards. Relatively large-sized specimens of *Guembeltrioides nuttalli*, showing secondary sutural apertures, appear in the upper part of this interval (385 m). All these characteristics suggest the transition from Zone E7 to Zone E8 of Berggren & Pearson (2005) (equivalent, respectively, to Zones P9 and P10 of Berggren *et al.* 1995).

The rest of the succession (from 408 to 700 m) is characterized by reverse magnetic polarity and interpreted as Chron C20r. In accordance with this interpretation, the first occurrence of calcareous nannofossil *Chiasmolithus gigas* is recorded at 474 m, marking the base of Subzone CP13b of Okada & Bukry (1980). In terms of planktonic foraminifers, the first occurrences of *Acarinina praetopilensis* and hantkeninids are recorded at 408 m and 633 m, respectively, whereas the last occurrences of *M. caucasica* and *M. gorrondatxensis* are recorded at 522 m and 547 m, respectively. All these characteristics indicate Zone P10 of Berggren *et al.* (1995) and Zone E8 of Berggren & Pearson (2005). Globigerinathekids, including *Globigerinatheka mexicana*, become very abundant 80 m above the top of the succession studied herein (see Orue-Etxebarria *et al.* 1984; Orue-Etxebarria & Apellaniz 1985; Payros *et al.* 2006), suggesting Zones P11 and E9 of Berggren *et al.* (1995) and Berggren & Pearson (2005), respectively.

Zonal correlation reliability

Problems for precise biostratigraphic studies were acknowledged in the Gubbio successions, on which the standard correlation schemes were largely based. For instance, planktonic foraminifera are not well preserved and, in addition, must be analyzed, at least in part, on thin sections (Lowrie *et al.* 1982; Napoleone *et al.* 1983). Similarly, nannofossil preservation is not good (Monechi & Thierstein 1985). Other Ypresian–Lutetian sections that seem to agree with the standard correlation scheme also show problems for reliable zonal correlations (e.g. absence or scarcity of key calcareous nannofossil species in the Agost section by Molina *et al.* 2000).

The correlation between calcareous nannofossil Zones, nummulitid Zones and magnetic polarity Chrons

in the Gorrondatxe section matches the standard biomagnetostratigraphic scheme of Berggren *et al.* (1995), Serra-Kiel *et al.* (1998) and Luterbacher *et al.* (2004). The main difference between the Gorrondatxe section and the standard biomagnetostratigraphic scheme lies in the correlation of the planktonic foraminifer zonal scale with the other scales (compare Fig. 1 and Fig. 3B). Despite such discrepancies, we consider that the results from the Gorrondatxe section are fully reliable. The following five arguments support our consideration.

- (1) Fossils are well preserved, and assemblages are very diversified in the Gorrondatxe section; the palaeomagnetic signal is also well recorded. Sampling resolution allowed accurate zonations to be achieved.
- (2) Biostratigraphic problems due to reworking can be ruled out. Although reworked nannofossil specimens are common in most of the Gorrondatxe samples, this fact does not hinder reliable biostratigraphic zonation, since the bases of all Zones and Subzones, except Subzone CP13c, are defined by first occurrences (see Fig. 1).
- (3) The Gorrondatxe section is among the thickest Lower–Middle Eocene deep-marine successions in the world, demonstrating a very high sedimentation rate (Bernaola *et al.* 2006). Hence, successive biomagnetostratigraphic events are more separate and can thus be chronologically ordered more easily than anywhere else.
- (4) First and last occurrences of several calcareous nannofossil key species in the Gorrondatxe section follow precisely the same pattern described elsewhere and depicted in the standard charts. The sequence of planktonic foraminiferal events also agrees with the standard pattern, the only exception being the first occurrence of hantkeninids, which in the Gorrondatxe section occur higher than theoretically expected (Bernaola *et al.* 2006). It should be noted, however, that hantkeninids were rare at their inception and, furthermore, they seldom became abundant (Premoli Silva & Boersma 1988, p. 323; Coxall *et al.* 2003, p. 237; Berggren & Pearson 2005). Therefore, the first occurrence of hantkeninids in the Gorrondatxe section might not represent their appearance in the stratigraphic record.
- (5) First occurrences of nannofossil species in the Gorrondatxe section, when correlated with the magnetic polarity Chrons, are found at exactly the levels that would have been expected on the basis of the standard correlation scheme. The only exception is the first occurrence of *N. fulgens*, which is placed at the lower part of Chron C21n

in the standard chart but correlates with the upper part of Chron C21n in the Gorrondatxe section. Interestingly, however, in a recent study of the Possagno section, Agnini *et al.* (2006) also found the first occurrence of *N. fulgens* at the upper part of Chron C21n. First occurrences of planktonic foraminiferal species are also located at intervals with magnetic polarities that agree with those shown in the standard chart, the only exception being the aforementioned first occurrence of hantkeninids. However, a major difference between the Gorrondatxe section and the standard correlation chart is that the planktonic foraminiferal events that in the standard biomagnetostratigraphic scheme are correlated with magnetic polarity Chron C22r can reliably be assigned to Chron C21r in the Gorrondatxe section; the events formerly correlated with Chron C22n are included within Chron C21n in the Gorrondatxe section; and the events considered to have occurred during the timespan of Chron C21r are found within Chron C20r in the Gorrondatxe section.

Similar arguments can be applied to most of the other eleven successions that show unusual zonal correlation schemes (Fig. 2), providing the basis to also consider their results as fully reliable.

Given the problems for precise biostratigraphic studies in the Gubbio and other similar successions, the coherence of the correlation schemes derived from all the differing successions compiled herein (Figs 2, 3), and the reliability of the biostratigraphic and magnetostratigraphic data from the Gorrondatxe section, it is very plausible that the correlation scheme derived from the latter constitutes the correct framework.

An attempt at a new biomagnetostratigraphy

One of the most significant characteristics of the Gorrondatxe section is its great thickness, which indicates a very high sedimentation rate and allows successive biomagnetostratigraphic events to be readily identified in chronological order. Such a high sedimentation rate was largely caused by the addition of an extra sediment supply of turbiditic origin to the normal pelagic sedimentation (Fig. 4). Payros *et al.* (2006) showed that the distribution of turbidites is not homogeneous throughout the succession. Therefore, the distance between successive biostratigraphic and/or magnetostratigraphic events does not directly reflect the time lapse involved, but mainly the frequency and magnitude of sediment gravity flows. With the aim of analyzing the Gorrondatxe biostratigraphic

and magnetostratigraphic events from a true temporal perspective, we tried to distil the pelagic succession by removing all the turbiditic deposits, as indicated by Maurer *et al.* (2004). For that purpose, we followed a three-step method. First, we divided the succession into 70 ten-metre-thick slices. Second, we measured the thickness of every sandy turbidite thicker than 15 cm and their capping lutites in each of the slices (Fig. 5). The composite thickness of these turbiditic deposits was directly removed from the succession. Third, in order to remove the thickness of very thin-bedded turbidites, we analyzed arbitrarily selected 1-m-thick intervals in each of the 10-m-thick slices, measuring the thickness of thin-bedded turbidites, their capping lutites, and pelagic limestones and marls (Fig. 4C). Then we assumed that the percentage of pelagic deposits in the 1-m-thick interval was extrapolatable to the rest of the thickness remaining in the 10-m-thick slice (Fig. 5); this assumption was verified by analyzing up to three 1-m-thick intervals in some of the slices, a procedure that yielded values that differed by less than 10%. As a result, a hypothetical pelagic-only 195-m-thick succession was obtained (Fig. 5). Although variations in the accumulation rate of pelagic sediments may occur, they are much less pronounced than in turbiditic deposits. Therefore, the distance between the successive Gorrondatxe biomagnetostratigraphic events plotted on the pelagic-only succession must quite reliably reflect the timespan between them. The only problem concerns the biomagnetostratigraphic events that are not recorded at Gorrondatxe due to the fault at 100 m of the succession (i.e. the top of Chron C22n and the first occurrence of *T. frontosa*).

Refining the time framework around the Ypresian–Lutetian boundary can be attempted by comparing the results above with the standard biomagnetostratigraphic chart of Luterbacher *et al.* (2004). Considering that Chron C21n is one of the radiometric tie points on which the geomagnetic polarity time-scale was based (Berggren *et al.* 1995; Luterbacher *et al.* 2004), it can be assumed that the possible errors in the absolute ages assigned by the standard geomagnetic polarity time-scale to the other polarity Chrons included in this study are minimal. Given that the correlation between calcareous nannofossil events and magnetostratigraphic Zones is similar in both the standard scheme (as amended by Agnini *et al.* 2006) and the Gorrondatxe section, the absolute ages estimated for the nannofossil events in the standard biomagnetostratigraphic chart have also been considered as correct (encircled letters in Fig. 6). Therefore, we directly correlated the calcareous nannofossil events and magnetostratigraphic events of the Gorrondatxe section with their corresponding absolute ages in the standard chart (Fig. 6).

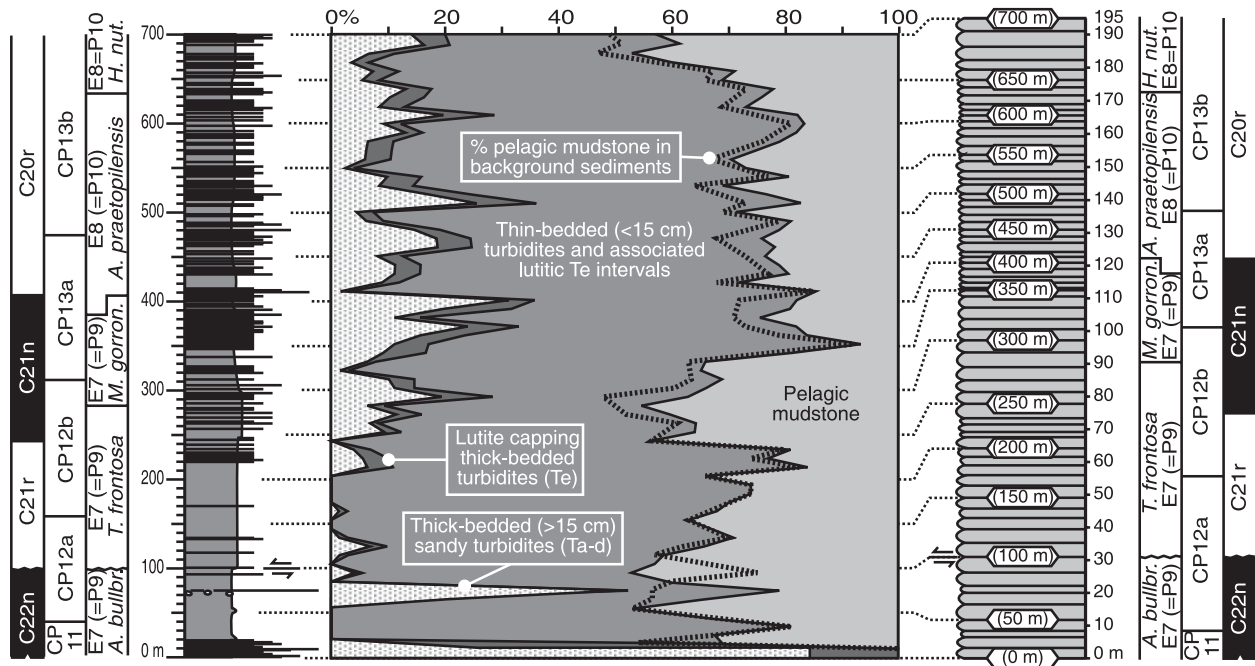


Fig. 5. Variations in the percentage of different types of turbiditic and pelagic sediments in the 700-m-thick Gorrondatxe beach section. A hypothetical pelagic-only log of only 195 m was obtained by removing the thickness of all the turbiditic sediments, which puts successive biomagnetostratigraphic events into a more realistic temporal perspective.

The results support the procedure followed in constructing the hypothetical pelagic-only Gorrondatxe section and allow further utilization in chronological estimates. Thus, the sedimentation rate obtained by correlating the pelagic-only Gorrondatxe section with the standard chronostratigraphic chart ranges between 21.6 m Myr^{-1} and 71.1 m Myr^{-1} , 28.1 m Myr^{-1} being the average (Fig. 6). These figures agree with the rates of pelagic sedimentation elsewhere (see Scholle *et al.* 1983; Stow *et al.* 1996). In addition, despite the generally high turbidite content, limestone-dominated and marl-dominated pelagic intervals can be visually recognized at least in five slices of the Gorrondatxe section (Fig. 4B). These pelagic limestones and marls alternate cyclically when turbiditic deposits are removed, defining limestone-marl couplets with an average thickness of 67 cm in the pelagic-only section. In three cases, five successive couplets change upwards from limestone-dominated to marl-dominated and back to limestone-dominated, defining bundles ca. 3.3 m thick in the pelagic-only section. Using the average pelagic sedimentation rate calculated above, it can be reckoned that the Gorrondatxe couplets and bundles represent ca. 24 Kyr and ca. 117 Kyr, respectively. These values are in accordance with the periodicities of orbital precession (19 to 24 Kyr) and eccentricity (100 to 110 Kyr) cycles, which are known to be usually recorded in pelagic successions.

Once the validity of the pelagic-only Gorrondatxe section is verified, the Gorrondatxe planktonic foraminiferal events (encircled numbers in Fig. 6) can be included in the correlation with the standard chronostratigraphic chart. This shows that the boundary between planktonic foraminiferal Zones P9 (=E7) and P10 (=E8), traditionally used to place the Ypresian-Lutetian boundary, is 3.1 Myr younger than hitherto considered. As a result, a new biomagnetostratigraphic framework is proposed, which integrates the most widespread zonal scales used in Early-Middle Eocene timescales (Fig. 7).

Conclusions

Thirteen Lower-Middle Eocene successions, including the Gorrondatxe section analyzed herein, show correlation schemes between planktonic foraminiferal biostratigraphic Zones, calcareous nannofossil biostratigraphic Zones and magnetic polarity Chrons that do not agree with any of the standard correlation schemes published so far (e.g. Berggren 1969, 1972; Martini 1970; Hardenbol & Berggren 1978; Berggren *et al.* 1985, 1995; Cavalier & Pomerol 1986; Aubry *et al.* 1988; Berggren & Miller 1988; Odin & Luterbacher 1992; Luterbacher *et al.* 2004; Berggren & Pearson 2005). The main discrepancy specifically concerns

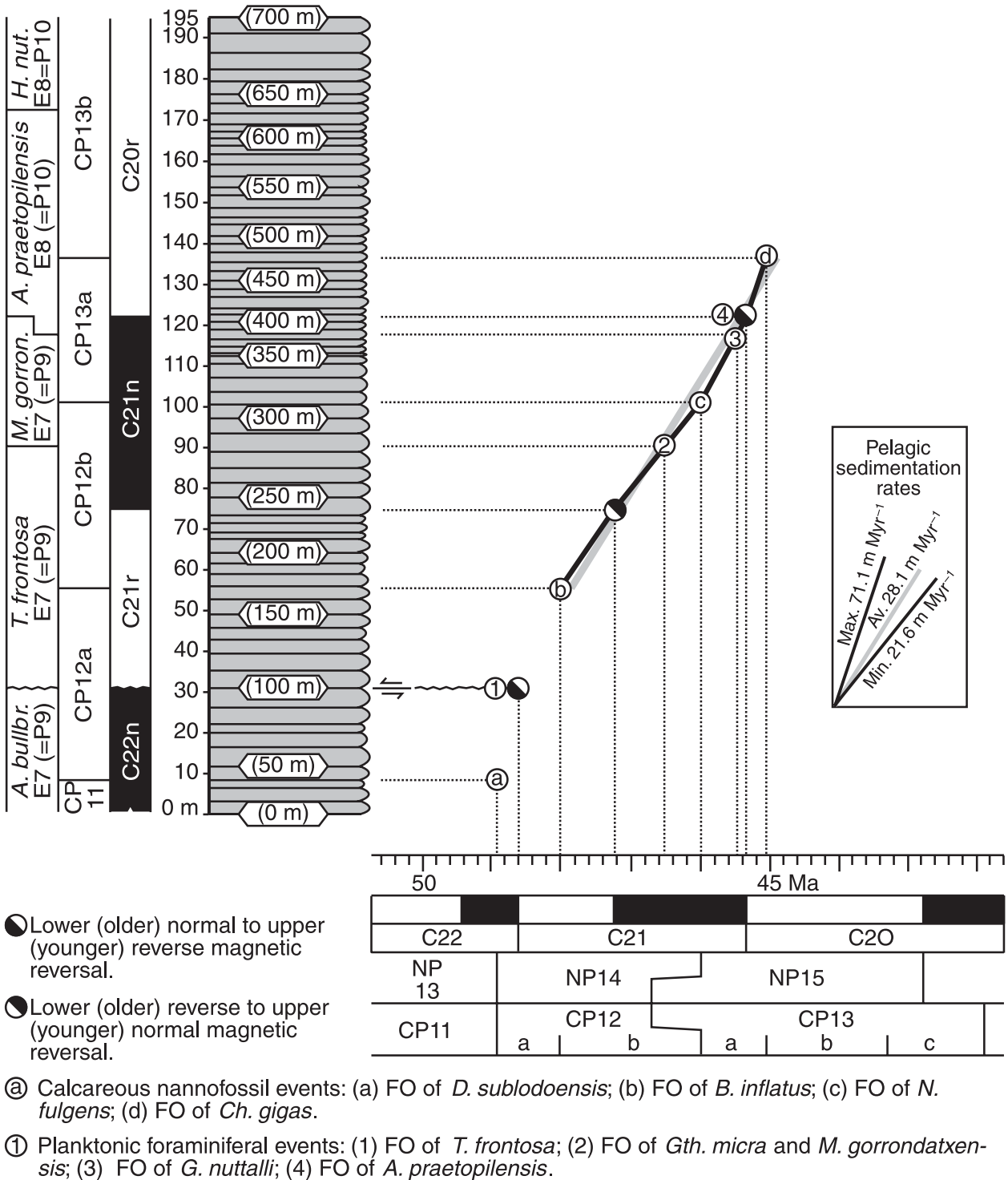


Fig. 6. Age model for the hypothetical pelagic-only Gorrondatxe section, as obtained by correlating magnetic and calcareous nannofossil (encircled letters) events with their corresponding ages in the standard biomagnetostratigraphic chart of Luterbacher *et al.* (2004) (FO: first occurrence); the younger age of the boundary between Zones NP14 (=CP12) and NP15 (=CP13), marked by the first occurrence of *Nannotetrina fulgens*, is according to Agnini *et al.* (2006) and adopted herein. The thick grey line between tie points (b) and (d) is the regression line that represents the average pelagic sedimentation rate. The Gorrondatxe planktonic foraminiferal events (encircled numbers) have been included in this correlation scheme to approximate their absolute ages.

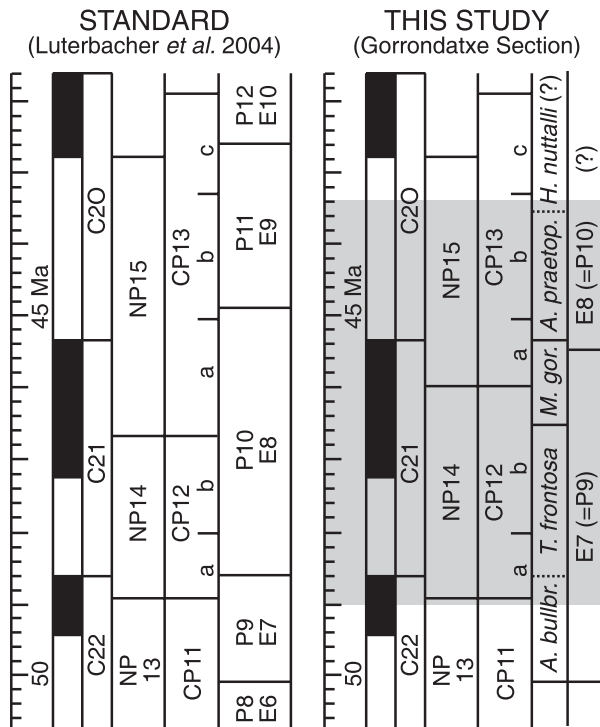


Fig. 7. Comparison between the late Ypresian–Lutetian standard biomagnetostratigraphical time-scale (Luterbacher *et al.* 2004) and the new correlation scheme proposed on the basis of the Gorrondatxe beach section data (grey box on the right-hand graph).

the position of the boundary between planktonic foraminiferal biostratigraphic Zones P9 and P10 (*sensu* Berggren *et al.* 1995; equivalent to Zones E7 and E8 of Berggren & Pearson 2005). According to the current standard correlation scheme (Fig. 1), this boundary is thought to occur within calcareous nannofossil Subzone CP12a of Okada & Bukry (1980) and at the boundary between magnetic polarity Chrons C22n and C21r. However, in the differing correlation schemes compiled herein (Figs 2, 3), the boundary between planktonic foraminiferal Zones P9 (=E7) and P10 (=E8) occurs close to the base of calcareous nannofossil Subzone CP13a and to the boundary between magnetic polarity Chrons C21n and C20r.

Given the problems in carrying out precise biostratigraphic studies in the successions on which the standard correlation schemes were largely based (e.g. Gubbio sections; see Lowrie *et al.* 1982; Napoleone *et al.* 1983; Monechi & Thierstein 1985), the similarities between the correlation schemes derived from the thirteen successions compiled herein (Figs 2, 3), and the reliability of the biostratigraphic and magnetostratigraphic data from the Gorrondatxe section (Fig. 3), it becomes clear that the biomagnetostratigraphy around the Early–Middle Eocene boundary needs

to be amended. From the viewpoint of stratigraphy (exposure quality, thickness and continuity of the succession) and data diversity and reliability, the Gorrondatxe section is the most suitable to elaborate a new correlation scheme. Therefore, an attempt at a new biomagnetostratigraphy has been made herein by removing the thickness of all the turbiditic deposits from the Gorrondatxe section (Fig. 5). Thus, a hypothetical pelagic-only succession was obtained, which puts the successive biomagnetostratigraphic events under a realistic temporal viewpoint and shows that the boundary between planktonic foraminiferal Zones P9 (=E7) and P10 (=E8) is 3.1 Myr younger than hitherto considered (Figs 6, 7).

The criterion most commonly used during the last half century to identify the base of the Middle Eocene was the first occurrence of hantkeninids (base of Zone P10 of Berggren *et al.* 1995), which has recently been suggested to be coeval with the first occurrence of *G. nuttalli* (base of Zone E8 of Berggren & Pearson 2005). If these planktonic foraminiferal events were eventually chosen by the International Commission on Stratigraphy as the official criterion to define the base of the Lutetian Stage, it would imply that the duration of the Early Eocene has generally been underestimated. It should be noted, however, that according to the new biomagnetostratigraphical evidence (Fig. 7) the base of planktonic foraminiferal Zone P10 (=E8) is ca. 2.5 Myr younger than the base of the Lutetian original Stratotype in Paris (see Blondeau *et al.* 1980), which is known to pertain to the lower part of calcareous nannofossil Subzone CP12b (Aubry 1986). The planktonic foraminiferal events that occur closer to the age of the lower Lutetian strata in Paris are the following: (1) the first occurrence of *T. frontosa*, poorly documented in the Gorrondatxe section due to a fault but which correlates with calcareous nannofossil Subzone CP12a and seems to be located around the boundary between Chrons C22n and C21r, being ca. 0.6 Myr older than the lower Lutetian strata in Paris; and (2) the first occurrences of *Gth. micra* and *M. gorrondatxensis*, which correlate with the upper part of calcareous nannofossil Subzone CP12b and occur at the lower part of Chron C21n, being ca. 1.5 Myr younger than the lower Lutetian strata in Paris.

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