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Covarying sedimentary and biotic fluctuations in Lower–Middle Eocene Pyrenean deep-sea deposits: Palaeoenvironmental implications

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Abstract

Analyses of expanded (1975 to 3330 m thick) deep-marine Ypresian–Lutetian successions from the Pamplona and Basque basins (W Pyrenees) demonstrate a recurring pattern of coeval sedimentary and biotic changes: intervals rich in resedimented deposits are typified by high-latitude planktonic foraminiferal indices, whereas intervals devoid of large-scale resedimented deposits (megabreccias) are characterized by low-latitude planktonic foraminiferal indices. Data from the megabreccia-free intervals record a reasonably good correlation between the vertical trend of planktonic foraminiferal indices from the two Pyrenean basins and the global curve of oxygen isotopes from deep-sea records. For instance, the Early Eocene Climatic Optimum and the long-lasting late Ypresian–Lutetian cooling are respectively recorded in the studied successions by an increase and by a progressive decline in abundance in low-latitude planktonic foraminiferal indices. This correlation may support the assumption that changes of planktonic foraminiferal indices in the megabreccia-free intervals were forced by global climatic changes.

The dominance of high-latitude planktonic foraminiferal indices in the megabreccia-bearing intervals is more difficult to interpret. Such dominance might record global cooling episodes that resulted in eustatic lowstand resedimentation events. However, the climatic cooling and sea-level fall do not fully explain the characteristics of these intervals. A reasonable scenario is that tectonically induced resedimentation processes resuspended large volumes of mud and organic matter, which led to the eutrophication of seawater. Such eutrophication would preferentially affect low-latitude oligotrophic planktonic foraminiferal species and lead to a relative or absolute increase in the cosmopolitan opportunistic species that typify high-latitude groups.

Keywords: Eocene; Megabreccia; Planktonic foraminifera; Climate; Resedimentation; Eutrophication

1. Introduction

The Eocene Epoch was crucial in the Earth's history. A rearrangement of tectonic plates resulted in new palaeogeographical configurations and ocean circulation patterns, and eventually led to a switch from greenhouse to icehouse global climate. That switch, in turn, caused regional and global environmental perturbations, including changes in the salinity, turbidity, productivity, temperature and/or level of seawater. Palaeoenvironmental and palaeoceanographic studies on the Eocene Epoch have mainly focused on either the warm climates around the Palaeocene–Eocene transition (e.g. Wing et al., 2003) or else on the Late Eocene–Early Oligocene interval, when large-scale ice sheets began to develop on

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the Antarctic continent (e.g. Prothero et al., 2003). In comparison, the Early–Middle Eocene intervening period, during which the climatic deterioration occurred, has received much less attention.

The most reliable proxy for past climatic and environmental changes is the variation in geochemical characteristics, particularly the oxygen isotopes, recorded in deep-sea sediment profiles from DSDP and ODP cores (e.g. Abreu and Anderson, 1998; Zachos et al., 2001; Pekar et al., 2005). However, the usually condensed (and occasionally incomplete) nature of these profiles raises the question of whether some small-scale oscillations in the general trend of the Eocene climatic deterioration might not have been recorded. This seems to be the case of the Early Eocene climatic oscillation recorded in the expanded continental sequences of the Bighorn basin (Wing et al., 2000), which was strong enough to affect planktonic biota (Kelly et al., 2001), and yet is not readily perceived in deep-sea oxygen isotopic profiles. Therefore, should more of these subtle climatic oscillations exist, an obvious archive in which to look for them would be the expanded deep-marine successions accumulated along continental margins.

In this paper we study Ypresian–Lutetian (Lower–Middle Eocene) successions deposited in two deep-marine basins (Pamplona and Basque basins) in the western Pyrenees. Since oxygen isotopic signals are altered in these Pyrenean land-exposed sections, other proxies such as sedimentary and palaeontological approaches have to be used. Therefore, we focused on the sedimentary facies and the planktonic foraminiferal assemblages, finding that recurrent changes in both characteristics occurred in close harmony. Then we correlated the covarying sedimentary and biotic fluctuations in the western Pyrenees with well-documented global events to try to decipher whether the environmental perturbations studied in this paper reflect global climatic changes, regional tectonism or a combination of both factors.

2. Geological and palaeogeographical setting

The oblique convergence of the Iberian and European plates during latest Cretaceous and Palaeocene times led to the formation of a narrow marine gulf opening northwestwards into the Bay of Biscay. It was located at approximately 37°N latitude and had shallow carbonate ramps on its northern and southern margins (Plaziat, 1981; Pujalte et al., 2002). Further plate convergence during Eocene times caused the tectonic uplift of the Pyrenees, which started in the east and then propagated towards the west. Deformation reached its maximum intensity during the Early and Middle Eocene (Verges et al., 1995; Pujalte et al., 2002), when two foreland basins developed to the south and north of the rising orogen (Fig. 1A; see also Payros, 1997). The present study focused on the western parts of these two foreland basins, here named the Pamplona and Basque basins, which are now more than 200 km apart and were even more separated in Eocene times, before the tectonic compression.

The Pamplona basin was infilled with a variety of sediments, mainly hemipelagic marls and limestones, coarse-grained calciclastics derived from the southern carbonate ramp (Payros, 1997; Payros et al., 2003), and thin-bedded siliciclastic turbidites that represent the distal part of the Hecho deep-sea submarine fan (Mutti, 1984), which was fed from the southeast (Fig. 1A). Similarly, the Basque basin received sediments from several sources, notably hemipelagic marls and limestones, calciclastic turbidites and debrites seemingly derived from northern sources, and siliciclastic turbidites coming from northern and eastern sources (Fig. 1A). Palaeodepth estimates for the Pamplona and Basque basins are, respectively, 500 and 1500 m (e.g. Orue-Etxebarria and Lamolda, 1985; Rodríguez-Lázaro and García-Zarraga, 1996; Payros et al., 2003). These basinal deposits, and remains of the southern shallow-water carbonate ramp, extensively outcrop in the western Pyrenees (Fig. 1B).

3. Lithostratigraphy and facies

3.1. Pamplona basin

An outcrop map and a lithostratigraphic scheme of the Lower and Middle Eocene deposits of the Pamplona basin are shown in Fig. 2. No continuous section of the whole succession exists, but a composite succession can be reconstructed by correlation of several local sections, mainly the Otsakar and Osinaga sections for the Ypresian to lowermost Lutetian interval, and the Anotz and Erro sections for the uppermost Ypresian to upper Lutetian interval (Fig. 2).

The lower and middle Ypresian Unanu and Ondatz Fms are composed of hemipelagic limestones and marls rich in planktonic foraminifers (Fig. 3). The overlying Anotz Fm (upper Ypresian to middle Lutetian) is composed of hemipelagic grey marls and mudstones, commonly slumped, and contains four discrete members of coarse-grained calciclastic turbidites and debrites encased within (Payros, 1997; Payros et al., 2003).

The Erro Fm is mostly composed of alternating hemipelagic marls and thin-bedded siliclastic turbi-

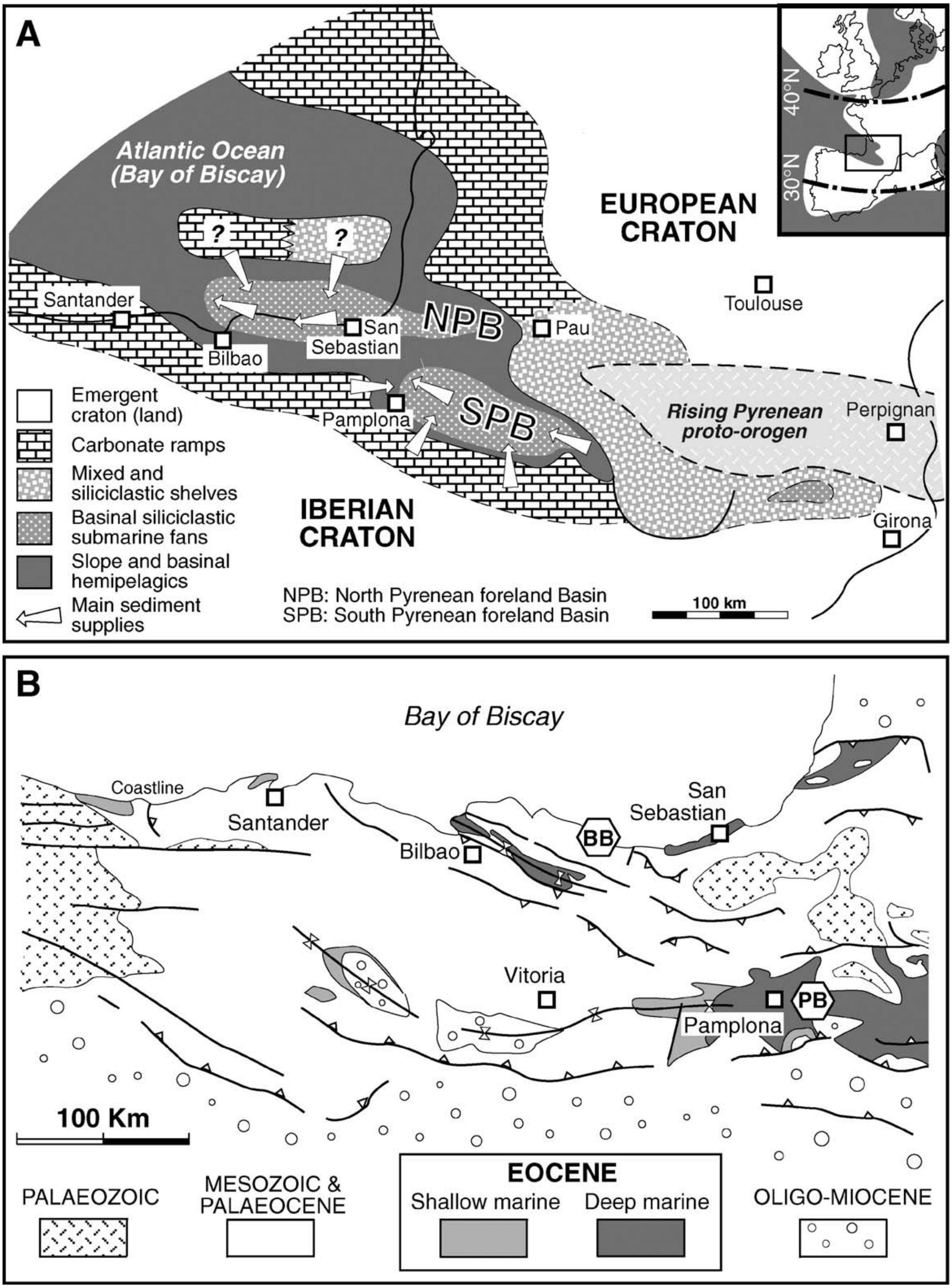

Fig. 1. (A) Early Palaeogene palaeogeography of the Pyrenean area without palinspastic restoration (partly based on Plaziat, 1981; Pujalte et al., 2002, and our own data). (B) Simplified geological map of the western Pyrenees showing the location of Eocene outcrops. Those of the southeastern belt correspond to the Pamplona basin (PB), whereas those of the coastal northern belt correspond to the Basque basin (BB).

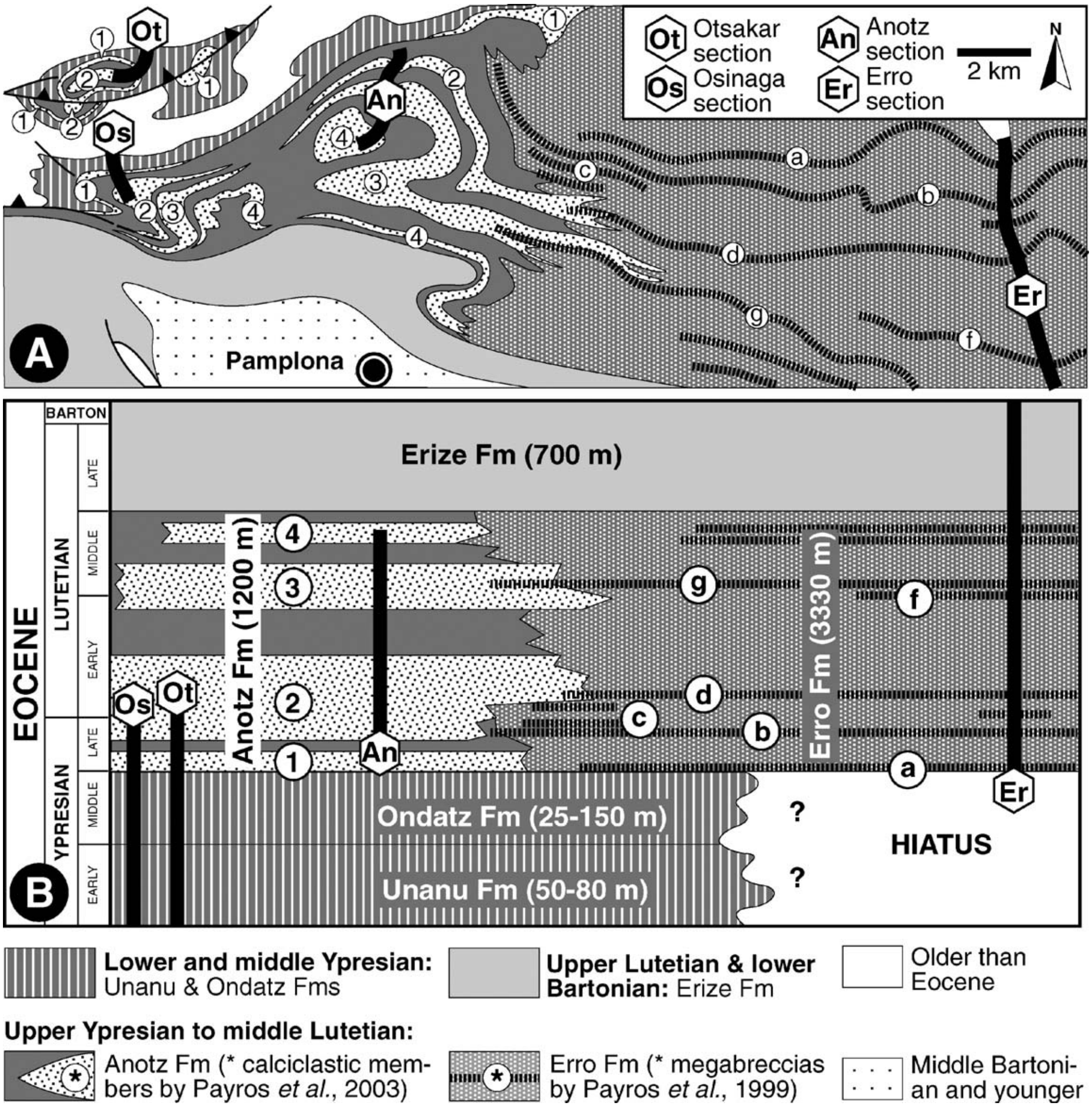

Fig. 2. Outcrop map (A) and chronostratigraphic summary (B) of the Eocene deposits of the Pamplona basin, both graphs showing the location of the Otsakar (Ot), Osinaga (Os), Anotz (An) and Erro (Er) sections. Based on Payros (1997).

dites but, most remarkably, it also contains several intercalations of impressive carbonate megabreccias, with individual thicknesses of up to 200 m and shelfal clasts that exceed 600 m in length and 40 m in thickness (Payros et al., 1999; Figs 3 and 4). The varied ages of the megabreccia clasts and of the resedimented planktonic foraminifers in the capping marlstone show that as the sediment gravity flows moved downslope they ripped up large amounts of bottom sediments. The megabreccia beds extend greatly to the east of the study area, the largest ones exceeding 130 km in strike section and having an estimated volume of 200 km^3 (e.g. Seguret et al., 1984; Labaume et al., 1987; Barnolas and Teixell, 1994; Payros et al., 1999). To the west, the megabreccias pinch out within the calciclastic members of the Anotz Fm (Fig. 2). According to Barnolas and Teixell (1994) and Payros et al. (1999), the megabreccias record the episodic catastrophic collapse of large portions of the southern carbonate ramp during phases of tectonic tilting. Planktonic foraminiferal biostratigraphic analyses carried out by Payros et al. (1999) demonstrated that the depositional events of the carbonate megabreccias took place during four discrete time intervals of relatively short duration (clusters 1 to 4 in Fig. 3), each cluster indicating a pulse of strong tectonic activity, separated by longer periods of comparatively tectonic quiescence.

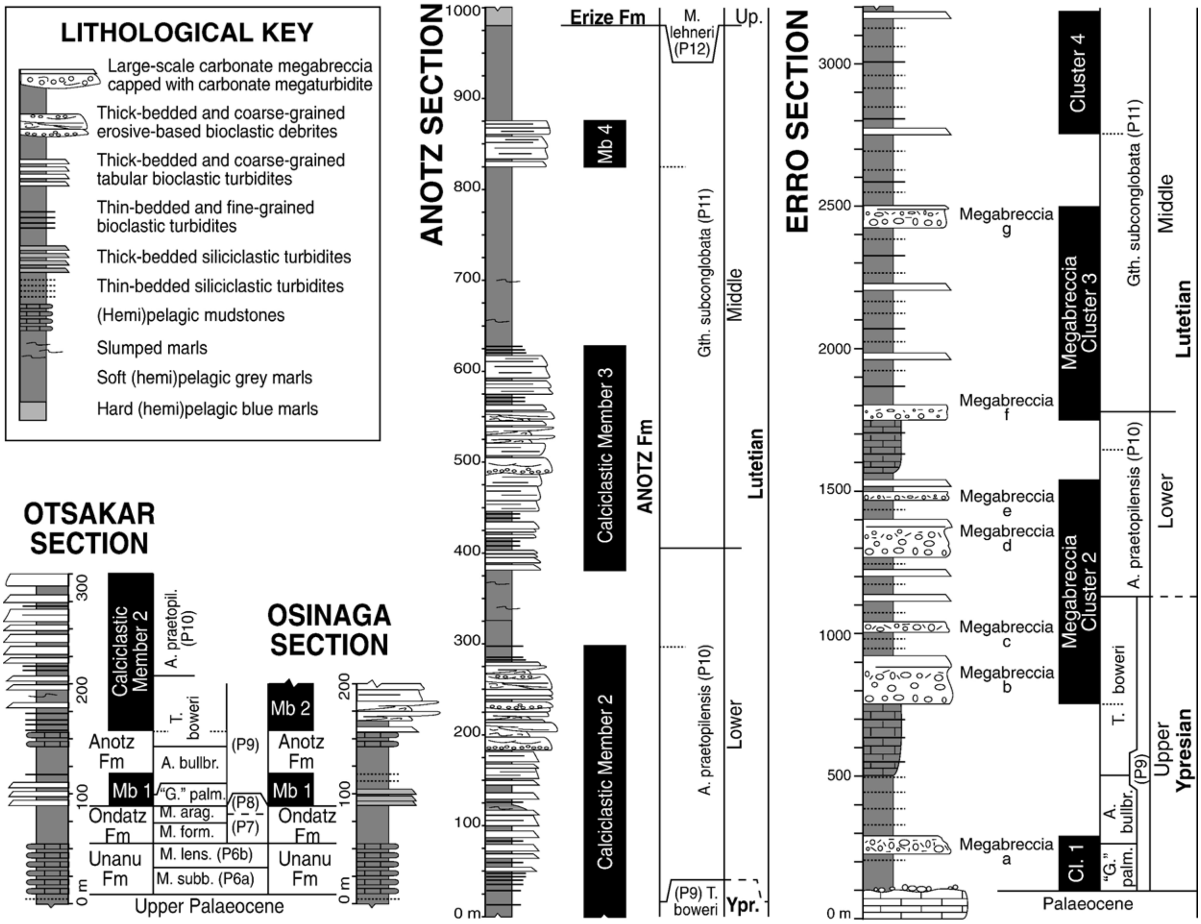

Fig. 3. Synthetic logs of the Otsakar, Osinaga, Anotz and Erro sections, showing lithostratigraphic units and biostratigraphic data (biozones after Orue-Etxebarria et al., 1984). Note that resedimented deposits are concentrated within the four calciclastic members of the Anotz Fm (based on Payros, 1997, and Payros et al., 2003) and within the four time-stratigraphic intervals of megabreccia clustering in the Erro Fm (based on Payros et al., 1999).

Finally, the upper Lutetian–lower Bartonian Erize Fm is up to 700 m thick and is mostly composed of hemipelagic marls almost devoid of turbidites, features that suggest deep marine low-energy conditions.

3.2. Basque basin

In the Basque basin the lower Ypresian–upper Lutetian succession is also entirely composed of deep-water deposits, its most complete and representative section being exposed in coastal cliffs just northwest of Bilbao (Sopela–Galea section, Figs. 1 and 5).

The bulk of the succession (i.e. from 0 to 1750 m in Fig. 5) is made up of hemipelagic limestones and marls with intercalations of siliciclastic and calciclastic turbidites. To assess volumetric variations of turbidites throughout the succession, the sedimentary features (lithology, thickness and shape, primary structures, grain fabric, palaeocurrents, etc.) of every turbidite bed thicker than 15 cm were investigated in the field. A semiquantitative estimation of the vertical variations in turbidite abundance was then obtained by plotting their composite thickness per every 10 m thick intervals. Such procedure has made evident that this part of the succession consists of six distinct intervals with variable amounts of turbidites (Fig. 5). The turbidite content of three intervals seldom exceeds 20% (average values are lower than 10%), certain levels being almost completely devoid of turbidites. These three intervals have been termed consequently "turbidite-poor." On the other hand, the other three intervals have been named "turbidite-rich" because their turbidite content ranges between 10% and 80%, and averages higher than 20%. We also note an increase in the proportion of reworked, shallow-water ostracods in the three turbidite-rich intervals (Rodríguez-Lázaro and García-Zar-

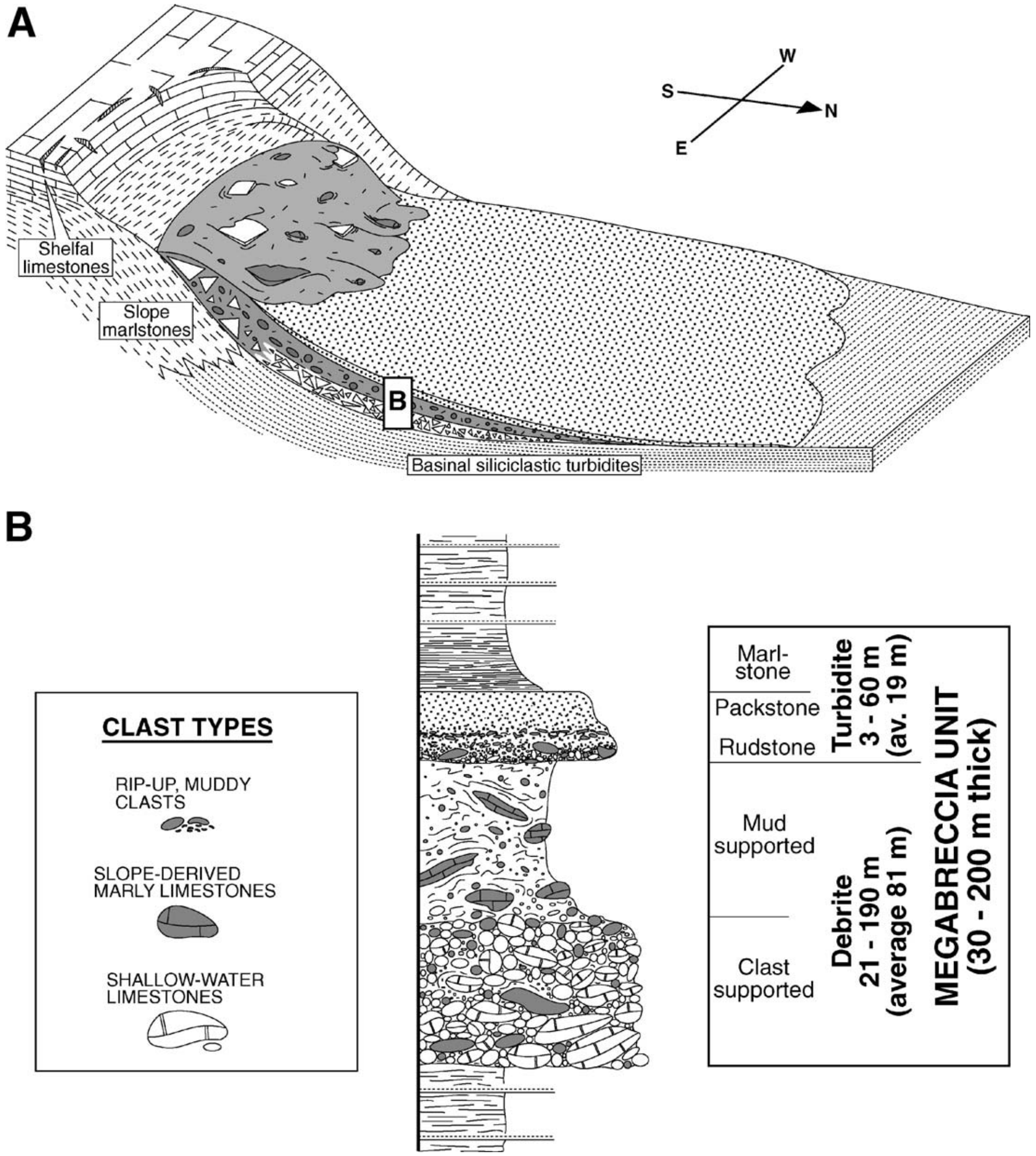

Fig. 4. (A) Idealized depositional model for a carbonate megabreccia in the Pamplona basin, showing the variations in the internal structure (not to scale). (B) Internal organization of the medial part of a carbonate megabreccia. A megabreccia unit records one single large-scale resedimentation event. Modified from Payros et al. (1999).

raga, 1996; Fig. 5), and also of carbonized plant remains.

The upper part of the section (from 1750 m to the top of the preserved succession; Fig. 5) is composed of hemipelagic marls and limestone with abundant intercalations of calciclastic turbidites, some of them reaching 1 m in thickness. Because of this abundance, this part of the succession has been included within the third turbidite-rich interval described above (Fig. 5). However, the most remarkable feature in this part of the succession is the intercalation of several carbonate megabreccia beds, some of them up to 35 m thick, that record large-scale resedimentation events (Pujalte et al., 1997) (Fig. 6). The megabreccias are mostly composed of contorted and/or fragmented strata of calciturbidites and hemipelagic marls and limestones. Such composition demonstrates that they record remobilization of basinal deposits. The megabreccias are capped by a calciturbidite mostly composed of shallow-water bioclasts, including larger foraminifera and red algae. Such composition is a clear proof of a shallow-water derivation. Thus, the simultaneous rese-

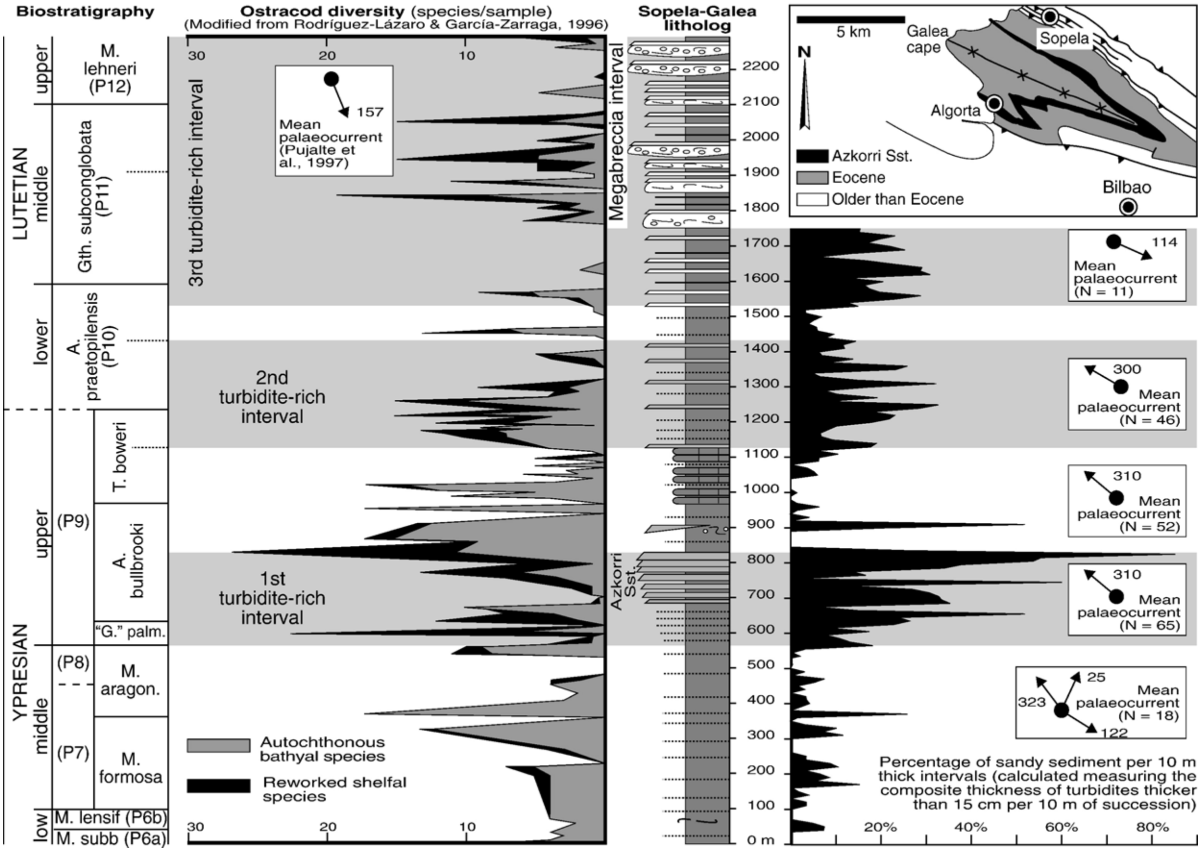

Fig. 5. Simplified litholog of the Sopela–Galea section (Basque basin) showing vertical variations in turbidite content (right-hand graph) and amount of reworked shelfal ostracods (left-hand graph; modified from Rodríguez-Lázaro and García-Zarraga, 1996). Biostratigraphic data from Orue-Etxebarria et al. (1984). See Fig. 3 for lithological key. Inset: geological map and location of the section.

dimentation of both basinal and shallow-water deposits strongly points to coeval earthquakes as the triggering mechanism (Pujalte et al., 1997). Finally, the marlstone capping the megabreccias demonstrates that the resedimentation events put a large amount of fine-grained sediment in suspension, which slowly settled back after the deposition of the coarser-grained sediments.

4. Planktonic foraminifera

4.1. Database and biochronostratigraphy

The most detailed study of the planktonic foraminifera carried out to date in the Pamplona basin is that of Canudo (1990), based on 41 samples from the Osinaga and Anotz sections. More recently, Orue-Etxebarria (in Payros, 1997, and Payros et al., 1999) provided data from 51 additional samples from the Otsakar, Anotz and Erro sections. In the Basque basin, the planktonic foraminifera from the Sopela–Galea section were studied in 90 samples by Orue-Etxebarria et al. (1984), with later additions by Orue-Etxebarria (1985), Orue-Etxebarria and Apellaniz (1985) and Orue-Etxebarria and Lamolda (1985). In all cases, the samples were soaked in distilled water and washed under running water through 250, 150 and 63 μm mesh sieves. The residues were studied under binocular microscope for their planktonic foraminiferal content, which varies between 60% and 90% of the total (planktonic plus benthonic) foraminiferal content in the Osinaga and Anotz sections and is generally above 90% throughout the Sopela–Galea section. From each sample at least 300 specimens were picked and identified. All of the micropalaeontological samples have been accurately positioned on the stratigraphic logs shown in Figs. 3 and 5. The stratigraphic distribution of the most significant species of planktonic foraminifera in the composite Osinaga–Anotz section is shown in Fig. 7, whereas their distribution in the Sopela–Galea section is shown in Fig. 8.

The general chronostratigraphic framework of the studied successions has been established by using several biohorizons well constrained in the standard scales

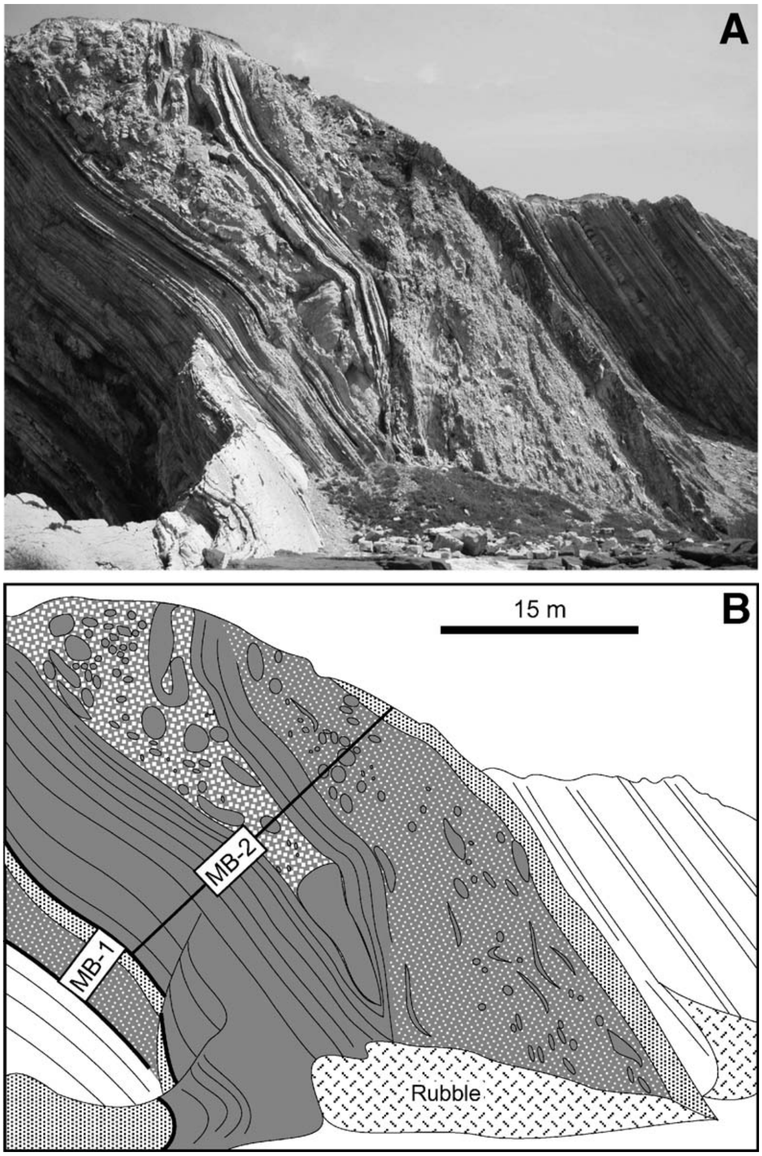

Fig. 6. Outcrop photo (A) and sketch (B) of the upper part of the Sopela–Galea section (Basque basin), showing two successive megabreccias (MB-1 and 2). After Pujalte et al. (1997).

of either Berggren et al. (1995) or Premoli Silva et al. (2003) (Table 1). It should be noted, however, that a criterion often quoted to mark the Ypresian/Lutetian boundary (i.e. the first occurrence of Hantkeninids) has not been followed, because Hantkeninids are comparatively rare in the western Pyrenees (Orue-Etxebarria et al., 1984; Orue-Etxebarria and Apellaniz, 1985; Canudo, 1990; Canudo and Molina, 1992b; Sztràkoz, 2000). Instead, the lowest occurrence of *A. praetopilensis* has been chosen as an approximate alternative biohorizon, as its first appearance is thought to be approximately coeval with that of Hantkeninids (Premoli Silva et al., 2003; Erbacher et al., 2004).

4.2. Planktonic foraminifera as biogeographical indices

The usefulness of Eocene planktonic foraminifers as palaeobiogeographic, palaeoecologic and palaeoceanographic indices was demonstrated, among others, by Premoli Silva and Boersma (1988, 1989) and Boersma and Premoli Silva (1991). They reasoned that the more specialized the planktonic foraminiferal morphology, the greater the tendency to inhabit lower latitudes. Thus, they defined several groups of planktonic foraminiferal species assumed to be representative of different palaeolatitudinal and/or palaeoenvironmental settings. Such an approach has been routinely used

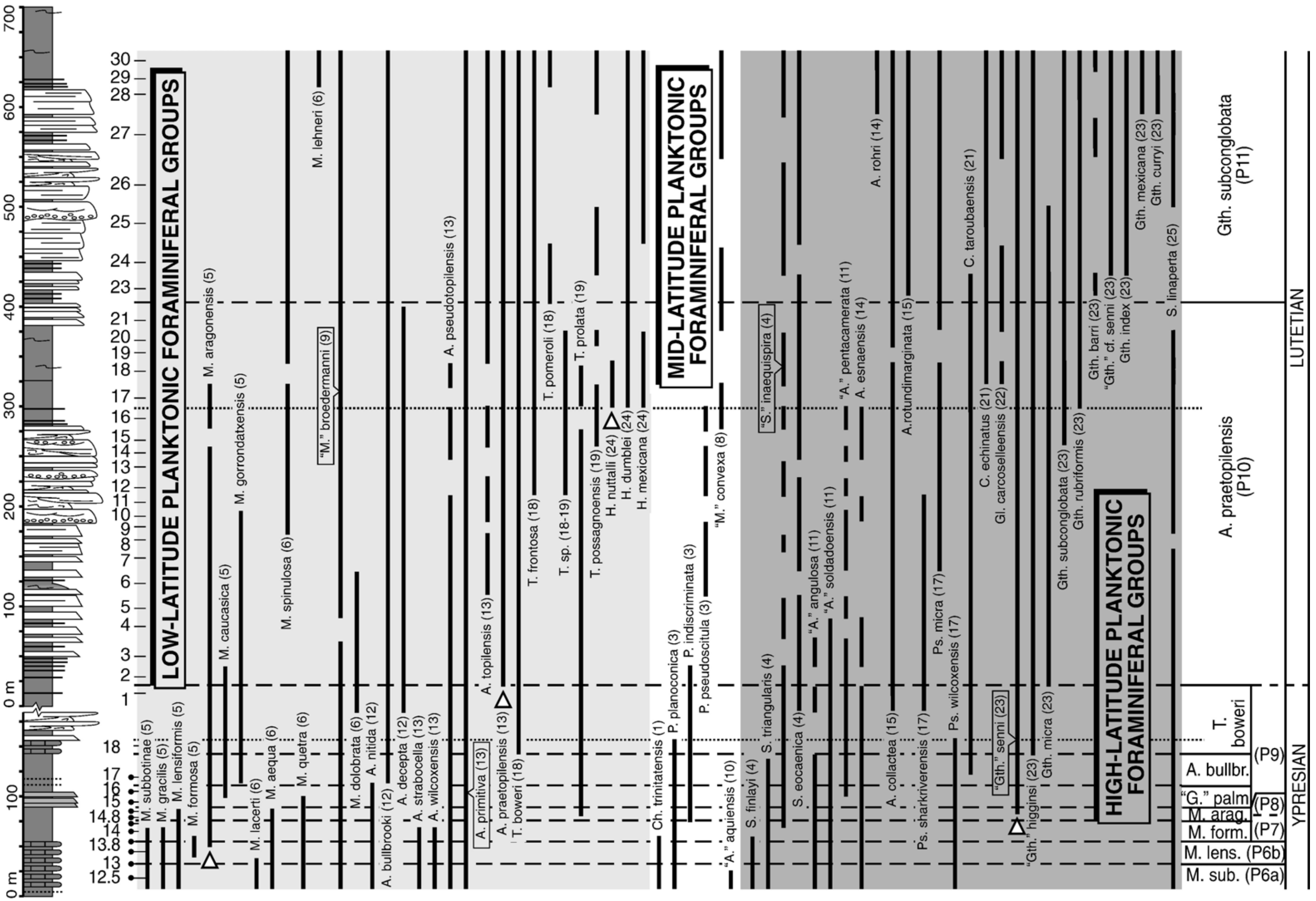

Fig. 7. Planktonic foraminiferal species ranges in the composite Osinaga–Anotz section (Pamplona basin) (based on Canudo, 1990); dots and numbers to the right of the lithologs correspond to the original samples. The genera-level classification has been modified herein and adapted to that of Premoli Silva and Boersma (1988): M=*Morozovella*; A=*Acarinina*; T=*Turborotalia*; H=*Hantkenina*; Ch=*Chiloguembelina*; P=*Planorotalites*; S=*Subbotina*; Ps=*Pseudohastigerina*; C=*Catapsydrax*; Gl=*Globorotaloides*; G=*Globorotalia*; Gth=*Globigerinatheka*. Numbers after species names refer to palaeobiogeographically significant planktonic foraminiferal groups (after Premoli Silva and Boersma, 1988): low- and middle-low latitude species shown on light grey background; high- and middle-high latitude species shown on dark grey background. White triangles: significant biohorizons discussed in the text. Planktonic foraminiferal biozones after Orue-Etxebarria et al. (1984), using a combination of data from Canudo (1990), Payros (1997) and from new samples from Osinaga.

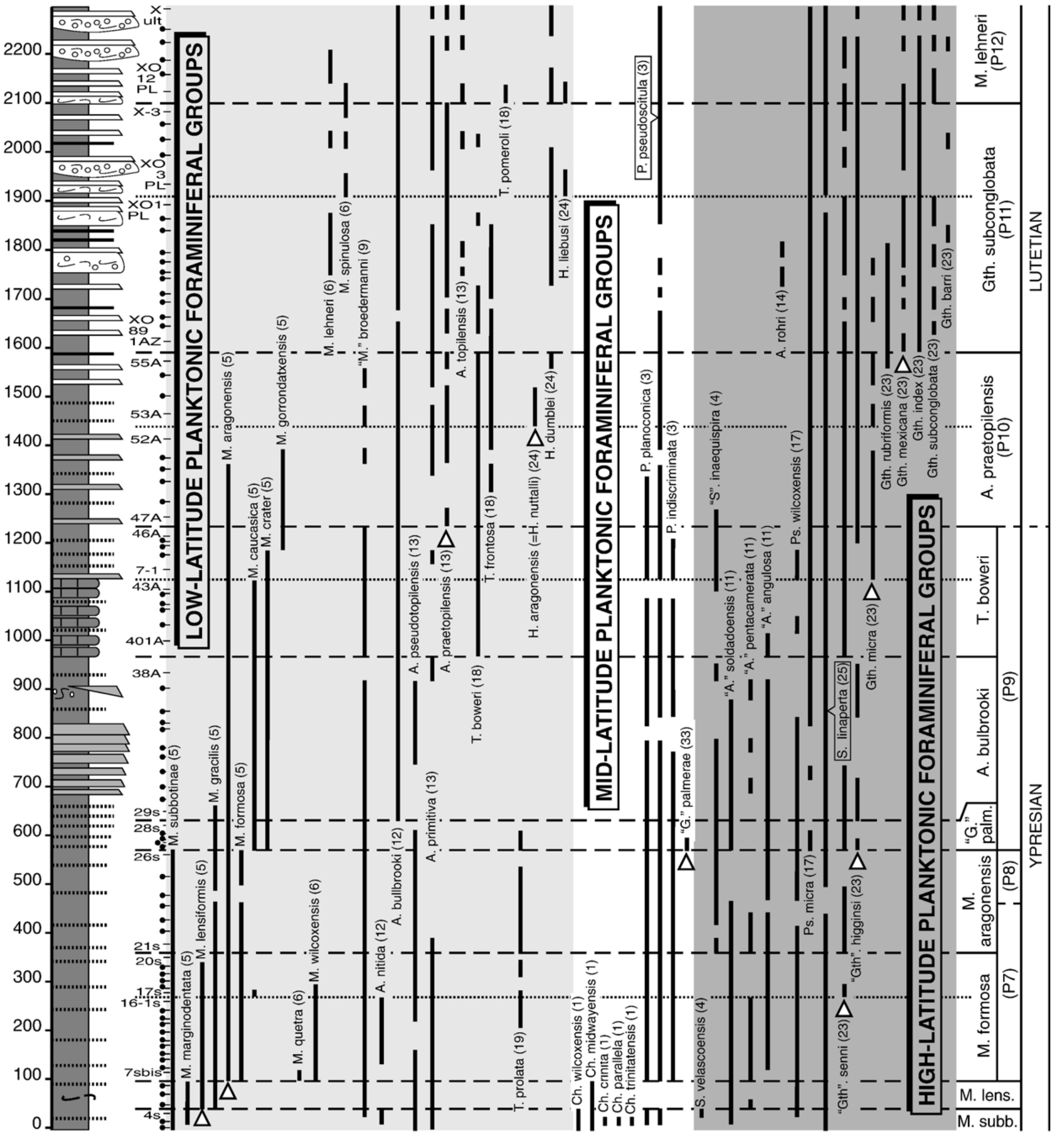

Fig. 8. Planktonic foraminiferal species ranges and zonation in the Sopela–Galea section (Basque basin) (modified after Orue-Etxebarria et al., 1984; uncertain occurrences not included); dots and codes to the right of the litholog mark position of studied samples. Symbols and abbreviations as in Fig. 7.

ever since for palaeoecological studies and palaeoceanographic reconstructions (e.g. Spezzaferri and Premoli Silva, 1991; Canudo and Molina, 1992a; Spezzaferri, 1995; Beniamovskii and Gladenkov, 1996; Arenillas et al., 1999; Pardo et al., 1999; Spezzaferri et al., 2002; Bicchi et al., 2003; Verducci and Nocchi, 2004).

Following the criteria of Premoli Silva and Boersma (1988, 1989) and Boersma and Premoli Silva (1991), individual planktonic foraminiferal species from the Pamplona and Basque basins (respectively Figs. 7 and 8) have been ranked as low, middle-low, middle, middle-high and high latitude taxa. The group of Globigerinathekids needs further comments,

Table 1
Characteristic planktonic foraminiferal biohorizons identified in the western Pyrenees and used for correlations with the standard biochronostratigraphy of Berggren et al. (1995)

Bioevent	Age (Ma)	References
Lowest occurrence of *M. lensiformis*	54	Premoli Silva et al. (2003)
Lowest occurrence of *M. aragonensis*	52.3	Berggren et al. (1995), Premoli Silva et al. (2003)
Lowest occurrence of *Gth. senni*	51.5	Premoli Silva et al. (2003)
Lowest occurrences of *G. palmerae* and *Gth. higginsi*	50.4	Berggren et al. (1995), Premoli Silva et al. (2003)
Lowest occurrence of *Gth. micra*	49.5	Premoli Silva et al. (2003)
Lowest occurrence of *A. praetopilensis*	Close to 49.0	Premoli Silva et al. (2003)
Lowest occurrence of *Gth. mexicana*	45.8	Premoli Silva et al. (2003)

as their palaeoecological preference is controversial. According to Premoli Silva and Boersma (1988, 1989) and Boersma and Premoli Silva (1991), Globigerinathekids thrived in high-latitude cool waters and in vigorous nutrient-rich waters during the Early and Middle Eocene, and they expanded to lower latitude warm waters in the late middle Eocene (zone P14 of Berggren et al., 1995). A similar evolution in ecological conditions is also known for other Cenozoic planktonic foraminifers, such as Acarininids, which appeared first in temperate or high-latitude sites and subsequently expanded their range into mid- and low-latitude regions (Quillévéré et al., 2001), and Hantkeninids, which occupied a deep sub-thermocline habitat and later shifted into warmer waters of the surface mixed layer (Coxall et al., 2003). In accordance with these assumptions, Galeotti et al. (2002) detected a Middle Eocene subantarctic warming event marked by the appearance of Hantkeninids but with no increase in the abundance of Globigerinathekids, whereas a Late Eocene warming peak was marked by an increase in Globigerinathekids. However, Verducci and Nocchi (2004) considered most Middle and Late Eocene Globigerinathekids as temperate indices. Spezzaferri et al. (2002) stated that Late Eocene Globigerinathekids hosted algal symbionts, but they were still regarded as cold-temperate and mid-high latitude (see their Table 2). Barbieri et al. (2003) indicated that in Late Eocene times the number of Globigerinathekids increased during periods of oxygen depleted and/or eutrophicated deep waters. Finally, unpublished information by members of the Paleogene Planktonic Foraminifera Working Group suggests that Globigerinathekids were symbiont-bearing organisms that thrived in temperate and mesotrophic waters. All things considered, Early and Middle Eocene Globigerinathekids are taken here as indicative of relatively cool and/or nutrient-enriched (not oligotrophic) waters similar to those in middle-high latitudes. It must be considered, however, that maybe some changes in species significance will be possible in the near future. The ratio of lower to higher latitude index species has been calculated for each sample by counting the occurrence of palaeobiogeographically significant taxa and by adding the abundance of middle-low and middle-high indices to that of low and high indices, respectively (for further details on the method see Spezzaferri, 1995, p. 52).

It has been found that high-latitude species fluctuate between 33% and 60% in the Pamplona basin, and between 25% and 75% in the Basque basin. To better visualize such fluctuations, the ratio of lower to higher latitude indices has been re-calculated as the percentage of deviation from the neutral assemblage containing 50% of low-latitude and high-latitude planktonic foraminiferal indices, the results having been plotted on symmetric, two-sided semilogarithmic graphs in Figs. 9 and 10 (for details on visualization methods see Spezzaferri and Premoli Silva, 1991; Spezzaferri, 1995).

5. Results

5.1. Sedimentary trends

Despite their different palaeogeographical settings, the Ypresian–Lutetian successions of the Pamplona and Basque basins do have several sedimentological features in common. Both successions consist of a vertical stacking of intervals alternatively poor and rich in turbidites. Furthermore, during the Ypresian and early Lutetian the intervals of increased turbiditic activity in both basins seem to have been coeval, first during a comparatively short period around the middle–late Ypresian (recorded by member 1 of the Anotz Fm in the Pamplona basin and by the 1st turbidite-rich interval in the Basque basin), and then for a longer period during the latest Ypresian–earliest Lutetian (i.e. member 2 of the Anotz Fm and 2nd turbidite-rich interval; Fig. 11). The middle Lutetian was also a time of increased turbiditic activity, particularly pronounced and long-lasting in the Basque basin (3rd turbidite-

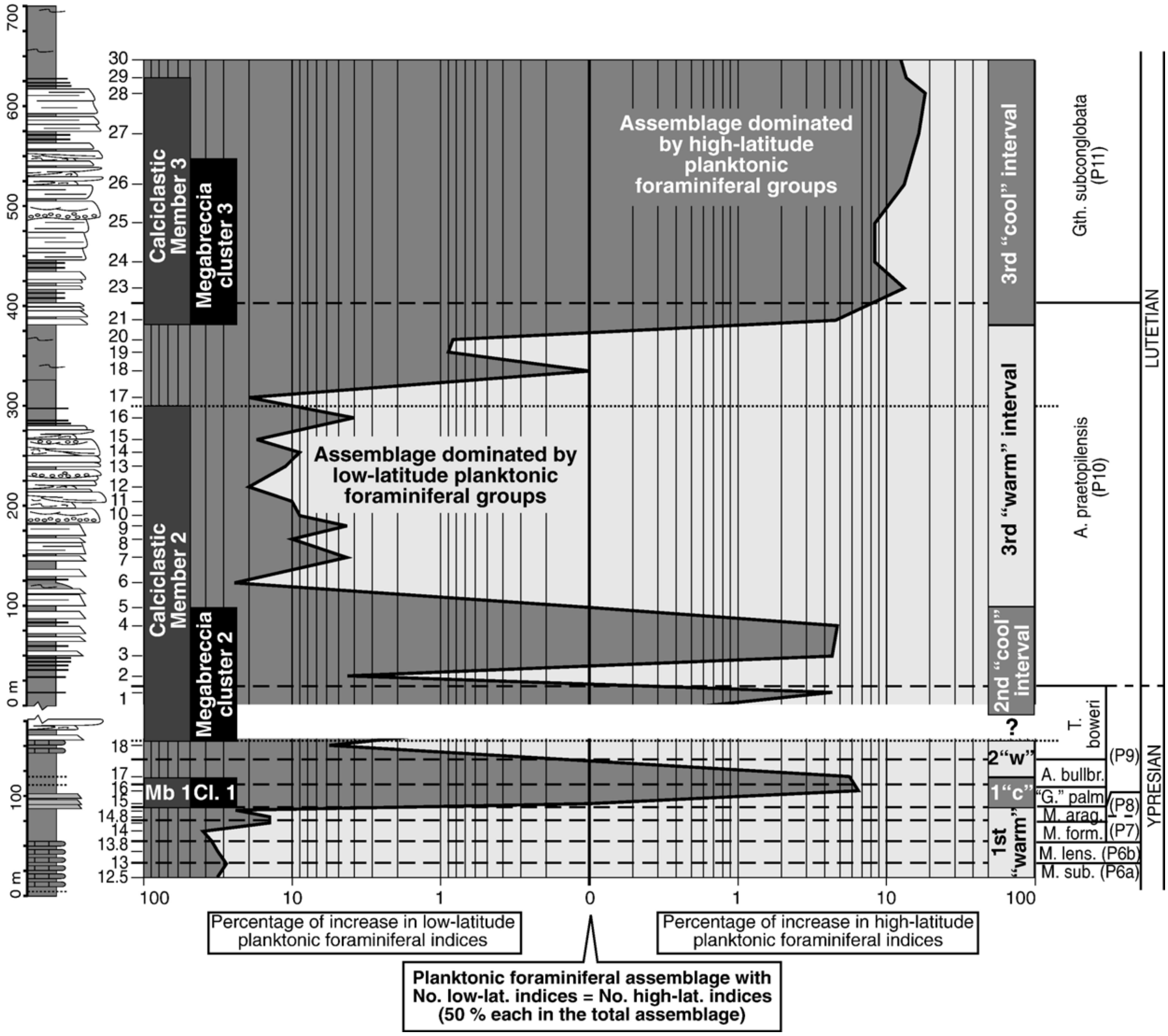

Fig. 9. Ratio of lower to higher latitude planktonic foraminiferal index species in the Osinaga and Anotz sections (Pamplona basin) calculated from data in Fig. 7 and plotted on a symmetric, two-sided semilogarithmic graph as the percentage of deviation from the neutral assemblage containing 50% of low-latitude and high-latitude planktonic foraminiferal indices. The true percentage of lower and higher latitude planktonic foraminiferal index species for each sample can be obtained by applying the following formula to the values in the graph: $\%=X/2+50$, where % is the true percentage and X corresponds to a given value in the graph. In general, low-latitude assemblages are dominant except for three discrete "cool" intervals included mostly within the Anotz calciclastic members. For correlation purposes, the extent of the megabreccia clusters is also shown.

rich interval in Figs. 5 and 11), whereas in the Pamplona basin this activity was of shorter duration and even slowed down to a near halt for a while (members 3 and 4 of the Anotz Fm and intervening turbidite-poor interval in Figs. 3 and 11).

Megabreccia beds that record catastrophic, large-scale resedimentation events occur in both basins, although their temporal distribution and sedimentological character are quite different in each case. The megabreccia beds of the Pamplona basin are demonstrably basin-wide in extent (Seguret et al., 1984; Labaume et al., 1987; Barnolas and Teixell, 1994; Payros et al., 1999) and their origin can be linked to collapses of the South Pyrenean carbonate ramp during times of tectonic tilting. As discussed above, the megabreccias are clustered within four discrete time periods that clearly record four peaks in tectonic activity in the Pamplona basin. The sedimentological characteristics of the Basque basin megabreccia beds suggest a period of active tectonism that spanned most of the middle Lutetian and, at least, the first part of the late Lutetian. This period was partly coeval with the megabreccia cluster 4 in the Pamplona basin, although the latter was of shorter duration (Fig. 11). Megabreccia clusters 1, 2

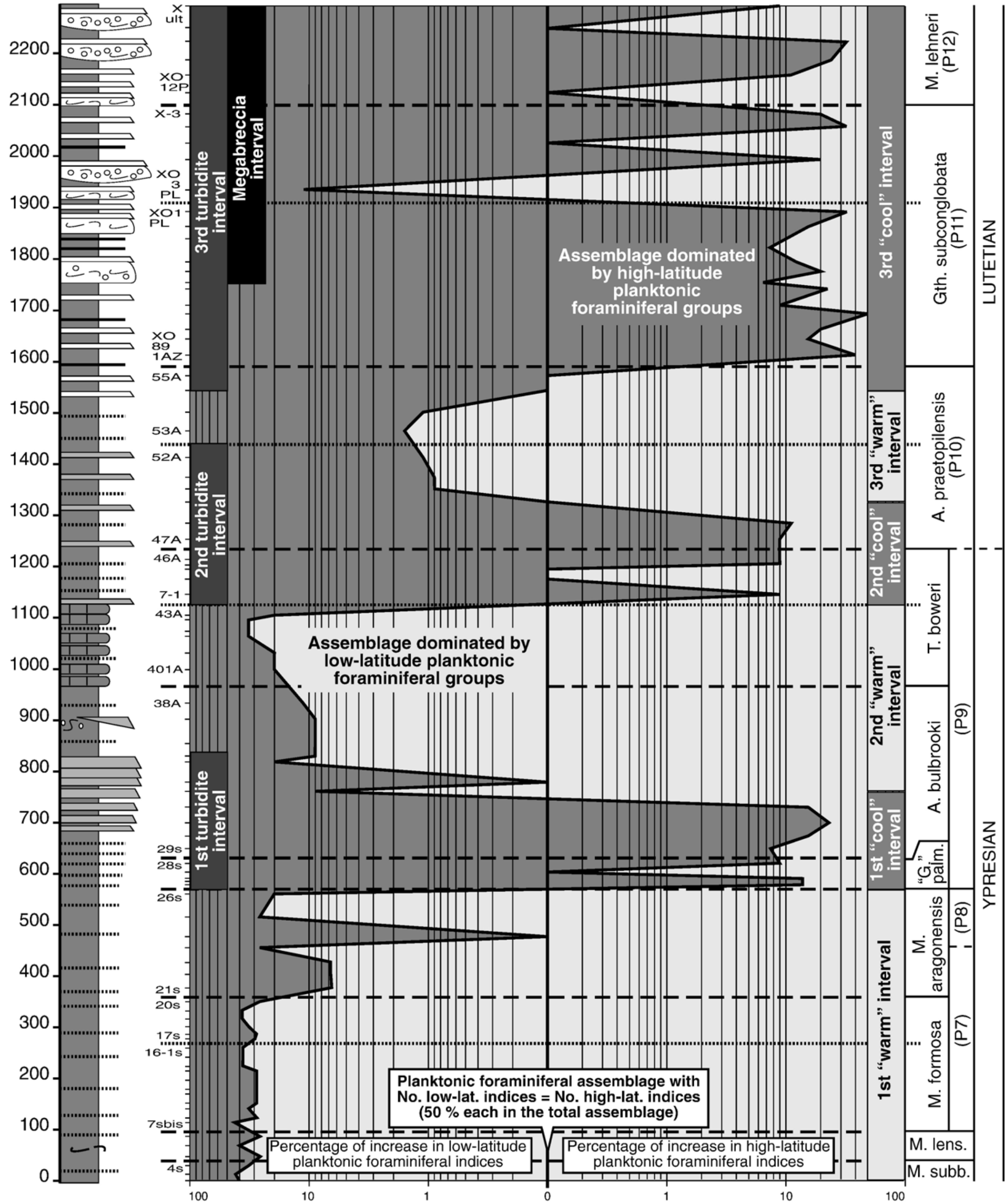

Fig. 10. Ratio of lower to higher latitude planktonic foraminiferal index species in the Sopela–Galea section (Basque basin) calculated from data in Fig. 8 and plotted on a symmetric, two-sided semilogarithmic graph as the percentage of deviation from the neutral assemblage containing 50% of low-latitude and high-latitude planktonic foraminiferal indices. In general, low-latitude assemblages are dominant except for three discrete "cool" intervals included within the turbidite-rich deposits.

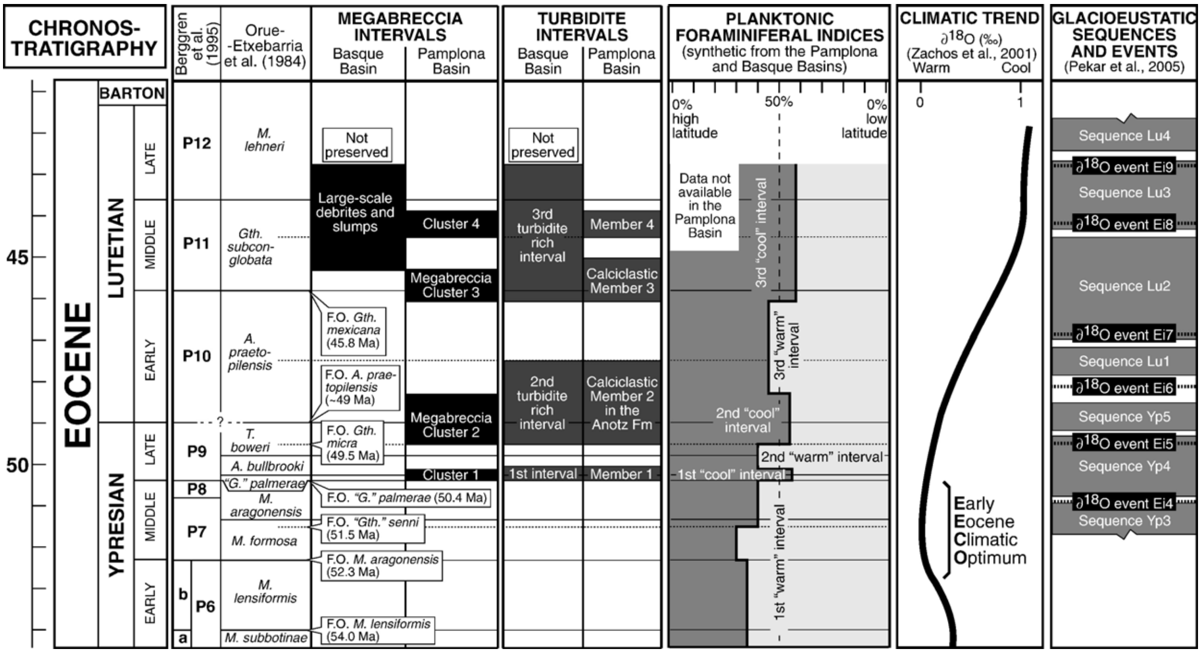

Fig. 11. Chronostratigraphic framework of the Pamplona and Basque basins, showing the temporal distribution of the different sedimentological and planktonic foraminiferal intervals. Correlation with the standard scheme of Berggren et al. (1995) is based on significant planktonic foraminiferal biohorizons shown in Table 1. Also shown are the stable isotope-based global climatic trend of Zachos et al. (2001) and the glacioeustatic sea-level falls identified by correlating sequence boundaries with ∂^{18}O increases (Pekar et al., 2005).

and 3 of the Pamplona basin have no equivalent in the Basque basin, a fact that can be attributed to the diachronism of the Pyrenean orogeny, which progressed from east to west during the Eocene (e.g. Plaziat, 1981; Verges et al., 1995; Pujalte et al., 2002).

Biostratigraphic data indicate that the megabreccias accumulated during the intervals of increased turbiditic activity. Furthermore, the data show that the megabreccia-bearing intervals involve lapses of time of shorter duration than those represented by the turbidite-rich intervals (Fig. 11). It can be concluded, therefore, that during Ypresian–Lutetian times tectonism in the Pamplona and Basque basins varied in intensity. The most active periods are recorded by large-scale resedimentation events, producing both megabreccias and turbidites. Periods of moderate tectonism are rich in turbidites but lack megabreccias. Periods of comparatively tectonic quiescence are poor in turbidites.

5.2. Planktonic foraminiferal trends

The vertical evolution of planktonic foraminiferal assemblages show similar trends in both the Pamplona and Basque basins, although minor differences in absolute values exist, which may in part be due to differences in sampling resolution (Figs. 7 and 8). A general trend towards associations richer in high-latitude indices can be clearly seen in the Ypresian–Lutetian record from both basins (Fig. 11). In addition, the studied successions are marked by distinct short-term alternating intervals of high and low-latitude planktonic foraminiferal indices. Thus, three short-term intervals characterized by low-latitude planktonic foraminiferal indices and another three typified by high-latitude indices have been recognized in the Pamplona and Basque basins (Figs. 7 and 8). The three intervals dominated by low-latitude planktonic foraminiferal indices have been named "warm" intervals, whereas those dominated by high-latitude indices are labelled as "cool" intervals.

The average magnitude of the fluctuations in planktonic foraminiferal indices is similar in both basins and they seem to be coeval (Fig. 11). Thus, the first "warm" interval has low-latitude indices averaging 65% in the lower Ypresian, peaking to 70% in the lower part of the middle Ypresian, and decreasing to 60% in the upper part of the middle Ypresian. The second "warm" interval, late Ypresian in age, is of shorter duration and shows an average of low-latitude planktonic foraminiferal indices of 60%. Finally, the third "warm" interval (early Lutetian) averages 55% of low-latitude indices. The three "cool" intervals are characterized by high-latitude planktonic foraminiferal indices with similar average values (56%, 55% and 58% from the oldest to the youngest). Their most interesting feature, however, is that their ages seem to match precisely with those of the intervals in which megabreccia beds accumulated either in the Pamplona basin, or in the Basque basin, or in both (Fig. 11).

6. Discussion

This study reveals that: (1) during the Ypresian–Lutetian interval the lower to higher latitude planktonic foraminiferal ratio fluctuated simultaneously in the Pamplona and Basque basins, suggesting alternating “warm” and “cool” episodes; and (2) the “cool” episodes are coeval with tectonically induced large-scale resedimentation events in one or in both basins. To explain these characteristics different scenarios can be proposed.

6.1. Scenario 1: climate forcing

Increases in the percentage of high- or low-latitude planktonic foraminiferal groups have been considered by many authors to reflect biotic latitudinal migrations induced by climatic cooling or warming episodes (e.g. Premoli Silva and Boersma, 1988, 1989; Boersma and Premoli Silva, 1991; Spezzaferri and Premoli Silva, 1991; Canudo and Molina, 1992a; Spezzaferri, 1995; Beniamovskii and Gladenkov, 1996; Arenillas et al., 1999; Pardo et al., 1999; Spezzaferri et al., 2002; Bicchi et al., 2003; Verducci and Nocchi, 2004). Another controlling factor is the variation in the depth of the thermocline, which depends on both insolation and pattern of circulation of deep-water oceanic currents, two factors that are intimately linked to climate. Unfortunately, thermocline variations are difficult to constrain in the fossil record and, therefore, we restrict our discussion to the possible influence of cooling/warming episodes.

The proportion of high- and low-latitude planktonic foraminiferal groups in the studied successions indicates generally “warm” conditions during the early and middle Ypresian, with a warmer episode in the middle Ypresian (i.e. between 52.3 and 51.5 Ma), followed by a late Ypresian–Lutetian long-term cooling mostly marked by three “cool” intervals (Fig. 11). This evolution broadly matches the general global climatic trend through the Early–Middle Eocene. Stable isotope analyses of deep-sea records established that the Early Eocene was a time of warm global climate, the middle Ypresian being the warmest interval (i.e. the so-called “Early Eocene Climatic Optimum”, EECO), whereas global temperatures decreased smoothly during the late Ypresian and Lutetian times (Fig. 11; see also Zachos et al., 2001; Prothero et al., 2003, and references therein).

On the basis of this broad match, it could be argued that the Pyrenean “cool” intervals record climatic events, which induced sea-level lowstands and triggered large-scale resedimentation processes (Fig. 12A). However, two main lines of evidence indicate that climatic forcing alone did not produce such palaeoenvironmental perturbations. First, on a finer scale no correlation can be established between the western Pyrenean record and short-term climatic oscillations. In effect, Pekar et al. (2005) recognized seven Early–Middle Eocene depositional sequences in ODP Site 1171, which they positively compared with successions in New Jersey and Europe. More significant, the sequence boundaries are approximately correlative with $\partial^{18}O$ increases, a strong evidence of the glacioeustatic origin of the sequences. In a climate-dominated scenario, even these 3rd-order glacioeustatic changes should be reflected in the planktonic foraminiferal indices, but no evidence of them is recorded in the study area (Fig. 11). Second, the climate-forced scenario also fails to explain why during middle–late Lutetian times two short-lived megabreccia clusters are found in the Pamplona basin, whereas only one long-lasting interval occurs in the Basque basin: had climate-induced sea-level falls been the leading factor, they would have affected equally, and be recorded similarly, in both basins. Therefore, an alternative scenario is proposed to explain the synchronous short-term increases in megabreccia deposition and high-latitude planktonic foraminiferal indices.

6.2. Scenario 2: changing trophic resources

Premoli Silva and Boersma (1988, 1989), Boersma and Premoli Silva (1991) and Hallock et al. (1991) have shown that high-latitude planktonic foraminiferal groups are dominated by opportunistic and cosmopolitan species, whereas symbiont-bearing K-strategist species thrive in oligotrophic, low-latitude assemblages. They also demonstrated that, in addition to biotic migrations during climatic changes, variations in nutrient flux to the seas could effectively modify planktonic foraminiferal assemblages. For that reason, eutrophication of surface waters and the demise of symbiont relationships can lead to the proliferation of morphotypes with high-latitude characters in low-latitude assemblages (see also Allmon, 2001; Wade, 2004).

Eutrophication is often related to the upwelling of nutrient-rich bottom currents, but according to ostracod analyses (Rodríguez-Lázaro and García-Zarraga, 1996),

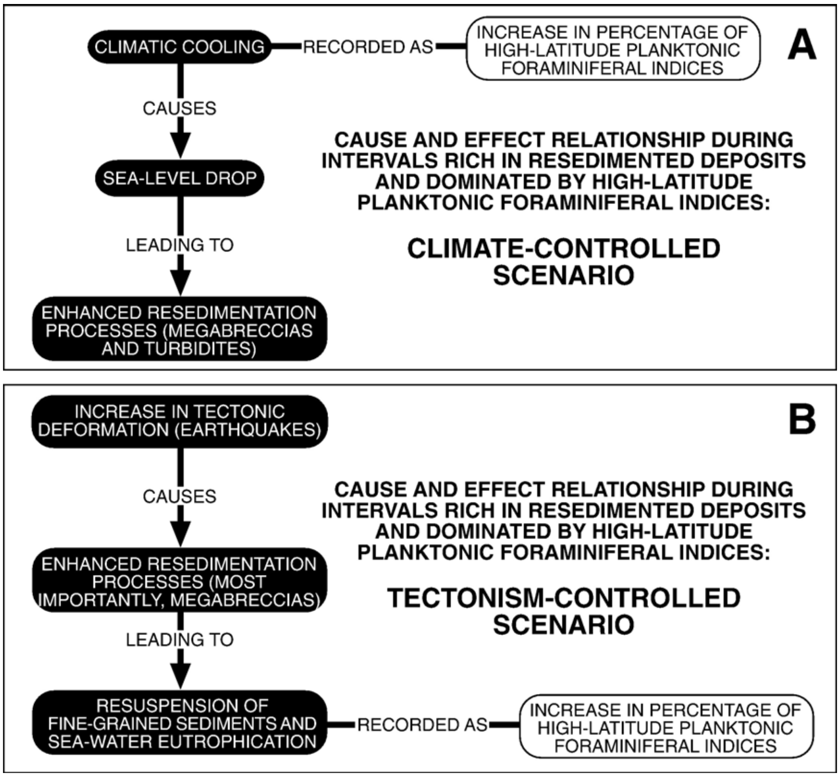

Fig. 12. Two hypothetical scenarios leading to intervals rich in resedimented deposits and high-latitude planktonic foraminiferal indices. (A) Climate-controlled scenario, where climatic cooling causes sea-level fall and accumulation of lowstand resedimented deposits. (B) Tectonism-controlled scenario, where tectonic activity causes resedimentation of huge megabreccias and concomitant eutrophication of seawaters. Further explanation within the text.

in the Pyrenean domain there is no evidence of high productivity bottom waters during Early and Middle Eocene times. Another mechanism leading to eutrophication may be resuspension of fine-grained sediments. This is so because fine-grained sediment resuspension commonly results in the transport of buried organic matter to surface waters, as well as in the release of soluble nutrients from interstitial water previously trapped in the sediment and of nutrients attached to sediment particles, all of which may become available for biological uptake (e.g. Tengberg et al., 2003). Furthermore, when sediment resuspension and surface organic productivity increase, light penetration and photosynthesis are attenuated. Such environmental perturbations may be enhanced when a large amount of sediment is resuspended by sudden catastrophic processes (e.g. Eadie et al., 2002). While the onset of such perturbations is often sudden, the recovery to normal conditions may be a much longer process. Therefore, it is possible that photosynthetic symbiont-bearing K-strategist planktonic foraminiferal crops could fail during the eutrophication episodes with reduced light penetration caused by the injection of large amounts of suspended fine-grained sediments in a marine basin. The most important processes driving deep marine fine-grained sediments into suspension are high-energy turbidity currents (e.g. Bonnin et al., 2002) and slope-failure events (e.g. Burd et al., 2000), both of which were frequent in the Pamplona and Basque basins during the Ypresian–Lutetian “cool” intervals.

Turbidity currents may originate either by direct river effluents transforming into hyperpycnal flows or by shelf-margin failures (e.g. Plink-Björklund and Steel, 2004). Whatever the origin, turbidity currents are able to put large volumes of very fine-grained sediment into suspension, which may include substantial amounts of organic matter and nutrients, provided either by terrestrial runoff or resuspension. In the studied successions the inception of some of the intervals rich in turbidites and those rich in high-latitude planktonic foraminiferal assemblages are simultaneous (Fig. 11). However, the duration of the turbidite-rich intervals 1 and 2 was longer than the corresponding “cool” intervals rich in high-latitude indices. This suggests that sediment resuspension, eutrophication and light attenuation caused by turbidity currents alone may be insufficient to cause a substantial decrease of low-latitude, K-strategist planktonic foraminiferal species.

There is a much better match between the timing of the "cool" intervals and that of deposition of huge debrites and megabreccias (Fig. 11). Such catastrophic episodes resuspended large amounts of fine-grained sediment, probably including buried organic matter and nutrients, which could have been further distributed by lateral advection (e.g. within nepheloid layers or tidal currents). Interestingly, the onset of the three intervals rich in high-latitude planktonic foraminiferal assemblages coincides exactly with the base of the three oldest megabreccia-bearing clusters in the Pamplona basin (Fig. 11). Furthermore, the top of the two oldest intervals rich in high-latitude indices is also coeval with the top of the two oldest megabreccia clusters in the Pamplona basin. The top of the third megabreccia cluster in the Pamplona basin (middle Lutetian in age) does not coincide with any remarkable change in planktonic foraminiferal indices, as they are still dominated by high-latitude species in both the Pamplona and the Basque basins (Fig. 11). However, large-scale debrites occur throughout the middle and upper Lutetian succession in the Basque basin. Thus, the third interval rich in high-latitude planktonic foraminiferal indices in the Pamplona and Basque basins is also coincident with debrite and megabreccia deposition, either in the Pamplona basin, in the Basque basin, or in both.

In summary, the three intervals rich in high-latitude planktonic foraminiferal indices in the Pamplona and Basque basins developed during times when megabreccias and turbidites were accumulating either in one or in both of the western Pyrenean basins. Therefore, seawater eutrophication produced by the joint occurrence of tectonically induced large-scale resedimentation processes and active turbidite deposition seems to be a plausible mechanism, alternative to climatic cooling, to explain the intervals rich in opportunistic, cosmopolitan, "high-latitude" planktonic foraminiferal indices in the study area (Fig. 12B).

7. Conclusions

Ypresian–Lutetian successions accumulated in two different, although interconnected, deep-marine basins in the western Pyrenees show synchronous and recurrent palaeoenvironmental changes, reflected both in the sedimentary and in the planktonic foraminiferal records. Intervals with scarce or no turbidite deposits in the Pamplona and Basque basins contain high proportions of symbiont-bearing K-strategist planktonic foraminiferal species, which typify low-latitude assemblages; conversely, high-latitude planktonic foraminiferal indices became dominant during times when large-scale megabreccia resedimentation events and active turbidite deposition occurred in one or in both basins.

Variations in planktonic foraminiferal assemblages found in the megabreccia-free intervals seem to have been forced by global climate. They are dominated by low-latitude species, an indication of the coeval warm climate (Zachos et al., 2001). Thus, the middle Ypresian interval (*M. formosa* biozone of Orue-Etxebarria et al., 1984; equivalent to P7 zone of Berggren et al., 1995, and approximately 52 Ma) is the richest interval in low-latitude assemblages (Fig. 11), a clear record of the Early Eocene Climatic Optimum of Zachos et al. (2001), the warmest episode of the Cenozoic. Further, planktonic foraminiferal assemblages of the megabreccia-free late Ypresian and early Lutetian intervals, while still rich in low latitude species, reflect progressively cooler conditions (Fig. 11), an evolution also in good agreement with the global climatic cooling subsequent to the Early Eocene Climatic Optimum (Zachos et al., 2001).

The dominance of high-latitude planktonic foraminiferal indices in the turbidite-rich intervals containing large-scale resedimented megabreccias is more difficult to interpret. One possibility is that such "cool" intervals were also climatically induced. In such scenario, climatic cooling episodes would have resulted in sea-level lowstands, which would have caused the coeval abundance in turbidites and large-scale megabreccias. However, several lines of evidence show that climatic cooling alone did not produce the palaeoenvironmental perturbations that resulted in the intervals rich in resedimented deposits and high-latitude planktonic foraminiferal assemblages. Hence, an alternative tectonically controlled model has been developed. In the alternative model pulses of strong tectonic activity induced both frequent turbiditic activity and occasional large-scale slope failures, recorded by the huge megabreccias (Fig. 12B). Combination of both processes put back into suspension large amounts of fine-grained sediment, organic matter and nutrients, which eutrophicated the seawater and led to the dominance of the cosmopolitan, opportunistic planktonic foraminiferal species typical of higher latitudes.

The present study, therefore, highlights that caution must be taken when using planktonic foraminiferal assemblages as proxies for palaeoceanographic analyses. Variations of planktonic foraminiferal palaoebiographical indices should be considered as climatically forced only when there is evidence that trophic resources did not change. The eutrophication model discussed here ultimately proclaims that large-scale catastrophic resedimentation events may have significant and long-lasting ecological consequences. In fact, data from the western Pyrenees suggest that resedimentation-induced eutrophication may affect wider areas than the resedimentation process itself. Thus, sediment gravity flows are sedimentologically recorded in limited areas, but the concomitant eutrophication can be biotically reflected throughout.

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