Biomagnetostratigraphic analysis of the Gorrotxatega section (Basque Country, Western Pyrenees): Its significance for the definition of the Ypresian/Lutetian boundary stratotype

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With 16 figures and 1 table


Abstract: The Gorrotxatega beach section is part of a 2300 m thick lower Ypresian–upper Lutetian deep-water marine succession and contains the most extensive Ypresian–Lutetian boundary interval so far reported. The entire 700 m thick uppermost Ypresian–lower Lutetian succession shows a good magnetic signal and is rich in well-preserved calcareous planktonic fossils. Moreover, some of the interleaved turbidites supplied abundant nummulitids, allowing the correlation and calibration of the zonal schemes of larger foraminifers and calcareous plankton. At the Gorrotxatega section, all the events traditionally used to identify the Ypresian–Lutetian boundary occur at different levels, demonstrating that before selecting a section to place the Ypresian–Lutetian boundary stratotype the specific criterion to identify this boundary should be defined. The high-resolution calcareous plankton and larger foraminifera biomagnetostratigraphic studies, coupled with the magnetostratigraphic analysis performed in the Gorrotxatega section, show the complete record of events that characterizes the Ypresian–Lutetian boundary interval, highlighting the position of several marker events that are suitable to be selected as the criterion to define the Ypresian–Lutetian boundary. The Gorrotxatega section fulfills most of the requirements demanded of a Global Stratotype Section and Point (GSSP) by the International Commission on Stratigraphy, and consequently it is proposed here as a candidate for the GSSP of the base of the Lutetian.

Keywords: Ypresian/Lutetian boundary, GSSP, Eocene, calcareaus nummulitids, planktonic foraminifers, nummulitids, magnetostatigraphy, Gorronsdætu, Pyrenees.

1. Introduction

During the 28th International Geological Congress held in Washington D.C. in 1989, the International Subcommission on Paleogene Stratigraphy (ISSP) agreed on a set of Paleogene stages. Subsequently, official Working Groups and Regional Committees were set up to find a Global Stratotype Section and Point (GSSP) for the lower boundary of each of these Stages. At present, all the GSSPs of the Paleogene epochs (i.e., base of Paleocene = base of Danian; base of Eocene = base of Ypresian; base of Oligocene = base of Rupelian; and top of Oligocene = base of Aquitanian) have been established and ratified by the International Union of Geological Sciences. The search for the remaining Paleogene GSSPs (i.e., base of Selandian, Thanetian, Lutetian, Bartonian, Priabonian and Chattian) is still in progress, and it is hoped to present all the proposals prior to the next International Geological Congress in 2008.
According to the International Commission on Stratigraphy (ICS) guidelines, clearly summarized by Remane et al. (1996), a prospective stratotype section should contain the best possible record of the relevant marker events and, in addition, should fulfill as many of the following requirements as possible:

(1) Geological requirements: exposure over an adequate thickness of sediments; continuous sedimentation; high rate of sedimentation; absence of synsedimentary and tectonic disturbances; absence of metamorphism and strong diagenetic alteration; potential for radiometric dating, magnetostratigraphy and chronostratigraphy; knowledge of the regional paleogeographic and sequence stratigraphic context.

(2) Biostratigraphic requirements: abundance and diversity of well-preserved fossils; absence of vertical facies changes at or near the boundary; favourable facies for long-range biostratigraphic correlations (open marine deposits).

(3) Infrastructure requirements: accessibility; free access; possibility to fix a permanent marker; permanent protection of the site.

The aim of this paper is to present new bio- and magnetostratigraphic data of the Ypresian/Lutetian (Early/Middle Eocene) boundary transition at the Gorredijk section (Basque Country, western Pyrenees), and to propose this section as a candidate to locate the GSSP of the base of the Lutetian Stage (i.e., Ypresian/Lutetian boundary), as the section fulfills most of the requirements listed above.

Originally, the Lutetian was defined by De Lapparent (1883) to refer to the so-called “Calcaire Grosier” of the Paris Basin. Later, Blondeau et al. (1980) proposed two neomorphic phases 20 km North of Paris, namely the Saint-Leu d’Esserent and Saint-Vaast-Lez-Mello sections. However, the Lutetian sections around Paris, and even elsewhere in northern Europe, are not suitable candidates to be designated as the GSSP since they display shallow-marine deposits and the base of these sections corresponds to a regional unconformity (e.g., Aubry, 1986, 1995; Steurbaut 1988).

The lower part of the Lutetian “Calcaire Grosier” is best typified by the occurrence of abundant specimens of Nummulites laevigatus, a species whose range coincides with Zone SBZ13 of Sierra-Kiel et al. (1996). In addition, Aubry (1986) demonstrated that, in terms of calcareous nannofossils, the base of the “Calcaire Grosier” pertains to the Subzone CP12b of Orada & Buzal (1980). Aubry et al. (1986) carried out the correlation of the Lutetian strata in Paris with those of the Hampshire-London basin based on calcareous nannofossil and Nummulites faunas. There, they integrated
Fig. 1. Tertiary – Lutetian standard biomagnetotoxicnagnostigraphic framework. The extent of the Lutetian strata in Paris is shown for comparison purposes. Absolute ages are from Luterbacher et al. (2004). Correlation between magnetic polarity chrons, planktonic foraminiferal zones, and calcareous nannofossil zones is from Berggren et al. (1995) and Berggren & Pearson (2005). Planktonic foraminiferal events are as follows: (1) Sloan et al. 1975; (2) Blow 1979; (3) Tornambe & 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 is based on Berggren & Miller (1988).

Biosstratigraphic and magnetostratigraphic data and proposed that the Lutetian strata correspond to magnetic polarity chrons C21.

Although planktonic foraminifera are rare in these North European sections, the criterion most commonly used during the last half-century to place the base of the Lutetian has been the first appearance of specimens belonging to the planktonic foraminiferal genus *Hauterina*, which also
marks the base of Zone P10 of Bergegren et al. (1995). Unfortunately, Eocene hantkeninids are restricted to lower and middle latitudes. In addition, they are not abundant at their inception and seldom reached high percentages in well preserved Eocene faunas (Pirimoli Silva & Borsa 1985: 323; Coxall et al. 2003: 237). Consequently, different planktonic foraminifer events have commonly been taken as approximate markers of the base of Zone P10 and, hence, of the Lucatian Stage (e.g., Olszewski-Ma et al. 1985; Erbauch et al. 2004; Zachos et al. 2004; Payrov et al. 2006). In this respect, Berggren & Pearson (2005) indicated that the first appearance of Globularina costata (= "Globigerinoides higginsi", which marks the base of their Zone ER, equivalent to Zone P10 of Berggren et al. 1995) occurs at a level close to the first appearance of hantkeninids and, therefore, that it can be used to date the base of the Middle Eocene. The correlation between magnetostratigraphic and different biostratigraphic scales has improved over time (e.g., Berggren 1972; Hardisty & Berggren 1978; Berggren & Miller 1985; Berggren et al. 1995; Luterbacher et al. 2004), and today it is considered that the first appearances of the first specimens of the genus Hantkenina and of the taxon Globularina costata coincides with the boundary between the magnetozones C22n and C23r (Berggren et al. 1995; Berggren & Pearson 2005). Fig. 1 summarizes the currently most accepted biostratigraphically magnetostratigraphic correlation scheme for the Ypresian/Lutetian boundary interval.

In the light of the geological, biostratigraphic and infrastructure requirements specified by the ICS for any prospective GSSP and the different criteria used so far to define the base of the Lutetian Stage, the study of the Gondwanian section was undertaken from the viewpoint of the general stratigraphic context (paleogeography, lithostratigraphy and sequence stratigraphy), calcareous nanofossil biostratigraphy, planktonic foraminiferal biostratigraphy, nummulitic biostratigraphy and magnetostratigraphy.

2. Geological Setting
The Gondwanian section is exposed on the cliffs of an easily accessible beach (also known as Azorri section because of the cape on the northeastern side of the beach) just northwest of Bilbao (Latitude: 43° 23′ N; Longitude: 3° 09′ W; Figs. 2 and 3). The beach, awarded the European Union Blue Flag for water cleanliness and beach services, is equipped with a car park, fountains, bars and bus services (further details at http://www.bizkaia.net/ingundigoa_Lurraldeia/Hondarribia/im_home3.htm).
3. Paleogeography

During Eocene times, the area studied formed part of a narrow marine gulf created by the oblique convergence of the Iberian and European plates (Fig. 2A). The gulf, located at approximately 35°N latitude, opened northwest into the Bay of Biscay 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, and two foreland basins developed to the south and north of the rising ocean (Fig. 2A; Vergès et al. 1995; Payros 1997; Pujalte et al. 2002).

Today, deep marine deposits are extensively exposed in the coastal provinces of the Basque Country, whereas remnants of the southern shallow-water carbonate ramp are found in the southern provinces (Fig. 2B). The present study focuses on the western, most distal part of the northern foreland basin.

This area received sediments from several sources, mostly hemipelagic turbids and limestones, calcareous turbidites and debris flows derived from northern sources, and siliciclastic turbidites coming from northern and eastern sources (Fig. 2A) (Payros et al. 2006). Estimated paleoshelf depth for this area is about 1500 m (Oró et al. 1985; Rodríguez-Lázaro & García-Zarraga 1996; Payros et al. 2006).

4. Lithostratigraphy

The Gorrondatze section is part of a 2300 m thick lower Ypresian-upper Lutetian succession that extends from the town of Sopela to the Gales Cape and is exposed in coastal cliffs (Fig. 3). It is entirely composed of deep-marine deposits, which were uplifted and tilted during the Alpine Orogeny and are now part of the northeastern limb of the Biscay Synclinorium. The succession, despite being almost continuous, is affected by several faults, one of which divides the lower part of the Gorrondatze section into two separate parts (Fig. 3).

The Sopela-Gales section has earlier been the subject of detailed sedimentological (Pujalte et al. 1997) and micropaleontological analyses.
(Orue-Etxebarria et al. 1984; Orue-Etxebarria 1985; Orue-Etxebarria & Lamolda 1985; Rodriguez-Lázaro & García-Zarzáegua 1996), one of which dealt specifically with the Ypresian/Lutetian boundary in the Gorrondatxe beach section (Orue-Etxebarria & Apellaniz 1985). However, only general stratigraphic descriptions of it have so far been produced (e.g., R a t 1959; Payros et al. 2006) and no formal lithostratigraphic units have yet been defined (Fig. 3). According to these descriptions, the lower half of the succession is composed of hemipelagic marls interspersed with siliciclastic turbidites, which peak in abundance in the so-called Azkorti Sandstone (R a t 1959). Reworked carbonate deposits become progressively more abundant in the upper half of the succession.

The Gorrondatxe beach section, 700 m thick, extends from the top of the Azkorti Sandstones to the base of the calciturbidite flysch (Fig. 3). It is mostly composed of hemipelagic marls and limecones, but thin-bedded (<10 cm) siliciclastic turbidites are also common. In addition, some thick-bedded (10-24 cm) mixed turbidites (siliciclastic and carbonate) occur at some levels of the succession.

5. Sequence stratigraphy

Sequence stratigraphic units (e.g., third order depositional sequences) are the result of eustatic or relative changes in sea level, which result in characteristic stratal architectures (e.g., Val et al. 1999). According to current sequence stratigraphic models, basinal lowstand deposits are best typified by turbidite accumulations, whereas basinal transgressive and highstand deposits are mostly hemipelagic.

Payros et al. (2006) investigated the sedimentary features (lithology, thickness and shape, primary structures, grain fabric, palaeocurrents, etc.) of every turbidite bed thicker than 15 cm in order to assess volumetric variations of turbidites throughout the Sopela-Galza section (Fig. 3). They

Fig. 3. (A) Simplified geological map of the study area, showing the location of the Gorrondatxe beach section. (B) Simplified litho log of the Sopela-Galza succession, showing the extent of the Gorrondatxe beach section. Phaneritic foraminnifera biostratigraphy (left-hand column) is from Orue-Etxebarria et al. (1984); informal lithostratigraphic units are mostly based on R a t (1959); vertical variations in turbidite content (right-hand graph) are from Payros et al. (2000); depositional sequences are those defined by Payros (1997) and Pujalte et al. (2000) in the Parapami area.
Fig. 3 (Legend see p. 74)
obtained a semi-quantitative estimation of the vertical variations in turbidite abundance by plotting their composite thickness in 10 m thick intervals. This procedure made evident that the Sopela-Galea succession consists of six distinct intervals with variable amounts of turbidites. The turbidite content of three intervals rarely exceeds 20%, average values being lower than 10% and some levels almost completely devoid of turbidites. These three intervals were called consequently “turbidite-poor”. On the other hand, the other three intervals were named “turbidite-rich” because their turbidite content ranges from 10% to 80%, the average being more than 20%. Payros et al. (2006) also noted an increase in the proportion of carbonized plant remains and reworked shallow-water benthic faunas in the three turbidite-rich intervals. However, the sequence stratigraphic interpretation of the Sopela-Galea section is not straightforward, since sequence stratigraphic units defined solely on the basis of 1D profiles are not reliable. Unfortunately, the platform areas from which the Sopela-Galea resedimented deposits derived have eroded away and, therefore, the significance of the turbidite-rich intervals in terms of sequence stratigraphy cannot be verified. Hence, the sequence stratigraphic framework of the Sopela-Galea section can only be established on the basis of correlation with neighbouring areas where both basinal and platform deposits are preserved. Payros et al. (2006) noted that the ages of the turbidite-rich intervals correlate precisely with those of rexedimented basinal units of the Pamplona area, 200 km southeast of the study area (see Fig. 2 for location). These, based on the study of deep and shallow-water deposits, Payros (1997) and Puigjolis et al. (2000) distinguished twelve third-order lower Ypresian—lower Bartonian depositional sequences, which were interpreted as the result of tectonically induced regional sea-level changes. The lowstand turbidite deposits of their fourth (Ca-2), fifth (Ca-L1) and sixth together with seventh (La-L1 = Lu-2) sequences correlate with the turbidite-rich intervals of the Sopela-Galea succession, supporting the interpretation of the latter as regional lowstand deposits (Fig. 3).

Fig. 4. Selected calcareous nannofossil species ranges and location of the main biozones across the Ypresian/Lateinian transition at the Goroundabe section. Broken lines indicate very rare occurrences. Zones in column (a) are following Ocampo & Brott (1980); those in column (b) are following Martini (1971).
6. Calcareous nanofossils

6.1. Sampling and methods

The calcareous nanofossil study is based on the analysis of a total of 56 samples (Fig. 4). Samples were taken every 20 m with closer intervals near the main biostratigraphic events. smear slides of samples were prepared from raw material using the pipette method for calcareous nanofossils (Bown 1998), avoiding mechanical or physical processes that could modify the original composition of the assemblage. All the smear slides were analyzed under a Leica DMLP petrographic microscope at 1500X magnification. In order to investigate the smallest species, to observe details of bigger forms and to take pictures, smear-slides were examined at 2000X magnification. Microphotographs of significant calcareous nanofossil taxa are shown in Figures 5, 6 and 7. At least 300 nanofossil specimens were counted per sample along a random traverse on the slide. Moreover, in order to detect rare species with key biostratigraphic value, three additional tracks were studied per sample.

In this paper, the biostratigraphic schemes of Martini (1971) and Okada & Burky (1980) are applied.

6.2. Results

According to the preservation criteria proposed by Roth & Thierstein (1972) all the studied samples from the Gorrondatze section yielded moderately to well-preserved calcareous nanofossil assemblages that occasionally show traces of dissolution and in lesser extent re-crystallization. Preservation of calcareous nanofossil is frequently excellent and delicate structures and coccolithes are usually present.

Fig. 5. All figures are from Gorrondatze section and were taken with parallel nics except (a), which was taken with cross-polarized light. The scale bar represents 10 μm in all figures. a-b) Ophiomorpha multifida, sample Az930; c-d) Opihostegia costata, sample Az987; f = lateral view, sample Az1002; g = sample Az1015; h = lateral view, sample Az1029; j = sample Az1103; k = sample Az1209; l = sample Az1246; m = p) Discosphaera subtilis, sample Az903; q) Nanoporella bulgens, m = sample Az1209; m = sample Az1246; n = sample Az154; n) Discoaster lobatus, l = sample Az969; s = sample Az896.
Fig. 6 (Legend see p. 81)
The high diversity and total abundance of calcareous nannofossils are remarkably regular throughout the succession with an average of 45 species per sample and 17 specimens per field of view.

The assemblages are dominated by common Reticulofenestra and Coccolithus, with less common Eucoccos, Sphenolithus, Zygospirillites, and Chiasmolithus, the latter increasing in assemblage in abundance and size.

Reworked nannofossils occur in all the samples. Most of them are of Cretaceous and in lesser quantity Paleocene and early Eocene age. The reworking results from the nature of the sediments, lime-marlstone alternations with a high number of interbedded turbidites. The presence of reworked nannofossils can Occasionally obscure the location of the latest occurrence (LO) of some taxa. Taking into account that the reworking is not very intense and is not equally present throughout the succession, the LO of a species was tentatively located at the end of its continuous occurrence. In this work, however, in order to minimize the possible error of considering the top of the continuous occurrence of a species as its latest occurrence, we only use the first occurrence (FO) of selected species.

The studied interval spans from the upper part of the Zone CP 11 to the Subzone CP 13b.

The summary of recognized zones and main biohorizons is given in Fig. 4 and described in detail below:

a) FO of Discocysta subdulcissima (CP 11/CP 12a; NP 13/NP 14). At the Gorrono section the FO of D. subdulcissima has been recorded in sample Az 840, 46 m above the base of the studied succession. From sample Az 840 to Az 890 this taxon is rare to very rare and its preservation is usually poor. In this 50-m-thick interval, transitional forms between Discocysta dulcissima and D. subdulcissima have also been found. These forms are six-rayed Discocysta with straight or only slightly curved arms (Fig. 5p). From sample Az 903.5 upward, the persistence of D. subdulcissima is more common and the…
specimens are better preserved (Figs. 51, 50). A similar abundance trend was also observed in the Passaggio section, Southern Alps (Aogni et al. 2006). This confirms that D. sublodoensis is usually rare in its lower range in many sections (Romein 1979; Varela 1989).

b) FO of Blackites periformis: The FO of B. periformis precedes the FO of Blackites inflatus, the CP12b marker. These two taxa could be confused in poorly preserved material, especially in those samples where recrystallization is strong. At the Gorrodattce section, the range of B. periformis is very short. It first appears in sample Az 961 and disappears at m 110 in the upper part of Zone CP12a.

c) FO of Blackites inflatus (CP12a/CP12b): As mentioned above, this species is prone to dissolution/recrystallization in poorly preserved material and is usually absent or very rare. In fact, the first appearance datum (FAD) of B. inflatus is one of the worst documented datums of the Ypresian/Luketian boundary time interval (Berggren et al. 1995). We found its FO at sample Az-969, 129 meters above the base of Zone CP12a.

d) FO of Naonotritea spp.: This biohorizon is usually used to define the base of CP13 in sections where the presence of Naonotritea folgensi is very rare or absent (Pergel-Nielsen 1985). However, we advise against the use of this biohorizon to mark the base of Zone CP13 as we actually found the FO of Naonotritea spp., N. cristata, in sample Az 987, in the lower part of Subzone CP12b. Other biohorizons, such as the LO of B. inflatus (Aubry 1983; Varela 1989) or the LO of D. sublodoensis (Lyde et al. 2002), have occasionally been used to approximate the base of CP13 Zone.

e) FO of Naonotritea folgensi (CP12b/CP13a; NP14/NP15): In the Gorrodattce section the FO of N. folgensi is recorded in sample Az1111.

Fig. 7. All figures are from Gorrodattce section and were taken with cross-polarized light except (a), (i), (l), (o) and (n), which were taken with parallel nicks. The scale bar represents 10 µm in all figures. a-b) Coccolithus sanctorii [= C. mutans (Pergel-Nielsen 1971) Bown 2005], sample Az 1409; c-d) Conogyraphaeus delia, sample Az 943; e-f) Chiasmolithus grandus, sample Az1316; g-j) Chiasmolithus solitus, sample Az 943; h-l, m-n) Chiasmolithus pogus, h-i - sample Az 1405, J-m - sample Az 1396. k, n) Reticulofenestra dicysida, k - sample Az 943, n - small form, sample Az 943.
271 m above the base of CP 12. This taxon is rare in the lower part of its range, but increases in abundance from sample AR 1246 upwards.

1) FO of *Chiasmolithus gigas* (CP13a/CP13b): This biocorona, marked by the first *Chiasmolithus* larger than 19 mm with a broad distal shield and restricted central opening spanned by a relatively small x-shaped structure with sigmoid bars, is located at sample AR 1274. We do not include in *Ch. gigas* the forms that Bown (2005) redefined as *Coccotrema mutans* (Percini-Nielsen 1971) Bown 2605. According to this author those forms (very large coccotrots with wide central area and narrow, axial, to slightly rotated cross-bars) are probably included in the *Ch. gigas* concept of Beaumette & Sullivan (1961). The last occurrence of *Ch. gigas* has not been detected, its presence being continuous up to the top of the studied interval.

7. Planktonic foraminifera

7.1. Sampling and methods

To analyse the planktonic foraminifera of the Grotteondatte section, 36 samples (each of about 1 kg) were collected, which were very close-spaced near the main biostratigraphic events (Fig. 8). The samples were washed and screened to obtain residues of a 100-630 μm size range, which were studied under a binocular microscope. The complete assemblage of planktonic foraminifers was recorded to species level. For taxonomic purposes significant species were imaged with a JEOL scanning electron microscope, model JSM-6400 (Figs. 9 and 10). After a separation with an Otto microsplitter, relative abundances of the different species were estimated based on counts of about 300 specimens. All residues contained planktonic foraminifers in sufficient quantity and degree of preservation to permit a semiquantitative study designed to determine the FO and LO of planktonic foraminiferal species. On the basis of these data, and taking into account the great thickness of the Grotteondatte succession, a new high-resolution planktonic foraminiferal biozonation is proposed for the studied interval, although the standard tropical-subtropical zonation schemes of Berggren et al. (1995)

[Fig. 8. Selected planktonic foraminifer species ranges and location of the main biohorizons across the Ypresian/Lutetian transition at the Grotteondatte section. Biocorona in column (a) are as described in this study, those in column (b) are following Berggren et al. (1995) (P scale) and Berggren & Pearson (2005) (P scale).]
and Bhogre & Pearson (2005) are also used for correlation purposes (Fig. 8).

7.2. Results

All the samples contain a diverse assemblage of well-preserved planktonic foraminifers, which represents more than 50% of the total (planktonic plus benthic) foraminiferal assemblage. The lower 100 m of the succession present a planktonic foraminiferal assemblage typified by Subbotina limapera, "Guembelitriades" Kazan, Globorotalia planispira, Neoeurizygia nitra, Marginotruncana angulosa, Marginotruncana canadensis, Marginotruncana cuneata, Lirinella buesemaniai and Aragonia balbroi, among others. Specimens similar in shape to G. nitida, albeit smaller in size and lacking supplementary natural spines, have been found throughout this interval; these specimens might correspond to intermediate forms between "G." kazanii and G. nitida (Tondem and Luterbacher 1985). This assemblage is here included in the "Arago nine balbroi" biozone, and is considered as equivalent to part of Zone P9 of Bhogre & Pearson (1995), Zone E7 of Bhogre & Pearson (2005). This interpretation is supported by the occurrence of Planorbulinoides palmae, master taxon of Zone P9, 250 m lower in the succession (see Chrobicki et al. 1984; Chrobicki et al. 1985; Pavlov et al., 2006).

The assemblage from the interval between 900 and 1083 m is characterized by A. baetica, P. nitra, I. brevibranchiata, S. limapera, Subbotina nitida, Marginotruncana incertae, Globorotalia planispira, M. cuneata, Marginotruncana outer and M. angulosa. The first specimen of the species Turborotalia frontosa, characterized by a rather high arch-like umbilical-extraumbilical aperture with a faint lip and a fairly well separated globular straight chamber (Fig. 9-10), appear at the base of this interval. According to these characteristics, this interval has been included in the "Turborotalia frontosa" biozone and is considered as equivalent to the upper part of Zone E7 of Bhogre & Pearson (2005).

Fig. 9a-c) Marginotruncana cuneata (Glaessner, 1937). a) - umbilical view, b) - lateral view, c) - spiral view.
Fig. 10a-c) Marginotruncana incertae (Glaessner, 1937). d) - umbilical view, e) - spiral view, f) - lateral view. Scale bar = 100 μm.
Fig. 9 (Legend see p. 86)
The simultaneous FOs of Globigerinatheca incisa and Monococculavon gordonaeformis at sample Az1083 mark the base of the Monococculavon gordonaeformis Biozone, which extends over 122 m. The nominate taxon, originally defined in the Gondwanate section (Orbel-Eyedberia, 1985), is of great biostatigraphic interest, at least in the Pyrenean area, since its distribution is restricted to the hemispheric biozone and the lower half of the overlying biozone (also see Canudo 1990, Canudo & Molina 1992). The FO of Pseudohastigerina wilhelmita and Gl. indiscernimata are recorded at the upper part of this biozone. Relative large-sized specimens of G. astalli, showing secondary external apertures, appear in the uppermost part of this biozone (sample Az1185). All these characteristics suggest that the Monococculavon gordonaeformis Biozone mainly correlates with the upper part of Zone E7 of Berggren & Pearson (2005) (equivalent to Zone P9 of Berggren et al. 1995), although its uppermost part corresponds to Zone E8 (P10). The FO of Glo. micra in the upper part of Zone E7 was also reported by Freiболi Silva et al. (2003) (Fig. 1).

The FO of Acarinina protoplagiis in sample Az129.5 marks the base of the hemispheric biozone, which extends over 225 m. It should be noted, however, that the first specimens of the nominate taxon differ from the holotype (Brow 1979) in that they are slightly smaller and have a less distinct circum-cameral muriocitisa. The very close FOs of A. protoplagiis and G. astalli supports the assumption of Orbel-Eyedberia & Apellanz (1985) that the FO of the former is a suitable event to place the Pyranean-Lutetian boundary in terms of planktonic foraminifera. The FO of a distinct morphotype of F. prinosa, characterized by a comparatively tight chamber and a distinct dorsal flattening, is recorded at sample Az202. The FO of M. caudata is recorded in the middle part of this biozone, whereas those of Subbotina inopsitops and M. gordonaeformis were found in the upper part. The Acarinina protoplagiis Biozone correlates with the lower part of Zone E8 of Berggren & Pearson (2005).

Finally, the base of the Subbotina inopsitops Biozone is defined by the FO of the nominate taxon at sample Az1431.5. It should be noted, however, that...
H. nutalli is rare in all samples. Given its rarity and the fact that its FO is located higher up than the LO of M. caucasica, the FO of H. nutalli in the Gorronoatax section might not correspond to its first appearance in the stratigraphic record. The FO of Truncorotaloides trigleriensis is recorded in the lower part of the Hantkenina nutalli Biozone. Globigerinathekedids, including Gla. mexicana, become very abundant 80 m higher up in the succession (see Oye-Etxebarria et al. 1984; Oye-Etxebarria & Apellanz 1985; Patros et al. 2006). All things considered, the Hantkenina nutalli Biozone is correlated with the upper part of Zone ES of Berggren & Pearson (2005).

8. Nummulitids

8.1. Sampling and methods

Larger foraminifera, mostly Nummulitids and Assimina specimens, as well as fragments of other shallow-water organisms (e.g., red algae and corals), occur in the basal part of many thick-bedded, mixed carbonate-siliciclastic turbidites. They occur either within rounded limestone clasts or as loose, individual grains surrounded by muddy or bioclastic matrix. All of the turbidites in the Gorronoatax section were examined for nummulitids. Some of them, despite bearing larger foraminifera, were not sampled because they were well cemented and individual nummulitids could not be extracted. In fact, the systematic analysis of nummulitids at specific level needs the observation of external and internal features in both microspheric and megaspheric forms. Therefore, it is necessary to have diversified populations where individual specimens can be separated. Sixteen of the Gorronoatax turbidites fulfill these requirements, from which different types of samples were collected (Fig. 11). When possible, bulk sediment samples were collected, but in some cases individual nummulitid specimens, slabs of turbidites or limestone clasts were taken. All the samples were washed in the laboratory and as many individual nummulitid specimens as possible were separated and studied following a two-step procedure. First, their external features (diameter and shape, morphology and arrangement of

Fig. 11. Nummulitid species occurrences in the Gorronoatax section. Broken lines on the right-hand columns indicate that the corresponding Shallow Benzie Zone is probably represented in the sample, whereas continuous lines indicate verified occurrences.
Fig. 11 (Legend see p. 98)
septal filaments and granules, etc.) were examined with a binocular microscope. Then, they were split along the equatorial section to study their internal features, such as number of whorls, rate of opening of the spire (whorl radius), number of chambers per whorl, septal and chamber shape, and the proloculus diameter of megasclerophorhic forms (Fig. 12). Biostratigraphic range of nummulitid species was assigned following SCHAUER (1981), TORSQIHLA & SERKAA-KIL (1996) and the standard Shallow Benthic Zones (SBZ) of SERKAA-KIL et al. (1998).

8.2. Results

Four out of sixteen samples did not provide reliable results, since nummulitid specimens were poorly preserved (samples Az905, Az934, Az1197 and Az1318). The remaining twelve samples yielded a wealth of nummulitid specimens, with a total of 45 different taxa representing a mixture of re-sedimented and displaced faunas (Fig. 11). In fact, nummulitids from limestone clasts recov the destruction and redisposition of older, well-cemented carbonate platforms, whereas loose nummulitids are probably the result of displacement from approximately contemporaneous unconsolidated shallow-water sediments. Most of the specimens could be classified at the specific level and proved suitable for biostratigraphic determination. Howev- ever, the systematic study was sometimes hindered because of the not fully diversified character of some samples. Most of the samples contained megasclerophoric nummulitids but lacked microsclerophoric forms. This situation is probably the result of the hydrodynamic sorting (i.e., grain-size classifi- cation) of the sediment involved in turbidity currents, which led to the accumulation of large microsclerophoric and small megasclerophoric nummulitid tests separately. Therefore, since complete nummulitid populations are not represented, a precise systematic determination was sometimes difficult to

Fig. 12. a) Nummularites tortuosus, A-form, sample Az1378; b) N. bonnaczi, A-form, sample Az1373; c) N. aff. silicicolus, A-form, sample Az1452; d) N. alpineicus, A-form, sample Az1432; e) N. aff. bonnaczi, A-form, sample Az1273; f) N. obesus, B-form, sample Az1230; g) N. variscoicus, A-form, sample Az1326; h) N. macciolae, A-form, sample Az1370; i) N. laceagei, A-form, sample Az1218; j) N. priscisori, A-form, sample Az1273; k) Assilina kurtivensis, A-form, sample Az1138; l) N. galloensis, A-form, sample Az1272; m) N. manfroidi, B-form, sample Az805; n) N. maccioi, A-form, sample Az809; o) N. maccioi, A-form, sample Az809; p) N. squidaceus, A-form, sample Az1378. Scale bars = 1 mm.
Fig. 12 (Legend see p. 92)
obtain. That is why the terms "cf." (confer), "gr." (group) and "aff." (affinis) are used in some cases. On the other hand, the most evolved morphotypes of a phylogenetic series were easy to recognize. In general, the most modern specimens are larger and show more complex test ornamentation. However, it is not straightforward to apply this rule to small-sized microspheric mammuloids, since small test size and simple ornamentation might be related either to a lower phylogenetic level (i.e. stratigraphically older specimens) or, alternatively, to the younger ontogenetic stage of more modern specimens.

These facts, along with the unsppecific biostratigraphic range of some species, sometimes made it difficult to distinguish whether a sample contained a homogenous association, with specimens belonging to a single biorite, or a mixed association with specimens belonging to more than one biorite. However, although these limitations hamper the precise reconstruction of the paleobionomosites at some levels, it was still possible to date the youngest possible age of the turbidites containing mammuloids (Fig. 11).

The association observed in sample Az 869 is constituted by: *Nannolites puettiformis*, *Avicula placcaearia* and *A. cf. ruffei*, taxa with a biostratigraphic range that spans SBZ 10 and SBZ 11; *N. echovii*, *N. gr. lempski*, *N. cf. ronduarius* and *A. gr. praegubrite*, with a range from SBZ 10 to SBZ 12; *N. tauvicus*, *N. nitisus* and *A. arcipinnus*, characterizing SBZ 11; *N. distans*, *N. reissi*, *N. cf. postgubrite*, ranging between SBZ 11 and SBZ 12; and *N. compressus*, *N. murius*, *N. aff. lempski*, *N. cf. formosus*, and *A. major*, characteristic of SBZ 12. Therefore, sample Az 869 presents an association of mammuloids that characterizes SBZ 11 and SBZ 12, as well as some species of unsppecific biostratigraphic range between SBZ 10 and SBZ 11 thus, possibly, belong to SBZ 11. This association indicates SBZ 12 as minimum age, with faunas reassembled from SBZ 11.

Sample Az 918 presents a mammuloid association constituted by *Nannulites cruciatus* (SBZ 11), *N. gr. lempski* (SBZ 10-12), *Avicula ruffei*, *narrow* (SBZ 12-13), *N. cf. formosus* and *A. major* (SBZ 12). In addition, specimens of the *N. perforatus*, *N. luquegus*, *N. distans* and *A. praegubrite groups were observed, which show that the samples correspond to the zone SBZ 12-13. Therefore, it was not possible to accurately place the boundary between these two zones.

Samples Az 1076, Az 1997, Az 1138, Az 1184 and Az 1210 yielded a mammuloid association constituted by *N. vanderschuiti*, *N. gr lempski* and *N. cf. pavlovoci* (SBZ 10-12), *N. distans* (SBZ 11-12), *A. major* (SBZ 12), *N. praegubrite* and *N. distans*-alpensis (SBZ 11-13), *N. gr. luquegus inder* (SBZ 12-13), and lower Lutetian (SBZ 13) taxa, such as *N. obscura*, *N. tehueri*, *N. mesita*, *N. luquegus*, *N. britannicus*, *N. varicarius* and *A. bericensus*.
Fig. 13. Bedding-corrected orthogonal plots of demagnetization data from representative specimens from the Gorronostra section. Solid (open) symbols represent projections onto the horizontal (vertical) plane. The stratigraphic level, the fitted ChRM direction, the NRM intensity and some demagnetization treatments are indicated.

Finally, samples Az 1273, Az 1378, Az 1415, Az 1452 and Az 1454 contain a mammalid association constituted by N. gr. lespoldi, N. cf. archiaci and N. cf. irregularis (SBZ 10-125, N. diceas and N. pratti (SBZ 11-12); N. fiesmus, N. aff. lespoldi and N. aff. escheri (SBZ 12); N. proctorielli
9. Magnetostratigraphy

9.1. Sampling and methods

Sampling for magnetostratigraphy was conducted throughout a 700 m thick interval of the Gorronozae section. A total of 65 unique sampling sites were obtained, comprising 2 to 3 hand-samples per site. Paleomagnetic sampling was basically restricted to the hemipelagic lithologies (mostly grey muds and marly limestones), which are potentially more suitable facies regarding paleomagnetic behaviour in comparison with turbidites. Hand-samples were oriented in situ with a compass and subsequently standard cubic specimens were cut in the laboratory for analysis. Natural remanent magnetization (NRM) and remanence through demagnetization were measured on a 2G Enterprises DC SQUID high-resolution pass through cryogenic magnetometer (manufacturer noise level of 10^-13 Am²) operated in a shielded room at the Laboratorio Nazionale di Geofisica e Vulcanologia (LNGV) in Rome, Italy. A Pyroscan in the shielded room was used for thermal demagnetizations and alternating field (AF) demagnetization was performed with three orthogonal coils installed inline with the cryogenic magnetometer.

Paleomagnetic analysis was conducted on 116 specimens corresponding to 1 or 2 specimens per sampling site. Progressive stepwise alternating field (AF) demagnetization was routinely applied and applied after a single heating step to 150°C. AF demagnetization included 14 steps (4, 8, 13, 17, 21, 25, 30, 35, 40, 45, 50, 50, 100, 100 mT). Characteristic remanent magnetizations (ChRM) were computed by least-squares fitting (Kirschvink 1980) on the orthogonal demagnetization plots (Zijderveld 1967). The ChRM declination and inclination for each sample has been used to derive the latitude of the virtual geomagnetic pole (VGP). This parameter has been used as an indicator of the polarity (normal polarity for positive VGP latitudes and reverse polarity for negative VGP latitudes).

9.2. Results

The NRM intensities are on the order of 0.1 mA/m, usually decreasing to 50 % or less at 150°C (Fig. 13). The characteristic remanent magnetization (ChRM) is conventionally defined as the linear segment trending towards the origin of the demagnetization diagram. Normally (class A samples), the
ChRM component can be isolated above 13-17 mT after removal of a viscous secondary component at low fields that conforms to the recent Earth’s magnetic field in geographic (in-situ) coordinates. The ChRM component most likely resides in a low-coercivity mineral like maghemite or magnetite although a minor contribution of a higher coercivity mineral (iron sulphide, hematite?) cannot be ruled out considering that in some instances (Fig. 13e and g) the ChRM is not fully demagnetized at the highest applied magnetic field (100 mT). The ChRM components present either normal (Fig. 13a-b, d-e) or reverse (Fig. 13c, f-i) polarity in bedding-corrected coordinates (Fig. 14). In a few cases, the calculated ChRM has been regarded as unreliable (class B samples) (Fig. 15). We consider the demagnetization
Fig. 15. Stratigraphic variation of the ChRM directions and virtual geomagnetic pole (VGP) latitude and interpreted magnetic polarity stratigraphy plotted on a lithologic log of the Geruodaxue section.

behavior as unsuitable for magnetostratigraphic interpretation in 30% of the analyzed specimens (class C samples) which mostly relate to very weak samples (Fig. 15). The magnetostratigraphy is based on Class A samples (Fig. 15).
The reversal test of McFadden & McElhinny (1990) has been performed on the ChRM components in order to assess the antipolarity of the normal and reverse populations (Fig. 15). This test classifies a "positive" reversal test on the basis of the angle $\gamma$ between the mean directions of the two sets of observations at which the null hypothesis of a common mean direction would be rejected with 95% confidence class 'A' if $\gamma < 5^\circ$ as 'B' if $5^\circ < \gamma < 10^\circ$, as 'C' if $10^\circ < \gamma < 20^\circ$, and 'Indeterminate' if $\gamma > 20^\circ$. The ChRM data for the Gorontalo section passes the reversal test as class C ($\gamma = 16.2^\circ$).

The primary nature of the ChRM is supported by: 1) the presence of a dual-polarity ChRM in addition to the low temperature present-day field overprint; 2) an unrealistic shallow inclination before bedding correction (Fig. 16) (e.g. not compatible with any geomagnetic Cenozoic field direction for Iberian); 3) changes in polarity do not seem to be lithological controlled. The VGP latitude derived from the ChRM directions yields a succession of four magnetozones (two normal and two reverse): the lower normal magnetozones, which correlates with planktonic foraminifera zones P9 and E7, calcareous nanofossil zones CP11-CPI2a, and larger foraminifera zone SIBJ2 can be directly correlated to zones C21n. The overlying reverse magnetozone is correlated to chron C22r based on its stratigraphic position above the interval interpreted as chron C22n and on the basis of calcareous nanofossil and nummulitic biostratigraphic data. The succeeding normal and reverse magnetozones correspond to chron C21n and C20r, respectively, on the same basis.

10. Discussion

10.1. Positioning the Ypresian/Lutetian boundary

All the events traditionally used to place the Ypresian/Lutetian boundary (i.e., the planktonic foraminifera P9 (= E7) / P10 (= E8) Zone boundary; the calcareous nanofossil CPI2a / CP12b Subzone boundary; the larger foraminifera SBZ12 / SBZ13 Zone boundary; and the boundary between magnetic polarity chron C22n and C21r) have been identified in the Gorontalo section (Fig. 16). However, a comparison of the Gorontalo data with the standard biomagnetostратigraphic scheme shown in Fig. 1 evidences that all these events, previously considered as simultaneous, actually occur at very different levels. A concomitant consequence arising from that observation is that before selecting a section to place the Ypresian/Lutetian boundary stratotype, the criterion to identify this boundary should be precisely defined. A first step should be the description of the succession of the events that characterize the Ypresian/Lutetian boundary interval,
Fig. 16. Summary of the biostratigraphy (calcaceous nanofossil, planktonic foraminifer and larger foraminifer) and magnetostratigraphy in the Gorrondoxtre section. The position of the boundary between the Ypresian (grey) and Lutetian (white) stages varies depending on the scale. The most important events traditionally used or suitable for defining the Ypresian/Lutetian boundary are depicted in the right-hand box.

which in this work has been informally considered as extending from the FO of *D. subladosiensis* to the FO of hantkeninids. Evaluating the pros and cons, and evaluating the usefulness of each of these events is beyond the scope of this paper, as this decision is the domain of the International Subcommission on Paleogene Stratigraphy (ISP5). Therefore, only the relative position of the different events suitable to be selected as “official” markers of the Y/L boundary, and their correlation with other zona/scales, will be highlighted below.

The tops of magnetic polarity chron C22n and larger foraminifer Zone SBZ12, previously used to define the Y/L boundary by magnetostratigra-
Phylogen and palaeontologists working with larger foraminifera respectively, are not preserved in the Gorronada section due to a fault at 900 m of the succession (Fig. 16). However, these events are found within calcareous nanofossil Zone CP12a, as already shown in the standard correlation scheme (Fig. 1), within planktonic foraminifera Zone E7 (~ P9), and seem to be approximately coeval with the FO of the planktonic foraminifer T. frontosa.

The FO of B. inflata is the most suitable calcareous nanofossil marker event to characterize the Y/L boundary, having the additional advantage of preserving the current concept of the Lutetian stage. In fact, calcareous nanofossil studies carried out in the 'original Lutetian stratotype in Paris provided an assembly indicative of Zone CP12b (Assuè 1988), whose base is marked by the FO of B. inflata. In the Gorronada section that event is well constrained at 969 m, and occurs within the upper part of chron C21r, the planktonic foraminiferal T. frontosa Biozone (upper part of E7b), and within larger foraminiferal zone SBZ13 (Fig. 16). Several additional calcareous nanofossil events have been identified slightly lower and higher in the succession (Figs. 4, 16). Relatively close to the FO of B. inflata we found the FO of T. frontosa, poorly documented in the Gorronada section due to the fault at 900 m, and the FOs of G. micro and M. gorrondatensis at 1083 m.

Based on planktonic foraminifera, the Ypresian/Lutetian boundary is marked by the supposedly simultaneous FOs of specimens belonging to the genus Hantkenina and G. nutalli (Berger & Pearson 2005) (Fig. 1). However, these events are very distant from each other in the Gorronada section (Figs. 8, 16). The FO of G. nutalli is recorded at 1185 m, relatively close to the FO of A. praeptonensis at 1208.5 m. These two events occur at the uppermost part and at the upper boundary of chron C21n, respectively; in the middle part of calcareous nanofossil Zone CP13a, which extends from 1167 to 1269 m; and within the upper part of larger foraminifer Zone SBZ13. The FO of hantkeninids is recorded at 1433.5 m, being correlative with chron C20r, calcareous nanofossil Zone CP13b, and larger foraminifera Zone SBZ14. However, in accordance with the opinions of Orličeva & Apelland (1989), Premoli Silva & Borerma (1988), Coxall et al. (2003) and Berger & Pearson (2005), the FO of hantkeninids in the Gorronada section might be younger than their effective first appearance in the stratigraphic record. It should be noted, however, that the FO of hantkeninids well after the FO of G. nutalli has also been reported in other areas (e.g., Premoli Silva et al. 2003).
10.2. Suitability of the Gorrondate section for the GSSP of the base of the Lutetian

The Gorrondate section satisfies most of the infrastructural, biostratigraphic and geological requirements listed by the International Commission on Stratigraphy (ICS) (Remane et al. 1996), as demonstrated above. In particular, the great sedimentary thickness is one of the most outstanding features in favour of selecting the Gorrondate section as the GSSP of the base of the Lutetian. Table 1 shows the thicknesses of selected biostratigraphic and magnetostratigraphic zones in the Ypresian/Lutetian boundary interval of the Gorrondate section and in other well-documented successions, some of which have already been proposed as candidates for the GSSP of the base of the Lutetian. Table 1 readily demonstrates that the Gorrondate section is much thicker than all the other sections, a feature that indicates a much higher sedimentation rate. Hence, successive biostratigraphic and magnetostratigraphic events are better individualized in the Gorrondate section and their chronological succession can be more easily established than in all other sections that have been described until now (Fig. 10). Such a great thickness is the result of abundant intercalations of turbiditic beds (Figs. 3, 16). However, these turbidites do not diminish the suitability of this Gorrondate section as a candidate for the GSSP of the base of the Lutetian, since they are generally extensive, tabular-shaped and flat-based, recording therefore the effect of turbidity currents with low erosive capacity, which did not cause any significant disturbance on the sea floor. Quite to the opposite, some of these turbidite currents supplied abundant immature sediments, allowing thus the improvement of the correlation between larger foraminiferal and calcareous planktonic biostratigraphic events. Since larger foraminifers are transitional between open marine and terrestrial forms, they could eventually prove invalidative for the correlation of biostratigraphic zonal schemes based on open marine planktonic organisms with those from continental areas.

The only problem with the Gorrondate section is the fault located at 900 m. In fact, the tops of chondrites C22a and larger foraminiferal zone SBZ12 are not preserved in the Gorrondate section due to that fault (Fig. 16). Therefore, in the case of selection of either of these two events as a marker event for the Ypresian/Lutetian boundary, the Gorrondate section would not be an appropriate candidate for the corresponding GSSP. It should be noted, however, that these two events are now known to be older than the base of the original Lutetian stratotype in Paris.

If the base of Zone CP12b (marked by the FO of B. inflatus) were chosen as the Ypresian/Lutetian boundary marker event, the Gorrondate section should be considered as a firm candidate for the GSSP, since that event has
Table 1. Stratigraphic characteristics of selected sections displaying the Ypresian/Lutetian boundary interval. Duration of magnetic and biostratigraphic zones from Luterbacher et al. (2003).

<table>
<thead>
<tr>
<th>Section</th>
<th>Location</th>
<th>Lithology</th>
<th>Magnetic Zone Duration</th>
<th>Biostratigraphic Zone Duration</th>
</tr>
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<td>N/A</td>
<td>N/A</td>
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<tr>
<td>Cerro Alto Valley, Peru</td>
<td>No specific</td>
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been accurately located and correlated with other scales (Fig. 16). Based on the same line of reasoning, the same conclusion would be also valid, if the base of planktonic foraminiferal Zone E8 (marked by the FO of *G. exsulani*, and supposedly correlatable with Zone P19 as marked by the FO of *hastenlii*) would be the selected marker event.

### 11. Summary and Conclusions

A high-resolution multi-disciplinary study, including physical stratigraphy (lithostratigraphy, sequence stratigraphy and magnetostratigraphy) and biostratigraphy (calcareous nannofossil, planktonic foraminifera and larger foraminifera), has been carried out in the 700 m thick uppermost Ypresian-lower Lutetian interval of the Gorrondatzé section. The results show that the different events traditionally used to place the Ypresian/Lutetian boundary, hitherto thought to be virtually simultaneous (i.e., the planktonic foraminiferal P9 (= E7) / P10 (= E8) zonal boundary; the calcareous nannofossil CP12a / CP12b subzonal boundary; the larger foraminiferal SBZ12 / SBZ13 zonal boundary; and the boundary between magnetic polarity chron C22n and C22r), actually occur at very different levels. Therefore, before considering any section to place the Ypresian/Lutetian boundary stratotype, the International Subcommission on Paleogene Stratigraphy should decide on the criterion to precisely define this boundary. To this end, the succession of events pinpointed in the Ypresian/Lutetian boundary interval of the Gorrondatzé beach section might prove to be a useful database (Fig. 16).

The Gorrondatzé section fulfills most of the infrastructure, biostratigraphic and geological requirements required of a prospective stratotype section by the International Commission on Stratigraphy. In addition, the great sedimentary thickness, which implies a deep-marine sedimentation rate about ten times higher than in other Ypresian/Lutetian boundary sections (Table 1), provides the Gorrondatzé section an additional value, as it offers the opportunity to chronologically order successive biomagnetostratigraphic events more precisely than elsewhere. The only drawback with the Gorrondatzé section is that the "true" tops of chron C22r and larger foraminiferal Zone SBZ12 are not preserved due to a fault. Otherwise, all other possible Ypresian/Lutetian boundary marker events have been precisely pinpointed in the Gorrondatzé section. Therefore, we consider that, once the criterion to define the Ypresian/Lutetian boundary is selected, the Gorrondatzé beach section should be considered as a firm candidate to place the Global Stratotype Section and Point of the base of the Lutetian Stage.
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