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New high resolution calcareous nannofossil analysis across the Danian/Selandian transition at the Zumaia section: comparison with South Tethys and Danish sections

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ABSTRACT

A high resolution calcareous nannofossil biostratigraphic analysis was carried out across the Danian/Selandian transition at the Zumaia section (western Pyrenees). In the studied interval, spanning Varol's Subzone NTp7a to Zone NTp9, a sequence of 10 distinct calcareous nannofossil events is identified. The recognition of these bioevents confirms the continuous and expanded character of the Zumaia section and allows an accurate biostratigraphic correlation of the D/S transition between Zumaia, the Danish reference sections and the more southerly Tethys sections. According to this correlation, the abrupt transition from the upper Danian limestones (the calcisiltite unit) to the Lellinge Greensand that marks the D/S boundary in the type area correlates with the lithological change from the Aitzgorri Limestone Formation to the Itzurun Formation in Zumaia. The calcareous nannofossil bioevents recorded in connection with the organic-rich layer used to mark the base of the Selandian in the Tethys region were detected in Zumaia ~10 m below the top of the Aitzgorri Limestone Formation. This finding suggests that the organic-rich layer is considerably older than the Danian/Selandian (D/S) boundary at Zumaia and the type area, and thus using it to mark the D/S boundary in Tethys is not appropriate. According to a counting of limestone/marl couplets, which are demonstrated to be the stratigraphic expression of precession cycles throughout the Zumaia section, the organic-rich layer in the Tethys region is ~546 kyr older than the D/S boundary at the type area.

KEYWORDS **Danian/Selandian. Biostratigraphy. Calcareous nannofossil. Zumaia section.**

INTRODUCTION

The Paleocene Working Group of the International Subcommission on Paleogene Stratigraphy was created with the objective of searching for potential Global Stratotype Sections and Points (GSSPs) for the Selandian and Thanetian stages. To achieve this goal, the upper Danian and lower Selandian were intensively studied by various groups in a few regions, most notably in Denmark (Storebælt), Egypt (Qreiya), southeastern Spain (Caravaca), the western Pyrenees (Zumaia) and Tunisia (Sidi Nasseur).

These studies included constant efforts to correlate the studied sections with the magnetochronologic framework and with the type region in Denmark. However, this is difficult due to the lack of tropical-subtropical biostratigraphic markers in the high latitude reference section.

The Zumaia section has been, for a long time, a key reference section for the Paleocene. Its value for defining the lower Paleogene GSSPs has been reiterated by various workers, being recently selected as the leading candidate for both the Danian/Selandian (D/S) and Selandian/Thanetian (S/Th) boundaries (Gradstein et al., 2004). This prompted a series of detailed studies about its magneto-, chemo- and bio-stratigraphic records (i.e. Molina and Arenillas, 1998; Bernaola et al., 2006; Dinarès-Turell et al., 2007). A preliminary integrated stratigraphy of the section, including some of the most suitable criteria for the GSSP for the D/S and S/Th (Schmitz et al., 1998; Bernaola et al., 2006, Arenillas et al., 2008), was presented and discussed in a meeting of the Paleocene Working Group during the last CBEP congress held in Bilbao in June 2006. Based on previous calcareous nannofossil analyses of the D/S transition at Zumaia (Schmitz et al., 1998; Bernaola, 2002; Bernaola and Nuño-Arana, 2006), some members of the Paleocene Working Group questioned the stratigraphic continuity of the Zumaia section, suggesting the presence of a hiatus in connection with the marked lithologic change recorded at Zumaia between the Danian limestone and the Itzurun Formation (Fm). It was also pointed out that the calcareous nannofossil bioevent succession reported in previous studies of the D/S transition at Zumaia was not accurate enough to allow an unambiguous correlation of the D/S transition of this section with those of the type region and the Tethys area.

To get over these obstacles, a new high resolution calcareous nannofossil analysis was carried out at Zumaia across the upper 13.8 m of the Danian limestone and the lower 3.2 m of the Itzurun Fm. This new data set was presented at the last meeting of the Paleocene Working Group held in Zumaia in June 2007.

The new study provided a more precise succession of calcareous nannofossil events (see below) that a) confirms the continuous and expanded character of the section, b) revalidates the robustness of the geomagnetic signal reported for this stratigraphic interval by Dinarès-Turell et al. (2003), and c) allows an accurate biostratigraphic correlation of the D/S transition between Zumaia, Denmark, and Egypt.

GEOLOGICAL SETTING

The Zumaia section is a continuous lower Santonian to uppermost lower Eocene succession that crops out along a series of sea-cliffs and beaches to the west of San Sebastian (Latitude: 43º17,98'N; Longitude: 2º15,63'W) (Fig. 1). This easily accessible and beautifully exposed section contains a complete and expanded record of the Paleocene, including the D/S transition.

The Early Paleogene succession of Zumaia was deposited offshore of the Pyrenean basin at an estimated water-depth of about 1,000 m (Pujalte et al., 1998; Bernaola et al., 2007). Despite being situated in the subtropical belt, this basin opened westward to the proto-Bay of Biscay and the North Atlantic and was thus under the influence of northern temperate waters. As a result, this area is an important link between the tropical and temperate realms (Fig. 1).

In addition to being accessible, the Paleocene at Zumaia is rich in microfossils and is thus a good section to analyze the calcareous nannofossil associations across the D/S transition. For this purpose we used the bed-to-bed lithological column produced by J.I Baceta in Dinarès-Turell et al. (2003), where the log was used to delimitate precisely the position in the section of chron C27n and demonstrate the orbital forcing (precession) of the carbonate-marl couplets making up the succession.

Stratigraphically, the D/S transition comprises the upper part of the Danian Limestone Fm (Apellaniz et al., 1983) – here renamed the Aitzgorri Limestone Fm - and the lower part of the Itzurun Fm (Baceta et al., 2004) (Fig. 2). The Danian Limestone Fm is here renamed the Aitzgorri Limestone Fm, because its name is inappropriate according to the requirements established by the International Commission on Stratigraphy (ICS) for the formal naming of stratigraphic units (Aubry, pers. com.). Following to the ICS guidelines, the name of formal stratigraphic units (i.e. group, formation) should consist of an appropriate geographic name combined with an appropriate term indicating the kind and rank of the unit. Geographic names should be derived from permanent natural or artificial features at or near the stratigraphic unit. If a lithologic term is added to the name of a lithostratigraphic unit, it should be a simple, generally accepted term that indicates the predominant lithology of the unit.

The Aitzgorri Limestone Fm and the overlying Itzurun Fm are mainly composed of regular alternations of hemipelagic indurated limestones, marlstones and marls (Fig. 2). In the Aitzgorri Limestone Fm the limestones dominate, whereas in the Itzurun Fm, the proportions of the three lithologies vary considerably. In addition, both formations include minor but significant amounts of thin-bedded turbidites. The transition between the two formations is marked by an abrupt lithologic change, which is interpreted as the expression of the prominent sea level fall that characterized the end of the Danian across the whole Pyrenean Domain (Baceta et al., 2004; 2005; 2007).

The Aitzgorri Limestone and Itzurun Fms can be subdivided into a series of informal members easily identified in outcrop (Fig. 2). In the upper part of the Aitzgorri Limestone Fm, which is largely pink-reddish, the “crowded” and “stratified” members can be distinguished. The crowded member is 7 m thick and consists of amalgamated limestones or limestones with very thin marl interbeds. The stratified member, 9 m thick, takes its name from the well developed bedding and the obvious contrast between limestones and intervening marlstones, which produce some of the best examples of ca.110 kyr eccentricity cycles identified in the section (Dinarès-Turell et al., 2003).

The part of the Itzurun Fm considered here shows higher vertical variations in both the relative proportion of hemipelagic sediments and the amount of turbidite intercalations. In contrast to the Aitzgorri Limestone Fm, dark

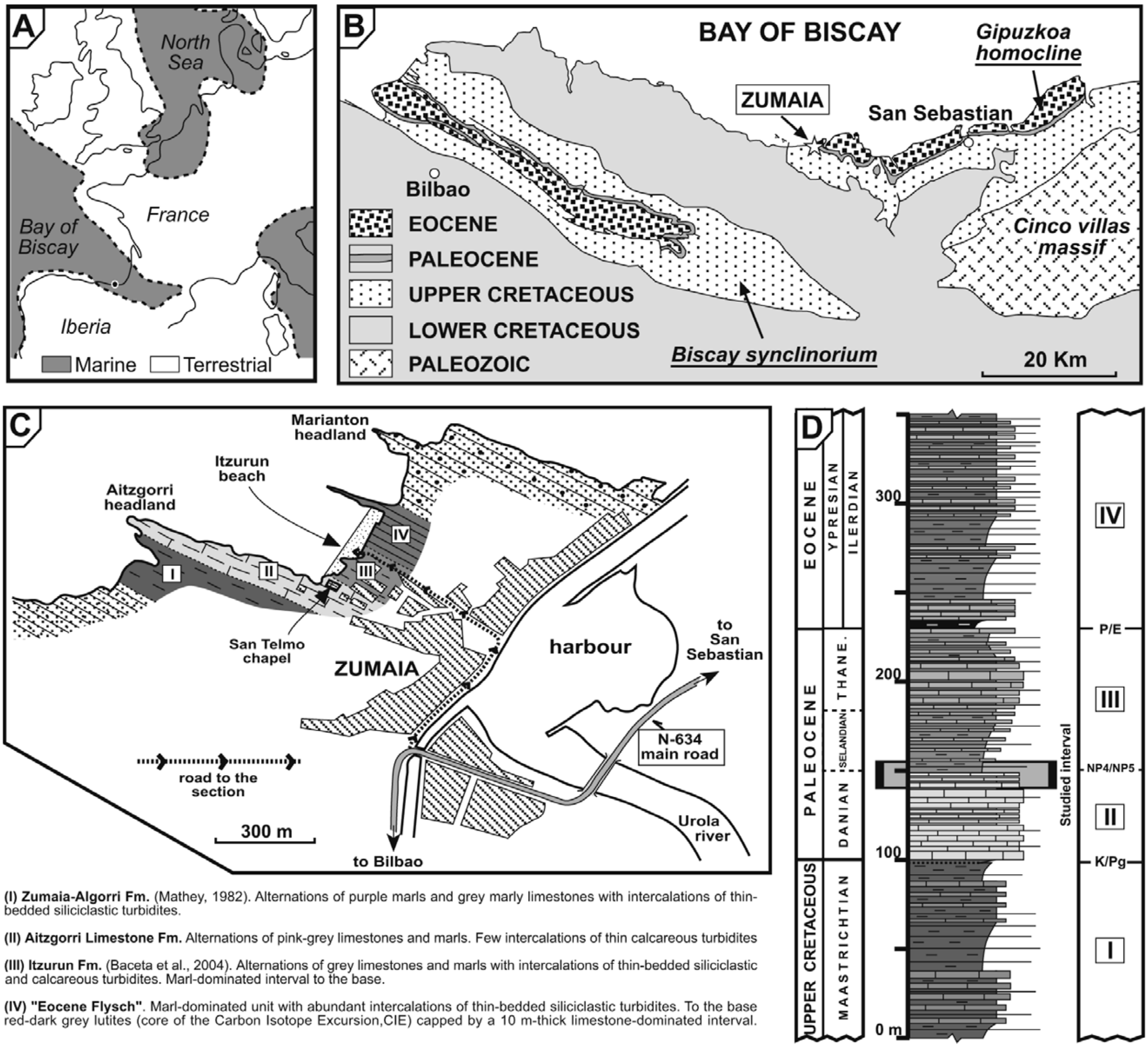

FIGURE 1 | **A) Generalized early Paleogene paleogeographic map of Western Europe. B) Simplified geologic map of the study region showing the most important Paleocene outcrops and the location of the Zumaia beach section. C) Geologic map of the Upper Cretaceous-Lower Paleogene outcrops in the Zumaia area. D) Synthetic lithologic section of the Uppermost Cretaceous-Lower Paleogene interval of the Zumaia section, showing four main stratigraphic units.**

to light grey colors dominate the Itzurun Fm. However, the base of the formation is defined by a 5.5 m thick interval of marls and marlstones of a characteristic red color (the “Red Marl”, see Fig. 2).

MATERIAL AND METHODS

The new calcareous nannoplankton study is based on a total of 59 samples, 43 from the upper 13.8 m of the Aitzgorri Limestone Fm and 16 from the lower part of the Itzurun Fm (Fig. 3). This new data set was integrated with the results of the more general calcareous nannofossil study of the Paleocene in the Zumaia section carried out by Bernaola (2002).

Smear slides were prepared following the standard methods of sample preparation for quantitative analysis (Bown, 1998), avoiding mechanical or physical processes that could modify the original composition of the assemblage. All the slides were analyzed under a Leica DMLP petrographic microscope at 1500x magnification. In order to investigate the smallest species, to observe the details of larger forms and to take pictures, smear-slides were examined at 2000x magnification. Microphotographs of significant calcareous nannofossil taxa are shown in Figs. 4 and 5. In order to detect rare species with key biostratigraphic value, at least 10,000 specimens were observed and identified per sample.

RESULTS

The calcareous nannofossil assemblages recorded in the D/S transition at Zumaia are well preserved, quanti-

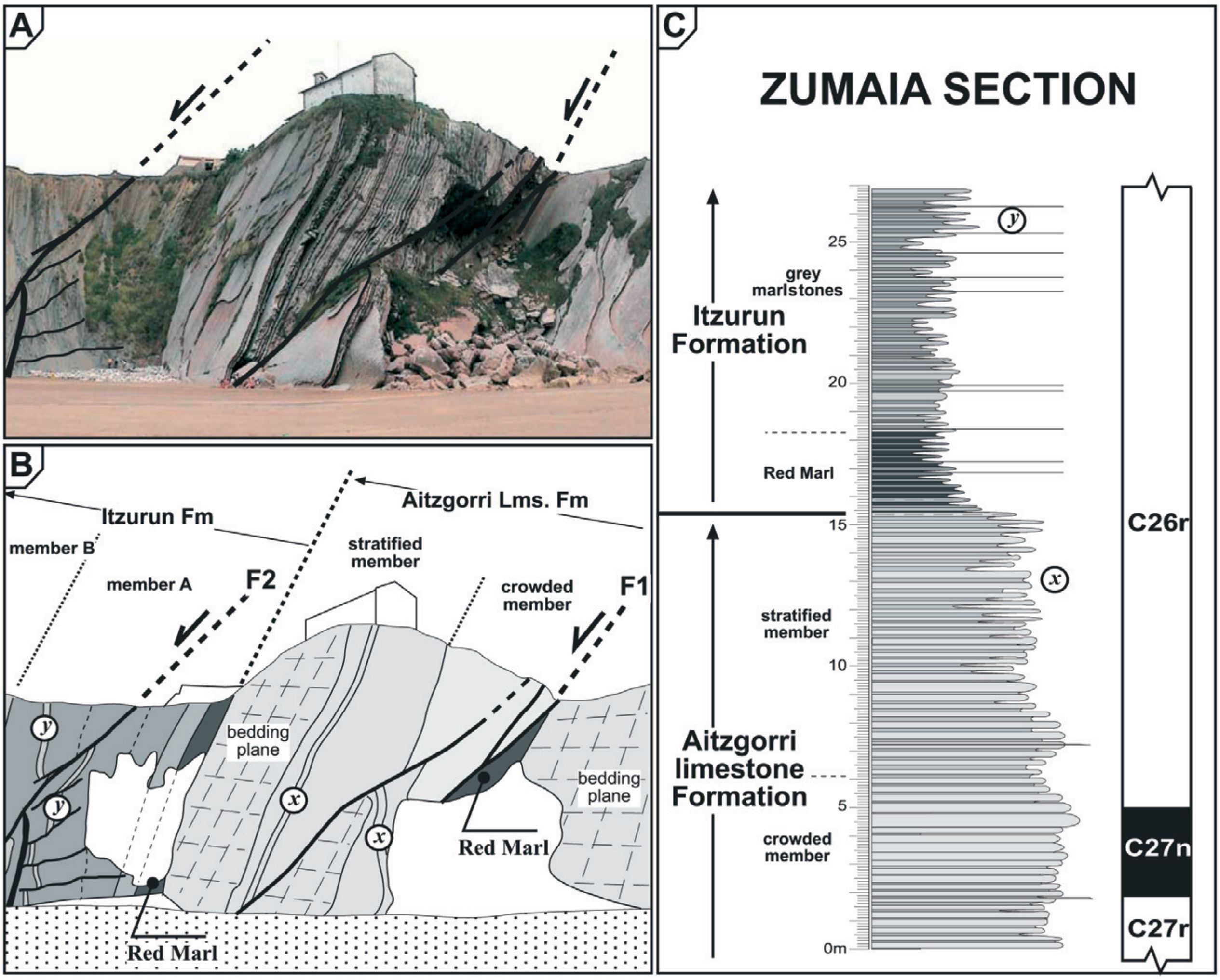

FIGURE 2 **A) Panoramic view of the Danian/Selandian transition. B) Synthetic sketch of the Danian/Selandian transition outcrops in the Itzurun beach, showing the distribution of the main lithological units/members and the fault systems that disrupt the succession. C) Detailed lithology of the Danian Selandian transition. The vertical variation in litholog width represents changes in the carbonate content. Longer lines correspond to thin-bedded turbidites. (x) and (y) reference level in sketch B. Magnetostratigraphy from Dinarès-Turell et al. (2003).**

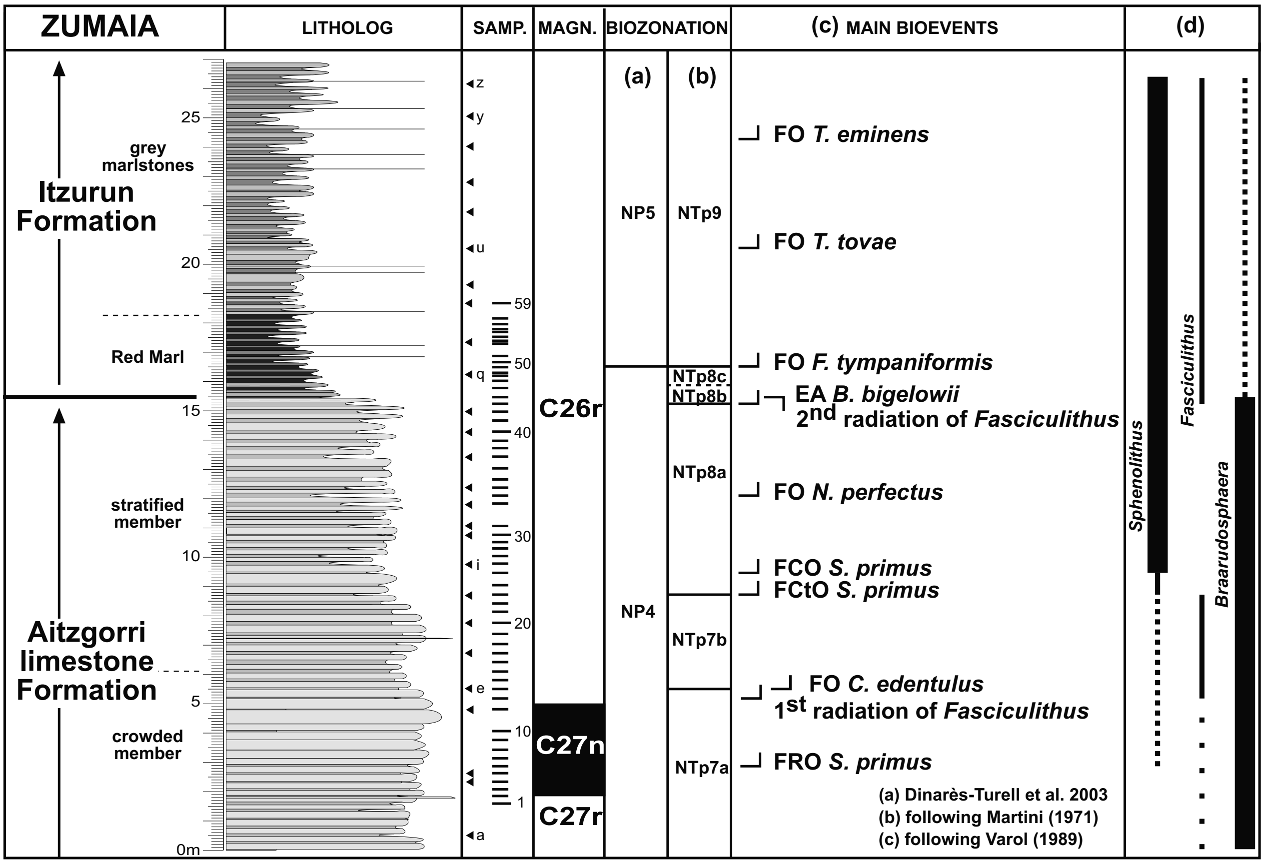

FIGURE 3 | **Integrated lithostratigraphy, magnetostratigraphy and calcareous nannofossil biostratigraphy of the Danian/Selandian transition of the Zumaia section. (a-b) Calcareous nannofossil zones following Martini (1971) and Varol (1989), respectively. (c) Location of the main bioevents. (d) Synthetic distribution and abundance range of *Sphenolithus*, *Fasciculithus* and *Braarudosphaera*. FO= First Occurrence, FRO= First Rare Occurrence; FCtO= First Continuous Occurrence, FCO= First Common Occurrence, EA= End of the Acme. Magnetostratigraphy after Dinarès-Turell et al. (2003). a-z: location of samples in Bernaola (2002), 1-59: location of samples studied in this work.**

tatively rich and very diverse. According to the preservation criteria proposed by Roth and Thierstein (1972), all the studied samples from the Zumaia section yielded well-preserved calcareous nannofossils, showing occasionally traces of dissolution and to a lesser extent recrystallization.

In the uppermost Danian, the upper part of Zone NP4, the calcareous nannofossil diversity is relatively high (S-H 2,1 and 26-31 species per sample), especially when compared to that registered in the lower Danian (S-H 1,5 and 15-20 species per sample in lower part of NP3 Zone; Bernaola, 2002). Throughout the last 15 m of the Aitzgorri Limestone Fm, the assemblage is dominated by *Coccolithus pelagicus*, *Prinsius martinii* and *Braarudosphaera bigelowii*, which together with *Sphenolithus primus*, *Ericsonia* spp., *Prinsius bisulcus* and *Toweius pertusus* form the major components of the assemblage.

An important calcareous nannofossil assemblage change occurs in connection with the marked lithological shift between the Aitzgorri Limestone and the overlying Itzurun Fm. Such change is recorded by a significant increase in the total abundance of calcareous nannofossils (from ~8 to ~23 spp/fv; specimens per field of view) and by a concomitant abrupt decrease in the relative and total abundances of *B. bigelowii*, which is plentiful in the uppermost Aitzgorri Limestone Fm (up to 22%) and becomes very rare in the Itzurun Fm.

In the Red Marl, the calcareous nannofossil assemblage is mainly defined by the same species that dominate in the Aitzgorri Limestone Fm, with the exception of *Br. bigelowii*. In its uppermost part, close to the boundary with the overlying grey marlstones, we observe a slight total abundance decrease in calcareous nannofossil from ~22 to ~15 spp/fv. Finally, the calcareous nannofossil assemblage in the grey marlstones of the Itzurun Fm is similar to that found in the underlying Red Marl and is mainly dominated by *C. pelagicus*, *P. martinii*, *P. bisulcus* and *T. pertusus*.

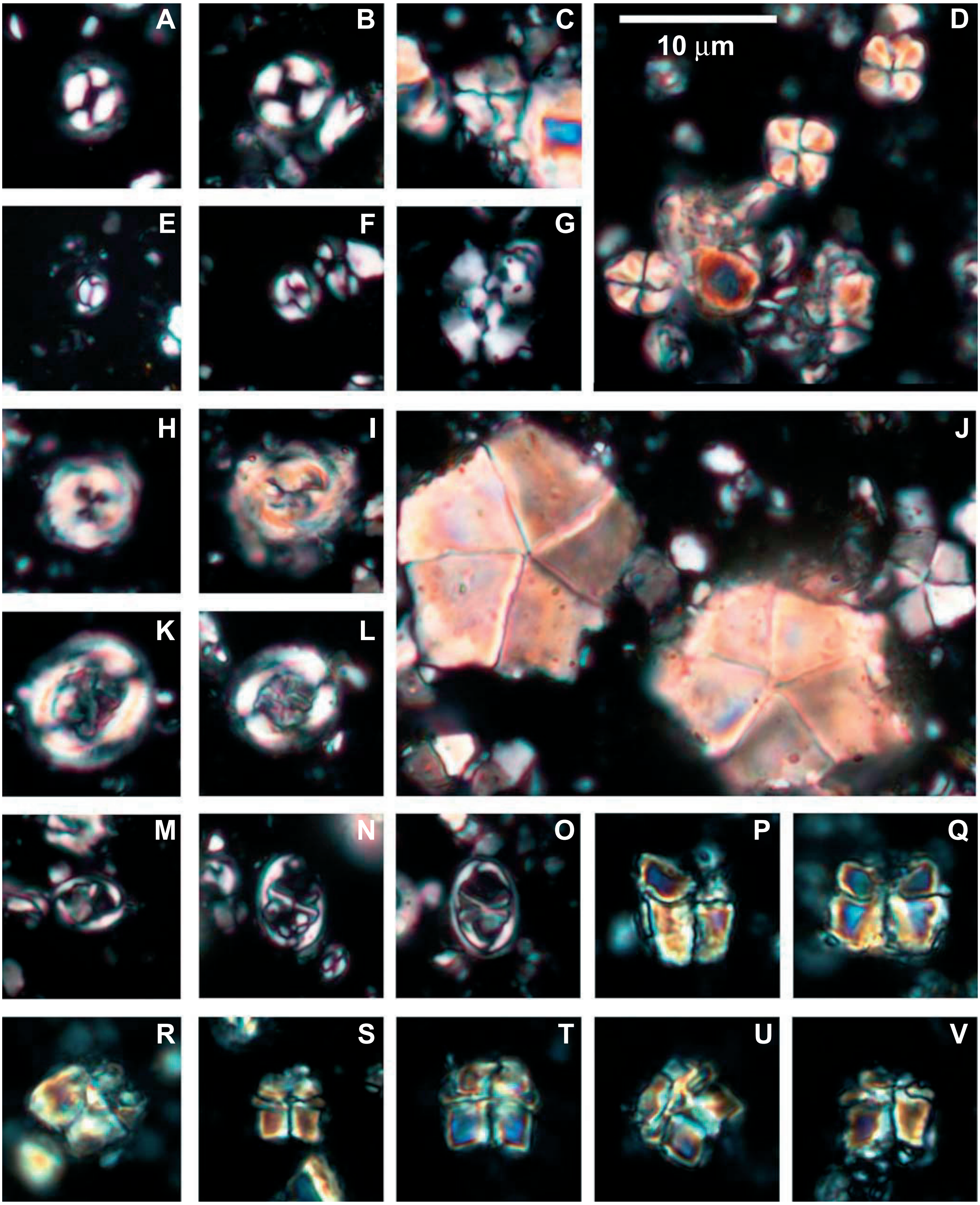

FIGURE 4 | **Calcareous nannofossil from the Danian/Selandian transition at Zumaia section. The scale bar represents 10 μm in all figures. A) *Coccolithus pelagicus*, Z-59. B) *Ericsonia subpertusa*, Z-56. C) *Sphenolithus primus*, Z-6. D) Three specimens of *Sphenolithus primus*, Z- 45. E) *Prinsius martini*, Z-23. F) *Toweius pertusus*, Z-40. G) *Ellipsollithus macellus*, Z- 57. H) *Toweius eminens*, Z-z. I) *Toweius tovae*, Z-w. J) Three specimens of *Braarudosphaera bigelowii*, Z-17. K-L) *Chiasmolithus edentulus*, k- Z-53, l- Z-57. M) *Neochiastozygus* cf. *N. perfectus*, Z-31. N-O) *Neochiastozygus perfectus*, Z-44. P-Q) *Fasciculithus* sp1, Z-13. R) *Fasciculithus* cf. *F. chowii*, Z-13. S-U) *Fasciculithus* sp2, Z-13. V) *Fasciculithus* sp3, Z-16.**

Biostratigraphy and main bioevents:

Following the standard biostratigraphic zonation of Martini (1971), the studied interval spans the upper part of Zone NP4 to the lower part of Zone NP5 (Fig. 3). The boundary between these two zones, defined by the first occurrence (FO) of *Fasciculithus tympaniformis*, is located 1.1 m above the lithological shift that separates the Aitzgorri Limestone Fm from the Itzurun Fm. However, the biozonation of Varol (1989) allows a more precise division of the studied interval and direct correlation with the Tethys area, where Varol's zonation has often been used (Steurbaut et al., 2000; Guasti et al., 2006). Following this zonation, the studied interval spans Subzone NTp7a to Zone NTp9 (Fig. 3).

Among the recorded calcareous nannofossil changes, ten bioevents -shown in Fig. 3 and described below- deserve a special mention.

FRO (First Rare Occurrence) of Sphenolithus primus

The FO of this taxon is not easy to pinpoint precisely since it is usually very rare in the lower part of its range. In Zumaia it first occurs 12.5 m below the top of the Aitzgorri Limestone Fm, where only one specimen was found. The presence of *Sphenolithus* is in fact very rare in the lower 5 m of its range and, as a result, it has not been detected in many of the samples of this interval. The continuous occurrence (FCtO) of this species begins 5.8 m above its FRO, and it is relatively abundant (FCO, First

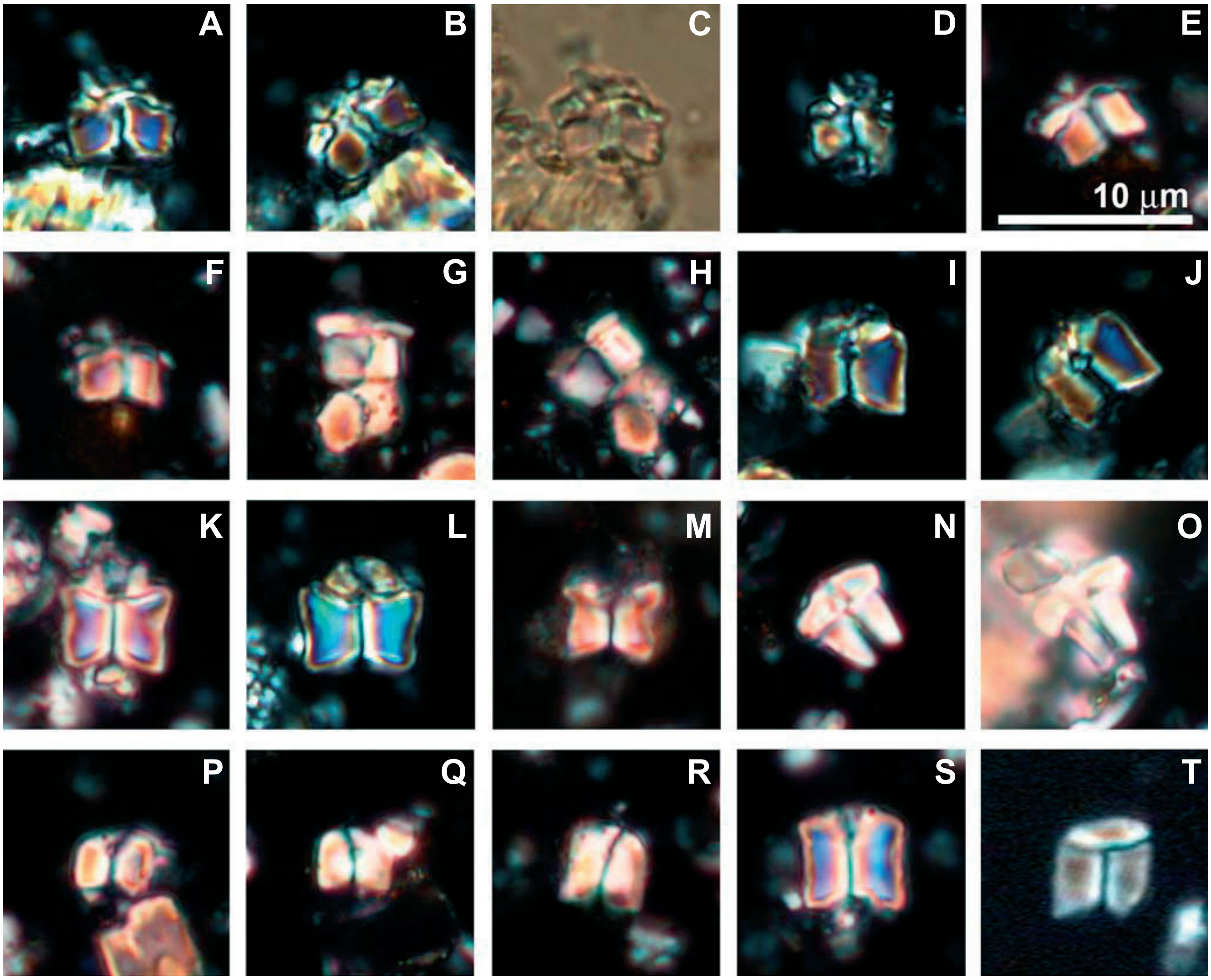

FIGURE 5 **Calcareous nannofossil from the Danian/Selandian transition at Zumaia section. The scale bar represents 10 µm in all figures. A-D) *Fasciculithus* sp3, Z-16. E-H) *Fasciculithus* sp4, e,f- Z-16, g,h- Z-17. I-J) *Fasciculithus* sp5, Z-21. K-L) *Fasciculithus ulii*, k- Z-45, l- Z-44. M) *Fasciculithus billii*, Z-51. N-O) *Fasciculithus janii*, n- Z-57, o- Z-55. P-R) *Fasciculithus tympaniformis*, p- Z-51, q,r- Z-49. S) *Fasciculithus involutus*, Z-59. T) *Fasciculithus pileatus*, Z-p.**

Common Occurrence) 0.8 m higher up. In Zumaia, the FRO of *Sphenolithus* occurs at the middle part of chron C27n, while its FCtO occurs at the base of C26r. Such a distribution is almost identical to the one recently reported by Agnini et al. (2007) and Monechi and Reale (pers. com.) at the South Atlantic Site 1262 and is also in agreement with the chronostratigraphic correlation of Berggren et al. (2000) at Site 384, where the FO of *Sphenolithus* - probably the FCtO of this taxon- occurs in the lowermost part of chron C26r.

FO of Chiasmolithus edentulus

The FO of this species marks the base of Subzone NTp7b of Varol (1989). At Zumaia it was first recorded 10 m below the top of the Aitzgorri Limestone Fm, in coincidence with the first radiation of the genus *Fasciculithus* (see below). The FO of *C. edentulus* is the last calcareous nannofossil biohorizon that can be used to directly correlate the Tethys and the type area across the D/S transition (Varol, 1989). The FO of this taxon in the type area is close to the C27n/C26r reversal (Clemmensen and Thomsen, 2005), a datum that matches our observations at Zumaia (Fig. 3).

FO of new Fasciculithus (1st radiation of fasciculiths)

The first representatives of the genus *Fasciculithus*, the large *F. magnus* and *F. magnicordis,* are very rare in the Zumaia section. For this reason we consider the occurrence of multiple new comparatively smaller *Fasciculithus*, as the first true diversification of the genus. Most of the specimens found in this interval do not fit with known *Fasciculthus* species (Figs. 4-5). As mentioned above, the onset of diversification is almost coincident with the FO of *C. edentulus*, 10.2 m below the top of the Aitzgorri Limestone Fm. The co-occurrence of these two biohorizons was also recorded in south Tethys sections in coincidence with a glauconite rich layer used to mark the D/S boundary in Tunisia and a little below the organic-rich bed used to mark this boundary in Egypt (Guasti et al., 2006; Sprong et al., this issue).

At Zumaia, the continuous and relatively common presence of these fasciculiths is restricted to a 3 m interval. Above this level and until the second radiation of the genus (see below) they are nearly absent. This same trend has been recorded at Site 1262 in the South Atlantic area (Agnini et al., 2007; Monechi and Reale, pers. comm.).

FCtO (First Continuous Occurrence) of Sphenolithus primus

Although the FO of *S. primus* marks the base of Zone NTp8a (Varol, 1989), at Zumaia the FCtO of *S. primus* fits better with Varol's biozonation scheme (see above). The FCtO of *S. primus* has been commonly used to delineate the uppermost part of the Danian in the Pyrenean basin since this datum is easy to recognize even in poorly preserved samples.

FRO Neochiastozygus perfectus

The FO of this taxon marks the uppermost part of the Danian in the type area in Denmark. At Zumaia, the FO of *N. perfectus* is not easy to pinpoint, since this species is rare throughout its range: it first occurs in the uppermost part of the Aitzgorri Limestone Fm but is only continuously present within the Itzurun Fm. Varol (1989), in the Kokaksu section, recorded specimens similar to *N. perfectus* as low as Subzone NTp5b. However, this author did not show the FO of *N. perfectus* s. str. up to Subzone NTp8a. If we consider the FO of *N. perfectus* s. str. the true FO of this species, the correlation of the global and North Sea area zonation schemes of Varol should be modified. As a result, the FO of *N. perfectus* at the North Sea would correlate with a level within Zone NTp8a in the Tethys, as is recorded in the Zumaia section.

Onset of the 2nd radiation of fasciculiths

The term "second radiation of *Fasciculithus*" could be misleading. This term has been widely used to name the diversification carried out by *Fasciculithus* in the upper Paleocene *Discoaster multiradiatus* Zone (NP9), close to the extinction of the genus (Romein, 1979; Perch-Nielsen, 1985; Aubry, 1989). The detection in this study of an earlier radiation of *Fasciculithus* in the middle part of *Ellipsolithus macellus* Zone (NP4) disrupts previous authors' terminology. The first and second radiations of previous authors are now the second and third radiations, respectively.

At Zumaia, the second radiation of this genus starts slightly below the top of the Aitzgorri Limestone Fm, in sample Z-43, where the FO *Fasciculithus ulii* s. str. is recorded (Fig. 3). The radiation of the genus, however, is not distinct up to the base of the Itzurun Fm, where we record the FOs of *F. billii*, *F. janii*, *F. involutus*, *F. tympaniformis* and *F. pileatus*.

End of the Acme (EA) of Braarudosphaera

This genus records an abrupt decrease in relative and absolute abundance in connection with the lithological change from the Aitzgorri Limestone Fm to the Itzurun Fm. A similar abrupt decrease in the relative abundance of this genus is described in the Danish area in connection with the D/S boundary, in the transition from the uppermost Danian limestones (the calcisiltite unit) to the Lellinge Greensand (Clemmensen and Thomsen, 2005). The EA of *Braarudosphaera* is not recorded at the Tethyan sections.

FO of Fasciculithus tympaniformis

The FO of *F. tympaniformis*, 1.1 m above the base of the Itzurun Fm, slightly postdates the EA of *Braarudosphaera*. According to recent cyclostratigraphic analyses (Dinarès-Turell et al., 2003; 2007) the FO of *F. tympaniformis* occurs 4-5 bedding couplets/precession cycles higher than the base of the Itzurun Fm, which, assuming a mean period of 21 kyr, would represent 84-105 kyr.

FOs of Toweius tovae and Toweius eminens

T. tovae and *T. eminens* first occur 5 and 8.5 m above the base of the Itzurun Fm, respectively (Fig. 3). These two species are easily recognizable and postdate the FO of *F. tympaniformis* in many reference sections, such as Sites 384 and 1262 in the Atlantic Ocean (Berggren et al., 2000; Westerhold et al., 2008; Monechi and Reale, pers. comm.).

DISCUSSION

The continuous character of the Zumaia section

It was suggested that a significant hiatus may exist at the Zumaia section in connection with the lithological change from the Aitzgorri Limestone Fm to the Itzurun Fm. The main evidence for such a hiatus was the short distance between the first radiation of *Fasciculithus* and the FO of *F. tympaniformis* reported by Bernaola and Nuño-Arana (2006) in the Zumaia section, estimated in only 1.1 m (Fig. 6). In Qreiya section, Egypt, the stratigraphic interval between these two bioevents is about 5.2 m (Rodriguez and Aubry, 2006), and therefore the lower thickness at Zumaia, despite its more expanded nature, could only be explained by a hiatus. The new high resolution calcareous nannofossil data resolve this issue: as demonstrated, an earlier diversification of *Fasciculithus* is present at the Zumaia section about 10 m below the previously reported diversification of this genus (Bernaola and Nuño-Arana, 2006). As a result, the distance between the first diversification of *Fasciculithus* and the FO of *F. tympaniformis* at Zumaia is about 13.5 m, 7.3 m thicker than in Qreiya, in accordance with the more expanded character of the section (Fig. 6). It is important to stress that if the distance between the FO of *S. primus* to that of *F. tympaniformis* is taken into account, it is possible to come to the same conclusion with the data provided by Bernaola and Nuño-Arana (2006). These facts, together with the succession of calcareous nannofossil events described above, argue against the existence of any biostratigraphically recognizable hiatus in the studied section.

The sedimentological analysis also confirms the continuous character of the D/S succession at Zumaia. Throughout the studied interval, limestone-marlstone bed transitions are always gradual, and no abrupt lithological changes, distinct mineral concentration levels or evidence for hardgrounds have been identified (Fig. 2). The presence of turbidites does not involve erosion, since they

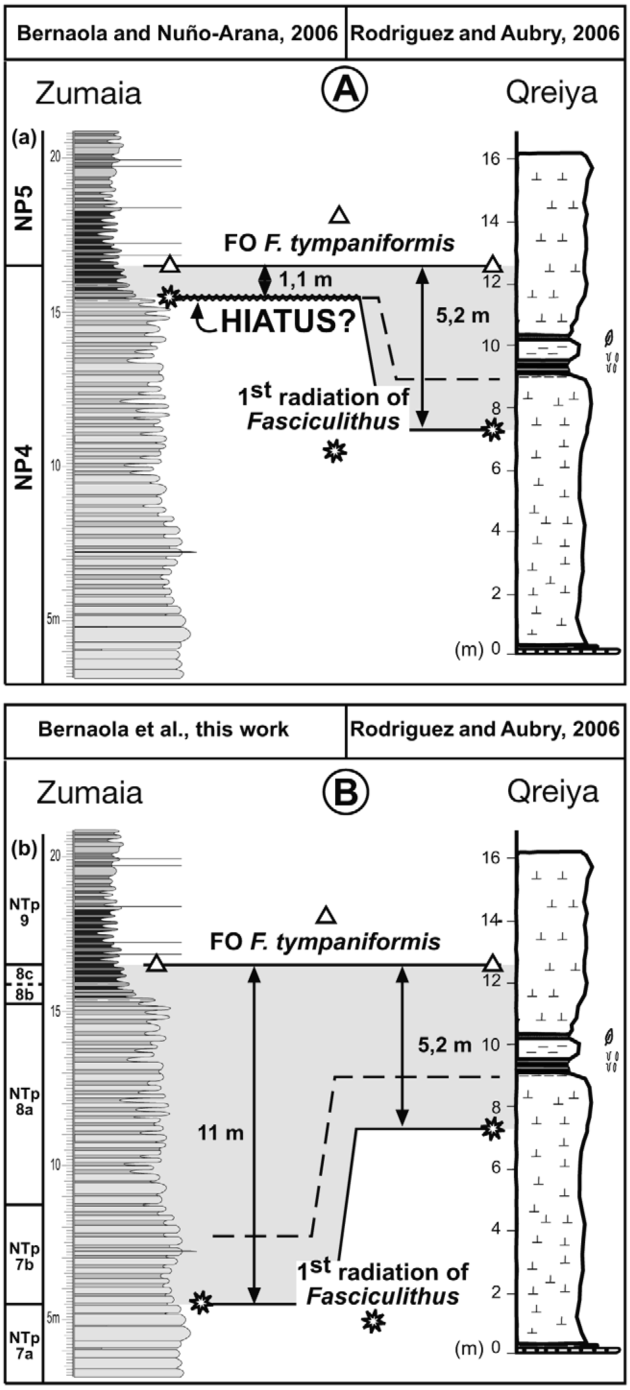

FIGURE 6 | **Correlation between Zumaia and Qreiya sections based on: A) Previous calcareous nannofossil analyses (Bernaola and Nuño-Arana, 2006; Rodríguez and Aubry, 2006); and B) A revised correlation after this work. (a) Calcareous nannofossil zones following the biozonation of Martini (1971). (b) Calcareous nannofossil zones following the biozonation of Varol (1989).**

occur as thin beds (<5 cm) with Tc-e Bouma sequences and do not show evidence of channelling. Moreover, trace fossils occurring throughout the studied interval, mainly *Zoophycus, Planolites* and *Chondrites*, show no evidence of truncation.

Inter-regional correlation of the Danian/ Selandian transition:

The new calcareous nannofossil succession here described allows accurate correlation between the Zumaia section, the D/S boundary at the type area and the organic-rich bed that is used as a tentative D/S boundary at Qreiya and other tropical sections (Fig. 7). Such correlation is possibly due to the intermediate position of the Pyrenean basin, situated in the subtropical belt but open to the proto-Bay of Biscay and the North Atlantic, and thus under the influence of northern temperate waters. The Zumaia section contains faunal and floral elements representative of both regions, which facilitate inter-regional correlations.

Based on the EA of *Braarudosphaera,* the marked lithological change that labels the D/S boundary at the type area can be unambiguously correlated with the abrupt transition recorded from the Aitzgorri Limestone Fm to the Itzurun Fm at Zumaia. The identical stratigraphic distribution of the C27n/C26r reversal and the marker species *C. edentulus* and *N. perfectus* in the Zumaia section and the type area below the EA of *Braarudosphaera* supports this correlation (Fig. 7).

The organic-rich layer recognized at Qreiya is approximately 1 m above the FOs of *C. edentulus* (the NTp7b marker) and the small fasciculiths (Sprong et al., this issue). Since these events were recorded ~10 m below the top of the Aitzgorri Limestone Fm at Zumaia, the obvious conclusion is that the organic-rich layer recognized at Qreiya is considerably older than the D/S boundary at the type area in Denmark (Fig. 7). According to recent cyclostratigraphic studies at Zumaia (Dinarès-Turell et al., 2003; 2007) the FO of *C. edentulus* and the FCtO of *Sphenolithus* are 33 and 23 bedding couplets/precession cycles below the top of the Aitzgorri Limestone Fm, respectively. Assuming a mean period of 21 kyr for the precession cycles, the FO of *C. edentulus* and the FCtO of *Sphenolithus*

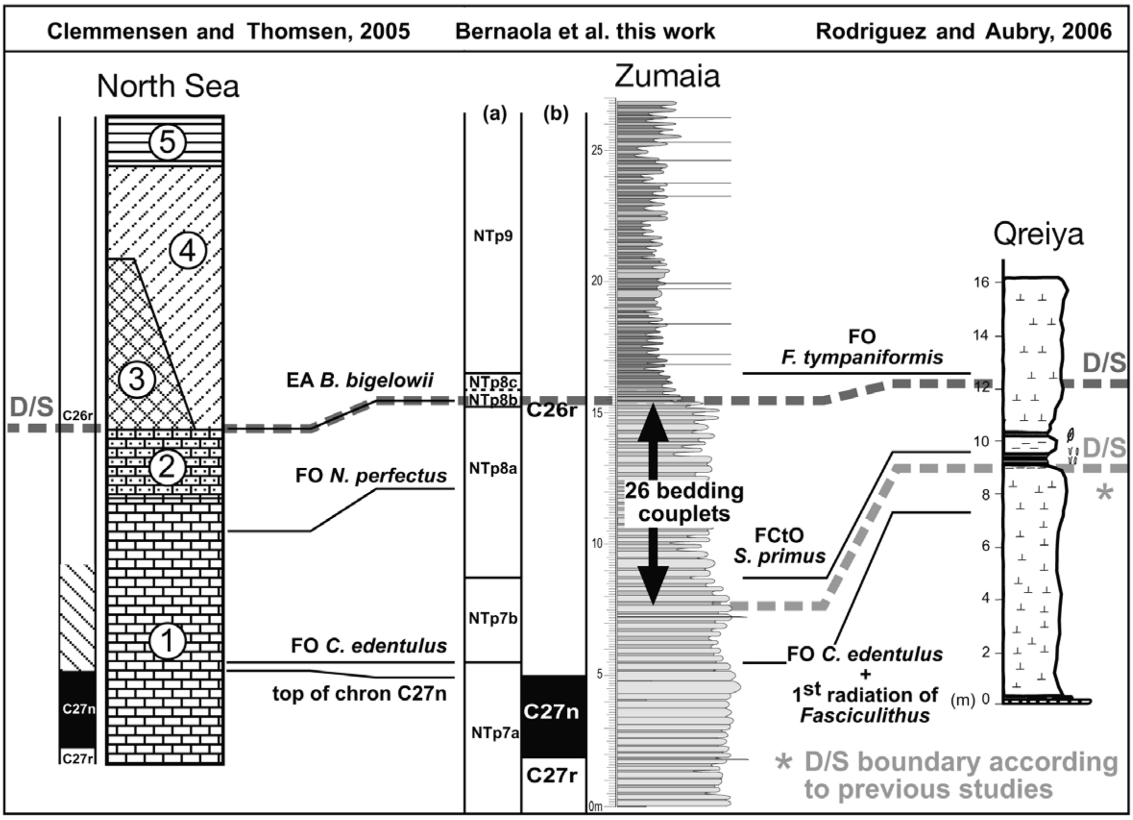

FIGURE 7 **Biostratigraphic correlation of the Zumaia section with South Tethys (Qreiya) and Danish sections. (a) Calcareous nannofossil zones following the zonation of Varol (1989) and (b) magnetostratigraphy after Dinarès-Turell et al. (2003). Units in the synthetic litholog from the North Sea: 1) Bryozoan limestone, 2) Calcisiltite, 3) Lellinge Greensand, 4) Kerteminde Marl, and 5) Æbelø Formation.**

would be respectively 693 kyr and 483 kyr older than the top of the Aitzgorri Limestone Fm. Since the Qreiya organic-rich layer is situated between these two events, it is approximately 546 kyr older that the top of the Aitzgorri Limestone Fm at Zumaia and the D/S boundary at the type area in Denmark.

The GSSP of the base of the Selandian:

During the last meeting of the Paleocene Working Group, the Zumaia section was unanimously selected for the GSSP of the base of the Selandian stage and it is now awaiting formal ratification by the International Commission on Stratigraphy (ICS) and the International Union of Geological Sciences (IUGS).

The lithostratigraphic change from the Aitzgorri Limestone Fm to the overlying marls of the Itzurun Fm was chosen as the reference level/point to define the base of the Selandian. As discussed above, this level is coincident with the EA of *B. bigelowii,* a calcareous nannofossil event that in the classical type section also occurs in connection with the D/S boundary. Since the EA of *B. bigelowii* cannot be detected in subtropical and tropical paleolatitudes, the D/S boundary in these areas should be located with supplementary events. The onset of the second radiation of *Fasciculithus* and the FO of *F. tympaniformis* bound the EA of *B. bigelowii* and the D/S boundary at Zumaia, and thus these two events should be used in subtropical and tropical areas to locate the D/S boundary.

The recent cyclostratigraphic analyses carried out at Zumaia section, where the precession and short eccentricity origin of the couplets and bundles that make up the succession were roughly confirmed (Dinarès-Turell et al., 2003; 2007), allow the relative chronostratigraphic positioning of all the events recorded around de D/S boundary. In the absence of accurate radiometric ages, the measurement of orbital-climatic cycles within the Milankovitch band is demonstrated to be a good practical method for determining the approximate duration of discrete intervals, such as some individual early Paleogene magnetochrons and the distinct PETM and MPBE events (Norris and Röhl, 1999; Cramer, 2001; Röhl et al., 2000; 2001; 2003; Dinarès-Turell et al., 2002; 2003; 2007; Bernaola et al., 2007; Westerhold et al., 2007). The "floating" astronomical time scales constructed for such discrete intervals are based on the number of cycles with short periodicities recorded within the target interval (mainly precession and obliquity cycles), multiplied by the estimated period of the corresponding astronomical cycle at that time. According to Herbert et al. (1995), it is reasonable to assume the modern mean durations of 21 and 41 kyr for precession and obliquity cycles, respectively, identified in series not older than the upper Cretaceous; however, we must always bear in mind the cumulative errors derived from the secular variation of orbital parameters (Berger et al., 1992).

TABLE 1 **Selected bioevents age determination. Vertical position and relative ages of relevant bioevents of calcareous nannofossils within the Danian/Selandian transition in Zumaia section.**

FO: First Occurrence; FRO: First Rare Occurrence; FCtO: First Continuous Occurrence; FCO: First Common Occurrence
LCO: Last Common Occurrence; EA: End of the Acme.

Bioevents	Position in the section (m)	Relative position (m below and above the top of the Aitzgorri Fm)	Precession cycles from the top of the Aitzgorri Fm	Relative age (kyr before and after the top of the Aitzgorri Fm)
FRO *Sphenolithus primus*	2.9	-12.5	40.5 ± 0.5	850.5 ± 10.5
1st radiation of *Fasciculithus*	5.2	-10.2	34.5 ± 0.5	724.5 ± 10.5
FO *Fasciculithus* sp1	5.2	-10.2	34.5 ± 0.5	724.5 ± 10.5
FO *Chiasmolithus edentulus*	5.5	-9.9	33.5 ± 0.5	703.5 ± 10.5
FCtO *Sphenolithus primus*	8.7	-6.7	23.5 ± 0.5	493.5 ± 10.5
FCO *Sphenolithus primus*	9.5	-5.9	21.5 ± 0.5	451.5 ± 10.5
FO *Neochiastozygus perfectus*	12.1	-3.3	11.5 ± 0.5	241.5 ± 10.5
2nd radiation of *Fasciculithus*	15.2	-0.2	1.5 ± 0.5	31.5 ± 10.5
FO *Fasciculithus ulii*	15.2	-0.2	1.5 ± 0.5	31.5 ± 10.5
EA *Braarudosphaera bigelowii*	15.4	0	0.5 ± 0.5	10.5 ± 10.5
FO *Fasciculithus tympaniformis*	16.5	1.1	-4.5 ± 0.5	-94.5 ± 10.5
FO *Toweius tovae*	20.5	5.1	-20.5 ± 0.5	-430.5 ± 10.5
FO *Toweius eminens*	24.3	9.4	-36.5 ± 0.5	-766.5 ± 10.5

Precession-related bedding couplets are particularly well recorded across the D/S transition at Zumaia, and following the above-mentioned procedure of cycle counting this allows the approximate estimation of the relative chronostratigraphic positions of the calcareous nannofossil bioevents identified in this study (Table 1). According to these estimates, the onset of the second radiation of *Fasciculithus* and the FO of *F. tympaniformis* occur 21 kyr before and 84-105 kyr after the EA of *B. bigelowii* and the D/S boundary, respectively.

The new cyclostratigraphic and biostratigraphic results presented in the last meeting of the Paleocene Working Group (Zumaia, 2007), including the calcareous nannofossil analysis presented in this work, turned out to be crucial in the election of the Zumaia section as the GSSP of the base of the Selandian. Other qualities, such as the extraordinary thickness of exposed sediments, the lack of recognizable stratigraphic gap or condensations, the available magnetostratigraphy, the abundant and well diversified marine fossil content, the good exposure and easy accessibility were also taken into account in this election.

CONCLUSIONS

A new high resolution calcareous nannofossil biostratigraphic analysis carried out at the Zumaia section (western Pyrenees) has led to a precise delineation of the positions of 10 distinct calcareous nannofossil bioevents, which allow the accurate biostratigraphic correlation of the D/S transition between Zumaia, the North Sea type area and the more southerly Tethys regions. In these 10 bioevents, there are some of the key calcareous nannofossil markers recently used to define the D/S transition in both the Danish sections (Clemmensen and Thomsen, 2005) and the Tethys area (Guasti et al., 2006; van Itterbeeck et al., 2007, Sprong et al., this volume). This is due to the intermediate position of the Pyrenean Basin, which, despite being situated in the subtropical belt, was open to the North Atlantic and thus subjected to the influence of northern temperate waters.

Based on the EA of *Braarudosphaera,* the lithological change that marks the D/S boundary at the type area can be directly correlated with the abrupt transition recorded from the Aitzgorri Limestone Fm to the Itzurun Fm at Zumaia. This lithological change, however, is ~10 m above the FO of *C. edentulus* and the first radiation of *Fasciculithus*, the calcareous nannofossil bioevents recorded in connection with the organic-rich layer used to mark the base of the Selandian in the southern Tethys area. This suggests that the organic-rich layer found in Tethyan sections is considerably older than the D/S boundary at the type area and consequently that its use to pinpoint the D/S boundary is not appropriate. According to the cyclostratigraphic studies carried out at Zumaia, where the limestone/marl couplets are demonstrated to be the stratigraphic expression of precession cycles (Dinarès-Turell et al., 2003; 2007), the organic-rich layer recorded in the Tethys region would be ~546 kyr older than the top of the Aitzgorri Limestone Fm at Zumaia and, as a result, ~546 kyr older than the D/S boundary as originally described in the North Sea area.

The new calcareous nannofossil analysis confirmed the continuous and expanded character of the Zumaia section, dispelling all doubts about the suitability of this section as the GSSP for the base of the Selandian.

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