Proposed Global Stratotype Sections and Points for the bases of the Selandian and Thanetian stages (Paleocene Series)

Prepared for the
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by the
Paleocene Working Group

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Paleocene GSSPs - background to this document

The International Commission on Stratigraphy has suggested that all Global Stratotype Sections and Points (GSSPs) for the Geological Time Scale should be settled by the time of the 33rd International Geological Congress in Oslo in August 2008. The Paleocene Working Group was commissioned in 1993 by the International Subcommission on Paleogene Stratigraphy to define GSSPs for the bases of the Selandian and Thanetian stages. After fourteen years of research the time was ripe to conclude the activities, and a meeting was held in Zumaia (Basque Country, Spain) from June 19 to 20, 2007, to discuss the content of the stages and determine an appropriate level for their respective GSSPs. The meeting was attended by 23 scientists, including a majority of the scientists that participated in the founding meeting in 1993 in Göteborg, Sweden (Schmitz 1994), plus a very important group of younger researchers, that has become subsequently involved in the activities. After constructive discussions during two days the meeting participants held a vote that resulted in unanimous agreement that the GSSPs for the second and third Paleocene stages should be placed in the Zumaia section in Spain, at the stratigraphic levels discussed in the following proposal. This document has been prepared for the vote on the GSSPs in the International Subcommission on Paleogene Stratigraphy.

The Selandian and Thanetian stages - historical background

The division of the Paleocene Series into three stages, Danian, Selandian and Thanetian, was decided by the International Subcommission on Paleogene Stratigraphy at the 1989 International Geological Congress in Washington (Jenkins and Luterbacher 1992). The base of the lower stage, the Danian, coincides with the Cretaceous/Paleogene boundary which has been formally defined in the El Kef section in Tunisia at the base of the iridium-rich clay layer that formed after a major asteroid or comet impact on Earth (Molina et al. 2006).

The second Paleocene stage, the Selandian, was originally described in Denmark by Rosenkrantz (1924) and consists of lower fossiliferous glauconitic marls (Lellinge Greensand and Kerteminde Marl) and upper unfossiliferous grey clay (now subdivided into Æbelø Formation, Holmehus Formation and Østerrende Clay) (Fig. 1). The succession unconformably overlies the Danian Chalk Formation and contains clasts of this unit in its basal part (Perch-Nielsen and Hansen 1981; Berggren 1994). In the original type area the Selandian deposits are overlain by the Ølst Formation and Fur Formation ("Mo Clay"), containing the numerous, well-known "numbered" ash layers. In the North Sea region the Danian/Selandian boundary reflects the end of ca. 40 million years of continuous deposition of open-marine carbonates, and represents a major change in the tectonic evolution of the northeastern Atlantic (Ziegler 1990; Berggren et al. 1995; Clemmensen and Thomsen 2005; Nielsen et al. 2007). It is notable that until the middle of the 20th century the Cretaceous/Tertiary boundary was still often placed at the top of the Danian limestone (see review in Berggren 1971). Based on Danish outcrop sections the Danian/Selandian boundary has traditionally been placed near the planktonic foraminifera zones P2/P3 boundary (e.g., Berggren et al. 1995), but this reflects the existence of major unconformities at the limestone/greensand boundary. Later studies of more continuous drill cores in the region indicate a more gradual lithological change and a significantly younger age, in the middle of the Zone P3 and close to the calcareous nannofossil zones NP4/NP5 boundary (Thomsen and Heilmann-Clausen 1985; Thomsen 1994; Clemmensen and Thomsen 2005).

The Thanetian Stage concept was first used by Renevier (1873) who included the Thanet Sands with *Cyprina morris* and the Woolwich and Reading Beds with *Cyrena cuneiformis*. Its meaning was subsequently narrowed by Dollfus (1880), who included only the Thanet Sands, the original type-strata on the Isle of Thanet in southeast England. Since 1880 the term Thanetian has consistently been used with the restricted meaning of Dollfus (Bignot et al. 1997). Intensive bio- and magnetostratigraphic studies and sequence stratigraphic analysis on outcrops and wells in the type area have led to a detailed understanding of the extent of the Thanetian with regard to the magnetobiochronologic time scale (Aubry 1994). The historical Thanetian strata span calcareous nannoplankton zones NP6-NP9 of Martini (1971), polarity chrons C26n-C24r (Ali and Jolley 1996) and dinoflagellate zones Viborg 4 and 5 of Heilmann-Clausen (1985, 1994). Studies of drill cores show that the base of the historical Thanetian Stage lies in the upper part of Zone NP6 and close to the base of Chron C26n (Hine 1994; Knox 1994a). A major increase in the abundance of the dinoflagellate *Alisocysta gippingensis* is considered a useful event for recognizing the base of the Thanetian within the North Sea Basin, while the last occurrence of *Palaeoperidinium pyrophorum* and *Palaeocystodinium australinum/bulliforme* are late Selandian events that are useful for interregional correlations (Heilmann-Clausen 2007).

Proposed GSSPs and stratigraphic ranks

Selandian Stage

The base of the Selandian Stage, the second or middle stage in the Paleocene Series, is placed at the base of the Itzurun Formation in the section at Itzurun Beach in Zumaia, Basque Country, northern Spain (Arenillas et al. 2008; Bernaola et al. 2008).

Thanetian Stage

The base of the Thanetian Stage, the third or upper stage in the Paleocene Series, is placed at the base of magnetochron C26n (i.e., C26r/C26n reversal) in the section at Itzurun Beach in Zumaia, Basque Country, northern Spain (Dinarès-Turell et al. 2007).

GSSP geography and physical geology

Location and geologic setting

The Zumaia section is part of an essentially continuous lower Santonian to lower Eocene sea-cliff outcropping along the coast of the Gipuzkoa province halfway between Bilbao and San Sebastian (Fig. 2). The Paleocene part of the section is represented by a ca. 165 m thick essentially complete record exposed along the main beach of the coastal town Zumaia (latitude/longitude 43° 17.98' N/ 2° 15.63' W; Spanish spelling is "Zumaya", but we use here the local Basque spelling). The bulk of the Paleocene is represented by rhythmic alternations of hemipelagic limestones and marlstones, plus numerous intercalations of thin-bedded turbidites (Pujalte et al. 1998). The lithological cyclicity has been attributed to orbital forcing (Ten Kate and Sprenger 1993; Dinarès-Turell et al. 2002, 2003, 2007). The sediments were deposited at an estimated water depth of 1000 m corresponding to a middle to lower bathyal setting (Pujalte et al. 1998; Arenillas et al. 2008). Sedimentation is hemipelagic with a terrestrial component supplied axially from the emerging proto-Pyrenees and marginally from shallow carbonate platforms to the south and north (Fig. 3). Other nearby sections such as at Ermua, ca. 25 km to the southwest, provide records of the sedimentation in the base of slope apron fringing the southern carbonate platform (Fig. 3), and contain a higher fraction of terrigenous matter, and also carbonate slump deposits and calciturbidites (Pujalte et al. 1998; Schmitz et al. 2001). Due to the superb quality of its exposure the Zumaia section already attracted the attention of pioneer workers in the region (e.g., Gómez de Llarena 1946). It was later the subject of general studies of planktonic foraminifera (Hillebrandt 1965), calcareous nannofossils (Kapellos 1974; Van Vliet 1982) or sequence stratigraphy (Baceta 1996; Pujalte et al. 1998), to mention a few. Several papers have focused on the analyses of the Cretaceous/Paleogene and the Paleocene/Eocene boundaries, including Alvarez et al. (1982), Wiedman (1986), Smit and Ten Kate (1992), Canudo and Molina (1992), Gorostidi (1993), Kuhnt and Kaminski (1993), Ward and Kennedy (1993), Canudo et al. (1995), Ortiz (1995), Schmitz et al. (1997a), Molina et al. (1998, 1999), Knox (1998), Apellaniz (1999), Arenillas et al. (1999, 2004), Arz and Arenillas (1999), Adatte et al. (2000), Arenillas and Molina (2000), Bernaola (2002), Orue-Etxebarria et al. (2004) and Caballero (2007). Both these important boundaries, the base and the top of the Paleocene, are excellently exposed and preserved in the section. Zumaia was the main challenger for hosting the GSSPs for both the Cretaceous/Paleogene and the Paleocene/Eocene boundaries, that were eventually placed at El Kef (Tunisia) and Dababiya (Egypt), respectively (Molina et al. 2006; Aubry et al. 2008).

The base of the Selandian - position, stratigraphy and completeness

Precise position

The stratotype point for the basal Selandian, at the base of the Itzurun Formation, is equivalent to the base of the marls overlying the uppermost limestone bed of the ca. 9 meters of limestone-marl couplets in the upper part of the Aitzgorri Limestone Formation (Fig. 4-9). The base of the Selandian is thus ca. 49 meters above the Cretaceous/Paleogene boundary, following the log of Dinarès-Turell et al. (2007).

Lithostratigraphy

The Aitzgorri Limestone Formation is dominantly made up of reddish limestone, with varying amounts of rhythmically appearing marl intercalations, whereas the dominant lithology in the lower part of the Itzurun Formation is greyish marlstones, however, color and lithology vary throughout the formation. The Danian/Selandian boundary is defined at the abrupt lithological change between the two formations (Fig. 4-9). In the upper part of the Aitzgorri Limestone Formation, largely of pink-reddish colors, the lower "crowded" and the upper "stratified" members can be distinguished. The crowded member is 7 m thick and consists of limestones amalgamated or with very thin marly interbeds. The stratified member, 9 m thick, takes its name from the well defined rhythmic bedding and the clearly distinguishable marl-limestone alternations. Some of the best examples of so called bundles representing the ca. 100 kyr eccentricity cycles can be identified in this part of the section

(Dinarès-Turell et al. 2003). The lower ca. 15 m of the overlying Itzurun Formation exhibits higher vertical variations in both the relative proportions of hemipelagic sediments and the density of turbidite intercalations. Dark to light grey colors dominate through the Itzurun Formation, but the basal 2.85 m interval of marls and marlstones has a characteristic red color (Fig. 7) (Schmitz et al. 1998). The Aitzgorri Limestone Formation has previously been referred to as the Danian Limestone Formation, however, according to the guidelines of the International Commission on Stratigraphy, 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 (Bernaola et al. 2008). Geographic names should be derived from permanent natural or artificial features near the stratigraphic feature. If a lithologic term is added to the name of a lithostratigraphic unit it should be a simple and generally accepted term that indicates the predominant lithology of the unit.

Careful examination of the Aitzgorri Limestone/Itzurun formational boundary indicate that the transition is conformable. There is no evidence for any lithological break or omission surface at this level. Throughout the Danian-Selandian transition limestone-marl stone transitions are always gradual and no evidence for hardgrounds have been recorded. The presence of turbidites does not involve erosion, since they mostly occur as thin beds (<5cm) with Tc-e Bouma sequences that do not show evidence of channelling. Trace fossils, common through the whole interval, mainly *Zoophycos*, *Planolites* and *Chondrites*, show no evidence of truncation. Precise bed-by-bed correlation is possible across the whole basin floor domain, even between sections 100 km apart, such as Sopelana and Hendaia, further indicating lack of major unconformities (Baceta 1996; Pujalte et al. 1998).

Calcareous nannofossils

The expanded nature of the Danian-Selandian transition at Zumaia is evident from the gradual sequence of first appearances of the typical calcareous nannofossils of the period (Fig. 8, from Bernaola et al. 2008). For example, the stratigraphic distance between the first diversification of *Fasciculithus* and the first occurrence (FO) (used in the same sense as lowest occurrence) of *Fasciculithus tympaniformis* at Zumaia is about 13.5 m. This is 7.3 m thicker compared with the very complete section at Qreiya in the Eastern Desert of Egypt (Monechi and Reale 2007; Rodríguez and Aubry 2007). The expanded nature of the record at Zumaia is also apparent by the thickness, 13.6 m, between the FO of *Sphenolithus primus* to the FO of *F. tympaniformis*. The base of the nannofossil Zone NP5 according to the scheme of Martini (1971) is defined by the FO of *F. tympaniformis*, which is located 1.1 m above the Aitzgorri Limestone/Itzurun formational boundary i.e. the proposed base of the Selandian (Schmitz et al. 1998; Bernaola et al. 2008). Another important global nannofossil event is a major radiation of the fasciculiths, which starts slightly below the top of the Aitzgorri Limestone Formation where the FO of *F. ulii* s.s. is recorded and continues through the base of the Itzurun Formation, where the FOs of *F. billii*, *F. janii*, *F. involutus*, *F. tympaniformis* and *F. pileatus* are recorded (Bernaola et al. 2008). This radiation is here named the second radiation of the fasciculiths because an earlier radiation, involving the large *F. magnus* and *F. magnicordis* is recorded 10.2 m below the top of the Aitzgorri Limestone Formation. An important regional event is the last common occurrence (LCO) (or the end of the acme) of the *Braarudosphera*. This genus exhibits an abrupt decline in the relative and absolute abundance in connection with the shift from the Aitzgorri Limestone Formation to the Itzurun Formation. Other important nannofossil events recorded in the stratigraphic sequence at Zumaia includes the first rare occurrence of *Neochiastozygus perfectus* in the uppermost part of the Aitzgorri Limestone Formation and the FO of *Chiasmolithus edentulus*, which marks the base of Subzone NPp7b of Varol (1989), at 10 m below the top of the Aitzgorri Limestone Formation (Schmitz et al. 1998; Bernaola et al. 2008). In summary, the sequence of calcareous nannofossil events shows that the Zumaia section is complete and continuous over the Danian-Selandian transition. This is also confirmed by comparison with the calcareous nannofossil record of ODP Site 1262 of Leg 208 at Walvis Ridge (South Atlantic) where an expanded and continuous Paleocene deep-sea sequence has been recovered (Agnini et al. 2007; Monechi and Reale 2007).

<u>Planktonic and benthic foraminifera</u>

Taxonomic problems in the definition of planktonic foraminiferal zone boundaries in the Zumaia section have been carefully evaluated by e.g. Caballero (2007) and Orue-Etxebarria et al. (2007a). Once these definitions are untangled and agreed upon, boundaries can be placed with high precision, giving strong support for the continuity of the Zumaia section across the mid-Paleocene.

Based on planktonic and benthic foraminifera Arenillas et al. (2008) have located five significant event horizons that have been considered as potential correlation criteria for the Danian/Selandian boundary (Fig. 5 and 9). This sequence of foraminifera events at Zumaia also confirms that the section is continuous and expanded. Level HDS1, ca. 15 m below the top of the Aitzgorri Limestone Formation, is characterized by increases of *Acarinina*, *Karrerulina* and *Spiroplectammina*, and corresponds to the lower boundary of the

Morozovella angulata Zone; some authors usually place the Danian/Selandian boundary at this biohorizon, i.e. at the P2/P3 zonal boundary (Berggren 1994; Berggren et al. 1995; Steurbaut et al. 2000). HDS2 at ca. 10 m below the top of the Aitzgorri Limestone Formation is characterized by an increase of *Morozovella* and corresponds to the lower boundary of the *Morozovella* cf. *albeari* Zone by Arenillas and Molina (1997) and probably the P3a/P3b boundary according to Berggren and Pearson (2005) and the lower boundary of the *Morozovella occlusa* Zone of Orue-Etxebarria et al. (2007). HDS3 at ca. 7.5 m below the top of the Aitzgorri Limestone Formation is characterized by an increase in *Karrerulina* and maximum values in percentages of *Morozovella*, coincident with a shift in color of the limestone-marl couplets from greyish to more reddish. HDS4, which occurs at the base of the Itzurun Formation, may correspond to the lower boundary of the *Igorina pusilla* Zone, as defined by Arenillas et al. (2008). Other features noted at this level are a slight decrease of *Morozovella* and increases of trochamminids and *Spiroplectammina*. HDS5 at ca. 3 m above the base of the Itzurun Formation coincides with the shift from basal red to grey Selandian marls. Minimum values in the percentages of *Morozovella* and maximum values for *Bifarina* are recorded here.

The benthic foraminifera give detailed information about the paleobathymetry at Zumaia. The presence of organically cemented and calcareous-cemented agglutinated foraminifera of the "flysch type", suggest a minimum water depth corresponding to lower-middle bathyal depths. The benthic foraminiferal assemblages are also characterized by taxa typical of deep-bathyal environments such as *Bulimina trinitatensis*, *Cibicidoides hyphalus*, *Cibicidoides velascoensis*, *Gyroidinoides globosus*, *Stensioeina beccariiformis*, *Nuttallides truempyi*, *Osangularia velascoensis*, *Nuttallinella florealis*, *Gaudryina pyramidata* and *Spiroplectammina spectabilis*. Most of them are typical of the Velasco-type fauna (Berggren and Aubert 1975). These data support depths of ca. 900-1100 meters or middle to lower slope, in agreement with Pujalte et al. (1995). The benthic foraminifera show no major change at the proposed base of the Selandian, a level which is commonly inferred to correspond to an important sea-level fall (see below), however, this is not contradictory because the water was too deep at Zumaia for the benthic foraminiferal assemblages to be affected even by a major sea-level fall (Arenillas et al. 2008).

<u>*Magneto- and cyclostratigraphy*</u>

The Zumaia section has provided an unprecedented integrated biomagneto- and cyclostratigraphy for the Paleocene (Dinarès-Turell et al. 2002, 2003, 2007). The section now provides the first complete astronomically derived Paleocene chronology where all polarity chrons have been established, rendering this section a master reference section. The proposed base of the Selandian occurs approximately at the top of the lower third of Chron C26r (Fig. 8). The next lower magnetochron, the top of Chron C27n occurs 10 m below and this chron spans ca. 4 m of section. The cycle-duration estimates for the critical chronozones across the upper Danian and the Danian-Selandian transition are as follow: C27r (50 precession cycles, 1050 kyr), C27n (11 precession cycles, 231 kyr), and C26r (137 precession cycles, 2877 kyr). The base of the Itzurun Formation is located 32 precession cycles (774 kyr) above the top of C27n. Precession cycles can also be used for approximate estimates of relative time difference between different lithologic and biostratigraphic events. For example, the onset of the second radiation of the fasciculiths and the FO of *F. tympaniformis* occur respectively 21 kyr before and 84-105 kyr after the proposed Danian/Selandian boundary (Bernaola et al. 2008). According to some generalized stratigraphic schemes (e.g., Berggren et al. 1995, Luterbacher et al. 2004) the top of Chron C27n is considered to coincide with the planktonic foraminifera P2/P3 zonal boundary, i.e. the level where also the Danian/Selandian boundary has been placed by convention. In the Zumaia section Dinarès-Turell et al. (2007) place the P2/P3 boundary ca. 8 m below the top of C27n, whereas Arenillas et al. (2008) place this boundary 9 m higher, i.e. one meter above the top of C27n. This discrepancy in foraminiferal zone boundaries relates to the use of different taxonomic concepts and illustrates the general difficulty in placing precise boundaries in a gradual, evolutionary sequence of morphological change in foraminifera species (Caballero, 2007; Orue-Etxebarria et al. 2007a).

A robust Astronomical Polarity Time Scale (APTS) has been constructed during the last two decades, starting at the young end of the time scale and then moving progressively deeper in time. A recent achievement in this effort has been the completion of an astronomical time scale for the Neogene, resulting in the "Astronomically Tuned Neogene Time Scale" (Lourens et al. 2004). Tuning the Paleogene becomes more challenging despite new full numerical solutions for the Solar System (Varadi et al. 2003; Laskar et al. 2004) due to limitations inherent to the chaotic behaviour of the Solar System and poor radioisotopic age control in the Paleocene in addition to uncertainties in the absolute numerical age of the monitor standards used for the radioisotopic dating methods. However, astronomical tuning based on the stable 404-kyr eccentricity cycle is appropriate (Westerhold et al. 2007) and should be the first-order approach to reach a consistent Paleocene tuned chronology. Although precise orbital solutions for shorter cycles are lacking, a suitable approach is to establish an integrated magnetostratigraphic and orbitally characterized template (i.e. cycle-duration estimates and main phase relationships) in a given succession. Even if definitive tuning to an orbital solution (and therefore "absolute" age estimates) may be provisional, the time duration and rate of processes (i.e. biological, paleoclimatic etc.) are readily extracted. Moreover, the potential for global correlation is amply facilitated.

Carbon isotope stratigraphy

A detailed carbon isotope stratigraphy has been established through the entire Paleocene section at Zumaia based on bulk rock samples (Schmitz et al. 1997a, 1998). This isotopic record shows the same general $\delta^{13}C$ trend as records measured in well-preserved deep-sea material, such as at Deep Sea Drilling Project Site 577. The characteristic global late Paleocene $\delta^{13}C$ maximum (Corfield 1994) is well represented at Zumaia. Only three major negative $\delta^{13}C$ shifts are registered: At the Cretaceous/Paleogene and Paleocene/Eocene boundaries and in the basal Itzurun Formation. The first two anomalies have also been found in many other sections worldwide, whereas it has been difficult to reproduce the anomaly at the base of the Selandian elsewhere. For example, the continuous mid-Paleocene record at Deep Sea Drilling Project Site 384 in the northwest Atlantic (Berggren et al. 2000) does not show a clear negative $\delta^{13}C$ spike similar to the one observed by Schmitz et al. (1997a, 1998) at the proposed base of the Selandian at Zumaia. At both localities, however, the inflection point of the increase in $\delta^{13}C$ that eventually culminates in the unusually high $\delta^{13}C$ values during the long-term late Paleocene $\delta^{13}C$ maximum, occurs very close to the boundary between calcareous nannofossil zones NP4 and NP5. This feature can apparently be used at least for first-order correlations between different sites.

The short-term negative spike in $\delta^{13}C$ at the proposed base of the Selandian at Zumaia may at least partly be related to local features associated with the prominent sea-level fall at this event (see later section). It is clear that in surface waters there is a gradient towards more negative $\delta^{13}C$ values landward because of an increasing contribution of land-derived organic detritus. A sea-level fall may have shifted the coastline closer to Zumaia. A small (ca. 0.7‰) negative $\delta^{13}C$ anomaly of short duration also occurs at 10 m below the base of the Itzurun Formation (Schmitz et al. 1997a), in the lower part of Chron C26r and at the base of the *Morozovella* cf. *albeari* Zone of Arenillas et al. (2008) (HDS2 in Fig. 5 and 9). This event is also associated with a sea-level fall, and may be of local significance only.

Sequence stratigraphy

The deep-water Zumaia embayment was bordered by shallow-water areas in which a 300–500 m thick carbonate succession was formed by the vertical stacking of consecutive carbonate platforms (Fig. 3). Development of this carbonate succession was punctuated by sea-level lowerings of at least regional extent, during which the platform top was subaerially exposed, platform growth ceased and extensive discontinuity surfaces were created. During the Paleocene-early Ilerdian interval six such drops have been identified, the inherent discontinuities having been used to subdivide the succession into depositional sequences, coded according to their age (Fig. 10; Pujalte et al. 2000; Baceta et al. 2004). The most prominent of these discontinuities, which marks the base of the Se/Th-1 sequence, is linked to a long-lasting period of low sea level in the Pyrenees that triggered large erosional collapses along the upper Danian margin and promoted a deep karstification of the Danian platform carbonates (Baceta et al. 2001, 2004, 2007). The basal Selandian proposed here represents the correlative conformity of this major uncontinuity.

The base of the Thanetian - position, stratigraphy and completeness

Precise position

The base of magnetochron C26n (or chrons C26r/C26n reversal) occurs 8 precession cycles (or 2.8 m) above the base of the core of the so called Mid-Paleocene Biotic Event (Fig. 11-15), which is marked by a distinct clay-rich interval, and characterized by important calcareous nannofossil and foraminifer assemblage changes (Bernaola et al. 2007; Dinarès-Turell et al. 2007). The base of the Thanetian occurs ca. 80 m above the Cretaceous/Paleogene boundary.

Lithostratigraphy

The Itzurun Formation that spans the entire Selandian and continues up through the lower Thanetian, shows higher vertical variations in both the relative proportion of hemipelagic sediments and the amount of turbidite intercalations compared to the underlying Aitzgorri Limestone Formation (Baceta et al. 2006). The lower part of the Itzurun Formation can be divided in a lower, 24 m thick, (informal) Member A, and an upper, 52 m thick Member B (Fig. 13). The Member A is largely dominated by marls, whereas the Member B includes significant proportions of indurated limestone. The boundary between the two members has been established arbitrarily at the point in which limestone beds reach and maintain $CaCO_3$ values higher than 60%. This boundary is situated ca. 6.5 m below the proposed base of the Thanetian. On a larger scale, the members A and B of the Itzurun Formation record a progressive increase in $CaCO_3$, after the abrupt decrease that characterizes the lower boundary of the formation. The $CaCO_3$ increase culminates in the upper part of Member B with values similar to those of the Aitzgorri Limestone Formation. The composition of the limestones in the Itzurun Formation is rather similar to those in the underlying Aitzgorri Limestone Formation (micritic mudstone-wackstone with planktonic foraminifera), but occasionally they also contain minor amounts of silt-sized quartz and glauconite, this latter as sub-mm grains and infillings of the foraminiferal tests (Baceta et al. 2006). The Itzurun Formation records a progressive change from illite-rich to illite/smectite-rich clays. Trace fossils, dominated by *Zoophycos*, are common. The Itzurun Formation differs from the Aitzgorri Limestone Formation also in the amount and type of turbidite intercalations. In the marly Member A they are predominantly of siliciclastic nature, whereas in Member B, which shows a higher number, they are usually of siliciclastic or mixed carbonatic-siliciclastic nature. The carbonate grains mainly correspond to abraded tests of planktonic foraminifera. A few meters above the limit between the members A and B of the Itzurun Formation, there is a prominent dark ca. 1 m thick interval recording a drastic decrease in $CaCO_3$ and relatively high values in magnetic susceptibility. This clay interval is interpreted as the expression of the Mid-Paleocene Biotic Event (Bernaola et al. 2007).

<u>*Calcareous nannofossils*</u>

The stratigraphic interval spanning the Selandian Stage and the proposed Selandian/Thanetian boundary is characterized by a smoothly evolving succession of calcareous nannofossil (Fig. 13 and 15), similar to records in apparently expanded and continuous records elsewhere, such as in the deep sea (Bernaola and Nuño-Arana 2006; Dinarès-Turell et al. 2007; Bernaola et al. 2008). Close to the boundary between the basal 2.85 m of red marl and the overlying grey marl beds (Member A) in the lower part of the Itzurun Formation, occurs a slight total abundance decrease in calcareous nannofossils in association with the FOs of *F. pileatus* and *Toweius tovae,* but no other significant change is recorded. The calcareous nannofossil assemblage across the grey marlstones (Member A) of the Itzurun Formation is similar to that found in the underlying red marl and is mainly dominated by *Coccolithus pelagicus,* *Prinsius martinii, P. bisculus* and *T. pertusus*. The most important change in the calcareous nannofossil assemblages across the A and B members of the Itzurun Formation is the occurrence and diversification of the genus *Heliolithus* and the first occurrence of the genus *Discoaster*, one of the most important calcareous nannofossil groups throughout the whole Paleogene. Across the upper A and lower B members of the Itzurun Formation the FOs of *Coronocyclus nitescens*, *Zygodiscus bramlettei, T. eminens, Heliolithus cantabriae, Sphenolithus anarrhopus, H. kleinpelli, Bomolithus conicus* and *Discoaster bramlettei*, among others are also recorded (Bernaola and Nuño-Arana 2006). The base of Zone NP6, marked by the FO of *H. kleinpelli* occurs ca. 22 m above the base of the Selandian Stage and ca. 6.5 m below the base of Chron C26n (Dinarès-Turell et al. 2007).

Planktonic foraminifera

No significant change in the planktonic foraminiferal association has been observed across the base of the Thanetian stage. However, at the onset of the Mid-Paleocene Biotic Event, 2.8 m below the base of the Thanetian, there is a decrease in both the proportion of the planktonic foraminifera relative to the total foraminifera assemblage (planktonic + benthic) and in the number of planktonic species. At the generic level there is an increase in the proportion of *Igorina*, but a decrease in the relative abundance of all other species. The lowest relative proportion of planktonic foraminifera and the minimum number of species occur in the upper part of the Mid-Paleocene Biotic Event interval, where most of the specimens preserved belong to the *Subbotina* genus. These changes, however, were transient, as a return to the conditions before the Mid-Paleocene Biotic Event is observed above the event. There is a change in coiling direction in the *Morozovella occlusa* and *M. velascoensis* group at ca. 10 m above the base of the Itzurun Formation towards the middle part of C26r, that passes from random to a predominant dextral coiling (80% of the tests) (Dinarès-Turell et al. 2007). The FO of *Igorina albeari*, marker of Zone P3b by Berggren and Pearson (2005), occurs at ca. 10 m above the base of the Itzurun Formation (Fig. 13) according to Arenillas and Molina (2000) and Orue-Etxebarria et al. (2007a). The lower boundary of the P4 Zone by Berggren and Pearson (1995), marked by the FO of *Globanomalina pseudomenardii*, occurs ca. 16 m above the base of the Itzurun Formation according to Orue-Etxebarria et al. (2007a). In the lower part of the P4 Zone there is an increase in planktonic foraminifera diversity, especially in acarininids and globanomalinids. Arenillas and Molina (2000) suggested that the lower boundary of the P4 Zone - or *Luterbacheria pseudomenardii* Zone of Arenillas and Molina (1997) - should be placed close to the C26r/C26n boundary at Zumaia.

Magneto- and cyclostratigraphy

The precise position and duration of Chron C26n has been established by detailed paleomagnetic work in the Zumaia section, and confirmed by complementary work in the nearby Ibaeta section (Fig. 11-15) (Dinarès-Turell et al. 2007). The magnetostratigraphy has been linked to detailed cyclostratigraphy providing an excellent APTS. The cycle-duration estimates for the mid-Paleocene critical chronozones where the Selandian-Thanetian transition occurs are as follow: C26r (137 precession cycles, 2877 kyr), C26n (11 precession cycles, 231 kyr) and C25r (69 precession cycles, 1449 kyr). The base of the proposed Thanetian Stage is 105 precession cycles above the proposed base of the Selandian Stage, which indicates a total duration of 2103 kyr for the Selandian Stage. There is no distinct lithological change (e.g., in carbonate content or turbidite abundance) or noticeable biological change in connection with the chrons C26r/C26n reversal, but the level can be located by reference to the distinct Mid-Paleocene Biotic Event (see following section).

Carbon isotope stratigraphy

The base of Chron C26r occurs in about the middle of the interval where $\delta^{13}C$ values gradually increase towards maximum values in the late Paleocene. There is no $\delta^{13}C$ anomaly associated with the proposed base of the Thanetian. In the clayey interval corresponding to the Mid-Paleocene Biotic Event, in addition to a 30% decrease in carbonate content, a 1 ‰ negative $\delta^{13}C$ shift is reported by Bernaola et al. (2007), however, such isotopic shifts associated with a change from limestone to marl may not necessarily reflect original trends, because diagenetic minerals can form in the soft marls (Schmitz et al. 1997a). In the Zumaia section reliable isotopic results can primarily be retrieved from the limestone beds. These were lithified during early diagenesis which restricted the exchange of isotopes with percolating pore waters.

Sequence stratigraphy

The Thanetian GSSP occurs within the transgressive systems tract of depositional sequence Se/Th-1 (Fig. 10). This systems tract is marked by the onlap of shallow marine Thanetian strata onto the discontinuity surface capping the Danian carbonates, and records the marine re-flooding of the shallow domain after the end-Danian sea level drop (Pujalte et al. 1998a; 2000; Baceta et al. 2005).

Relation to Mid-Paleocene Biotic Event

A few meters below the base of Chron C26n a global short-lived event of evolutionary significance is recorded and possibly related to a hyperthermal event (Fig. 11) (Bernaola et al. 2007). This so called Mid-Paleocene Biotic Event is represented at Zumaia by a distinct clay-rich interval characterized by important calcareous nannofossil and foraminifer assemblage changes. This interval, which is also characterized by a significant drop in carbonate content and a pronounced peak in magnetic susceptibility, is located ca. 4.5 m above the first occurrence of *H. kleinpelli*, the NP6 Zone marker, and within the planktonic foraminifera Zone P4. This is at a stratigraphic level equivalent to the red clay layer of the Mid-Paleocene Biotic Event found at Shatsky Rise in the Central Pacific and Walvis Ridge in the South Atlantic (Bralower et al. 2002; Zachos et al. 2004). At Zumaia the calcareous nannoplankton, planktonic and benthic foraminifera experienced a rapid and remarkable transformation (Bernaola et al. 2007). The major calcareous assemblage changes suggest a shift from relatively cool mesotrophic to warmer, more oligotrophic conditions. Diversity of benthic foraminifera assemblages, and the percentage of buliminids and of epifaunal suspension feeders decreased, whereas low food and opportunistic taxa (e.g. *Haplophragmoides*, *Karrerulina* and *Recurvoides*) show quantitative peaks at the clay-rich layer. These faunal changes are similar to those reported from other early Eocene deep-water disturbed environments during hypothermal episodes, which possibly affected metabolic rates of deep-sea faunas (Thomas 2005). The calcareous nannofossil and planktonic foraminiferal turnovers started earlier than the benthic foraminiferal changes, indicating that the environmental change a the sea floor occurred after the changes in the surface waters. This pattern is consistent with a top-down warming of the ocean, and is similar to that reported by Bralower et al. (2002) for the Paleocene/Eocene thermal maximum. The Mid-Paleocene Biotic Event was shortlived: according to precession cycles the event lasted for ca. 52-53 kyr, with the core of the event representing ca. 10-11 kyr (Bernaola et al. 2007).

Correlation to the historical stratotype areas

Base of Selandian

In all outcrop sections in Denmark, the historical type region for the Selandian Stage, the Danian/Selandian boundary is an unconformity with a variable number of biozones missing

(Berggren 1971; Thomsen and Heilmann-Clausen 1985; see further review in Clemmensen and Thomsen 2005). It has therefore been difficult to determine the exact biostratigraphic position of the Danian/Selandian boundary. These difficulties are exacerbated by the fact that the relevant index fossils used in the international zonation schemes are rare or absent in the North Sea Basin (Berggren 1971; Perch-Nielsen 1979; King 1989; Thomsen and Heilmann-Clausen 1985; Varol 1989). The basal Selandian is generally correlated with planktonic foraminifera Zone P3a, while the uppermost Danian is referred to zones P1c or P2. These correlations are primarily based on a single occurrence of the planktonic foraminifera *Morozovella angulata*, index fossil of Zone P3a, in the Selandian at Copenhagen (Hansen 1968), and on the presence of *Globoconusa daubjergensis* in the uppermost Danian at most boundary localities. The highest occurrence of *G. daubjergensis* is widely used to approximate the top of Zone P1c (Olsson et al. 1999). Berggren et al. (1995, 2000) proposed to place the Danian/Selandian boundary (arbitrarily) at the P2/P3 zonal boundary correlating, approximately, with the middle of the calcareous nannoplankton Zone NP4 and with the base of Chron C26r.

As predicted by Berggren (1971), younger Danian deposits which narrow the stratigraphic gap in the surface exposures are present in the subsurface of the Danish Basin. With the recovery of more continuous drill cores, including from the Storebælt area, a gradual and complete succession of the Danian-Selandian transition could be studied in great detail. The succession of calcareous nannofossils in these cores, and particularly the appearance of *Neochiastozygus perfectus* close to the boundary, indicates that the Danian to Selandian change from limestone to clay occurs in the upper part of Zone NP4, close to the NP4/NP5 boundary (Thomsen and Heilmann-Clausen 1985; Thomsen 1994; von Salis Perch-Nielsen 1994; Clemmensen and Thomsen 2005). According to Berggren et al. (1995) the NP4/NP5 boundary is situated in the lower part of planktonic foraminifera Zone P3b, suggesting that the uppermost part of the Danian deposits in the Storebælt cores should be referred to Zone P3a. This agrees well with magnetostratigraphic studies of the Storebælt core 8604A showing that the Danian/Selandian boundary occurs a bit up in the Chron C26r (Ali et al. 1994).

The detailed sequence of calcareous nannofossil appearances and the magnetochronology at Zumaia suggest that the lithological change from the Aitzgorri Limestone Formation to the marls of the Itzurun Formation reflects the same paleogeographic event that caused the facies shift from Danian limestones to Selandian greensands, clays and marls in Denmark. Such a relation was first proposed by Schmitz et al. (1998) who found the FO of *N. perfectus* in Zumaia close to the Aitzgorri Limestone/Itzurun formational boundary. Subsequent magnetostratigraphic and biostratigraphic studies referred to above give further strong support for such a correlation (e.g., Arenillas and Molina 2000; Dinarès-Turell et al. 2003, 2007; Arenillas et al. 2008; Bernaola et al. 2008). This included a revision of the FO of *N. perfectus* to ca. 3 m below the Aitzgorri Limestone/Itzurun formational boundary (Fig. 16). Considering the strong regional evidence for sea-level fall close to the NP4/NP5 boundary and in the lower part of magnetochron C26r both in Denmark and the Basque region (Knox 1994b; Baceta et al. 2007), and the fact that these regions are on the order of only 1500 km apart along the northeastern Atlantic margin, makes it likely that the same event has been registered.

These conclusions are further supported by a recent study of the Bidart and Loubieng outcrop sections in Aquitane in southwestern France (Steurbaut and Sztrákos 2007). High-resolution calcareous nannofossil and foraminiferal investigations of these sections defined a time calibrated sequence of 47 bio-events within the Danian/Selandian boundary interval. The Danian/Selandian boundary, as originally defined in Denmark, is coeval with the lithologic change from limestone-dominated (Lasseube Formation) to marly sedimentation (Latapy Member of the Pont-Labau Formation) in southwestern Aquitane. This horizon is also coeval with the Aitzgorri Limestone/Itzurun formational boundary at Zumaia. The Danian/Selandian boundary in these areas is marked by the end of the acme of the nannofossil family Braarudosphaeraceae, possibly due to the disruption of fresh water influx related to climatic changes (Steurbaut and Sztrákos 2007; Bernaola et al. 2008). Studies of sections across the upper Danian and lower Selandian in Belgium indicate a similar sea-level history in relation to biostratigraphy as in Denmark and the Bay of Biscay region (Steurbaut and Sztrákos 2007). The sea-level changes therefore are either eustatic or related to large-scale tectonic events affecting the entire northwestern Europe.

<u>Base of Thanetian</u>

Correlation to the historical type area is straightforward with the help of magnetostratigraphy (base of chron C26n) and calcareous nannofossils (upper Zone NP6) (Aubry 1994; Hine 1994; Knox 1994a; Ali and Jolley 1996). The basal Thanetian both in its original type area and at Zumaia and in shallow-water sections in the Pyrenees reflects a major transgression, most likely related to the same eustatic or regional isostatic event (Knox 1994a,b; Pujalte et al. 1998a, 2000).

Correlation to the Tethys

In the southern Tethyan realm (e.g. Egypt, Tunisia, Israel) sedimentation conditions in the early and middle Paleocene are very different compared to the margins of western Europe. Sections in the southern Tethys over this interval are typically characterized by monotonous brownish grey marls. One particular mid-Paleocene event level, represented either by an unconformity or, as in Egypt, a prominent organic-rich bed, laminated and rich in fish debris, has been considered to possibly represent the Danian/Selandian boundary event (Steurbaut et al. 2000; Speijer 2003; Steurbaut and Sztrákos 2007; Van Itterbeeck et al. 2007; Sprong et al. 2008). This level has previously been thought to correspond to the proposed base of the Selandian at Zumaia, but recent calcareous nannofossil and foraminiferal studies show that it is an event ca. 400-600 kyr older than the proposed basal Selandian at Zumaia (Steurbaut and Sztrákos 2007; Bernaola 2007; Sprong et al. 2008). In the Qreiya section the organic-rich layer occurs approximately 1 m above the FOs of *C. edentulus* and the small fasciculiths (Sprong et al. 2008). According to the cyclostratigraphic studies at Zumaia the FO of *C. edentulus* and the first continuous occurrence of *Sphenolithus* are 32 and 22, respectively, bedding couplets/precession cycles below the top of the Aitzgorri Limestone Formation (Bernaola 2007; Bernaola et al. 2008). Assuming a mean period of 21 kyr for the precession cycles this means that these events are repectively 672 and 462 kyr older than the top of the Danian limestones. At Qreiya the organic-rich layer is situated between these two events, and it is approximately 570 kyr older than the top of the Aitzgorri Limestone Formation in Zumaia and the Danian/Selandian boundary in the original type area Denmark.

Primary and secondary markers

Base of the Selandian

The best event for global, marine correlation is the second radiation of the important calcareous nannofossil group, the fasciculiths. Cyclostratigraphy combined with magnetostratigraphy may also be crucial, for example, in correlation to continental sections. For regional marine correlation, at least in northwestern Europe, the end of the acme of the nannofossil family Braarudosphaeraceae together with the cessation of long-term carbonate deposition and evidence of sea-level fall can also be used.

Base of the Thanetian

The magnetochrons C26r/C26n reversal is the best global correlation tool and can be applied to a variety of facies. Cyclostratigraphy together with the position of the Mid-Paleocene Biotic Event can be used for detailed marine correlation.

Accessibility, conservation and protection

Considering the exposure along the main "playa" of the town Zumaia accessibility to the GSSPs is optimal. There is even a hotel located on top of the cliff section (on the upper Thanetian part of the strata). The tilted nature of the strata allows a nice walk along the beach at the same time as one ascends or descends through the geologic record. During high tide and strong landward waves, however, a walk to the section may lead to wet feet. The GSSP section is above the highest level where wave action normally erodes the sea cliffs, and there is no risk that the section will be lost because of erosion. The sea cliffs and the beach are major tourist attractions and the local community understands the value of preserving the area from exploitation that may damage the GSSPs. There exists a firm commitment from the Zumaia town authorities, as well as the town's information center for natural history, the Algorri Interpretation Center, to take care of and protect the section, as well as to help and facilitate the access of any researcher interested in Paleocene stratigraphy. There are no restrictions to sampling, although it is advisable to contact the Algorri Interpretation Center. Moreover, because the Zumaia section also contains excellent records of the Cretaceous/Paleogene and Paleocene/Eocene boundaries, the Zumaia cliffs will soon be declared an area with special protection, within the programmes for Natural Reserves currently being developed by the Basque Government. Such a declaration further guarantees the preservation of the section. The Stratigraphy and Paleontology Department of the nearby Basque Country University at Bilbao has played a very active role in research on the Zumaia section and have made a firm promise to take responsibility for the practical arrangements with placing the golden spikes and to supervise the long-term protection of the spikes and accompanying information posts. A similar commitment exists from the researchers at the Department of Earth Sciences at the Zaragoza University, in Aragón.

Summary of selection procedures

There was a general recognition early in the selection procedure that Zumaia would be one of the prime candidates for GSSPs, but nevertheless detailed or pilot studies have been made of a large number of sections mainly in the countries around the Mediterranean. The following sections have been seriously considered: Gebel Aweina, Gebel Duwi and Gebel Qreiya in the Eastern Desert of Egypt (e.g., Charisi and Schmitz 1995, 1998; Speijer and Schmitz 1998; Speijer 2003), Ben Gurion in Israel (Schmitz et al. 1997b; Charisi and Schmitz 1998), Kalaat Senan and Sidi Nasseur in Tunisia (Steurbaut et al. 2000; Van Itterbeeck et al. 2007), Bottaccione Gorge and Contessa Highway in Italy (Corfield et al. 1991), and Caravaca and Zumaia in Spain (Schmitz et al. 1998). In its final stage the selection procedure was narrowed down to a comparison of two sections, Zumaia, and the Qreiya section in the Eastern Desert of Egypt. Because of their excellent records both sections have been studied in detail by several groups and considerable data now exists. A detailed profile across the Qreiya section was sampled by B. Schmitz, R. Knox, N. Obaidallah and M. Soliman in 2004. These samples have been distributed within the Paleocene Working Group and have resulted in several detailed studies (e.g., Bernaola 2007; Monechi and Reale 2007; Orue-Etxebarria et al. 2007b; Rodríguez and Aubry 2007).

One major advantage of chosing Zumaia is its position intermediate between the North Sea (or boreal) region, where the original stratotype sections for the Selandian and Thanetian were defined, and the more southerly Tethys region, e.g. Egypt, Tunisia and South Spain (Schmitz et al. 1998). The Zumaia section contains faunal and floral elements representative of both regions and this facilitates correlation between the North Sea and the rest of the world. During the Paleocene the Zumaia site appears to have been affected by the same sea-level and lithology changes as other northwestern European sites. Placing the GSSP for the base of the Selandian at the shift from limestone to marl in the upper NP4 Zone would pay homage to Alfred Rosenkrantz' original definition of the Selandian (1924) at the shift from limestone to grey marl in the Danish Basin, because most likely the change in lithology at Zumaia registers the same event. The Zumaia section is also superior relative to Qreiya because of its much better accessibility. A visit to the Qreiya section requires more or less a small expedition with at least two jeeps plus desert permits. The Zumaia section is also more expanded than the Qreiya section, at least across the Danian-Selandian transition. An important consideration is the fact that high-resolution cyclostratigraphy and good magnetostratigraphy exist for Zumaia, whereas these parameters cannot be used at Qreiya. This is a very strong argument in favor of Zumaia. The preservation of foraminifera and calcareous nannoplankton appear to be superior at Qreiya relative to Zumaia, but preservation at Zumaia is still sufficient for establishing a high-resolution biostratigraphy. At Zumaia correlations and comparative studies can be made with nearby coeval sediment sections representing a wide range of facies and environments, including base of slope apron, inner and outer shelf, deep-sea channels and even continental facies in the Tremp Basin to the southeast (Schmitz and Pujalte 2003). This correlation potential opens the prospect for detailed temporal and spatial reconstructions of eustatic sea-level changes at the Danian/Selandian and Selandian/Thanetian boundaries. At Qreiya there is also substantial correlation potential, but the spectrum of environments is not as wide as in the Pyrenean region. At the final meeting of the Paleocene Working Group these issues were discussed in detail, and based on evaluations of extensive and detailed data sets the Zumaia section was unanimously considered the best section for the GSSPs for the Selandian and Thanetian stages. The Working Group carefully evaluated the standing of the Zumaia section in relation to the requirements for a GSSP according to the International Commission on Stratigraphy, and found that Zumaia is close to ideal for placing the GSSPs (see further compilation in Fig. 17).

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Figure Captions

Fig. 1. Stratigraphic scheme for the Paleocene in Denmark by Rosenkrantz (1924). This is the first use of the regional stage "Selandien".

Fig. 2. (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. From Bernaola et al. (2008).

Fig. 3. Late Danian paleogeography of the Pyrenean domain with reference sections and localities. From Baceta et al. (2004).

Fig. 4. The transition at Itzurun Beach from the limestone-marl couplets of the upper Aitzgorri Limestone Formation (represented by cliffs) to the marls of the Itzurun Formation (in its lower part mostly covered by grass). The proposed base of the Selandian is at the base of the Itzurun Formation, marked by orange arrow.

Fig. 5. Panoramic photographs of the Danian and Danian-Selandian transition at Zumaia. The reference surfaces HDS1 to HDS5 are discussed in the text and shown in greater detail in Fig. 9. Surface HDS4 corresponds to the proposed base of the Selandian Stage, marked by orange arrow. (A) Stratigraphical positions of the horizons HDS1 to HDS5 in the upper block of a normal fault that affects the Danian-Selandian transition. (B) Stratigraphical positions of the Cretaceous/Paleogene boundary and the horizons HDS1 to HDS5 in the lower block of the fault. In (A) and (B), note the repetition of the upper Danian sequence along the section because of the fault. From Arenillas et al. (2008).

Fig. 6. (A) Panoramic view of the Danian-Selandian transition; (B) Synthetic sketch of the Danian-Selandian transition outcrop in the Itzurun Beach, showing the distribution of the main lithological units/members and the fault systems that disrupt the succession. (C) Detailed litholog of the Danian-Selandian transition. (x) and (y) reference levels in sketch B. From Baceta et al. (2006) and Bernaola et al. (2008).

Fig. 7. The transition from the 2.85 m of red marls to the first grey beds in the lower part of the Itzurun Formation. Red beds occur up to ca. 3.5 m after which beds turn completely grey. The Danian/Selandian boundary is covered by grass in this exposure.

Fig. 8. Integrated lithostratigraphy, magnetostratigraphy and calcareous nannofossil biostratigraphy of the Danian-Selandian transition of the Zumaia section. Location of the main bioevents and synthetic distribution and abundance ranges of *Sphenolithus*, *Fasciculithus* and *Braarudosphaera*. FO= First Occurrence; FRO= First Rare Occurrence; FCtO= First Continuous Occurrence; FCO= First Common Occurrence. From Bernaola et al. (2008).

Fig. 9. Detailed lithologic log across the Danian-Selandian transition of the Zumaia section with position of reference horizons HDS1 to HDS5 (Arenillas et al. 2008). These horizons are discussed in the main text and shown in Fig. 5. Surface HDS4 corresponds to the proposed base of the Selandian and is marked by orange arrow. Magnetostratigraphy from Dinarès-Turell et al. (2003). The Danian Limestone Formation has been renamed to Aitzgorri Limestone Formation.

Fig. 10. Biochronostratigraphic framework of the Paleocene-lower Ilerdian succession of the SW Pyrenees, showing depositional sequences and main facies. Age dating of the sequences based on platform margin, slope and basinal sections. Modified from Baceta et al. (2004).

Fig. 11. Position of the proposed base of the Thanetian Stage at Itzurun Beach. The relation of the GSSP relative to magnetostratigraphy and lithology is emphasized. Magnetostratigraphy according to Dinarès-Turell et al. (2007).

Fig. 12. Position of magnetochrons C26r, C26n and C25r in relation to lithology in the Ibaeta section, a complementary reference section for magnetostratigraphy across the Selandian-Thanetian transition. Magnetostratigraphy according to Dinarès-Turell et al. (2007).

Fig. 13. Integrated lithostratigraphy, biostratigraphy and magnetostratigraphy of the mid-Paleocene of the Zumaia section. (A) Main calcareous plankton bioevents. (B) Magnetic polarity stratigraphy. (C) Planktonic foraminifera biozonation. (D) Biozonation of Berggren et al. (1995). (E) Calcareous nannofossil biozonation. Biostratigraphic events represent first occurrences (FOs), otherwise they are

indicated as first common occurrences (FCOs), first rare occurrence (FROs) or last common occurrences (LCOs). Danian Limestone Formation = Aitzgorri Limestone Formation. From Baceta et al. (2006) and Dinarès-Turell et al. (2007).

Fig. 14. Computed virtual geomagnetic pole (VGP) latitudes and lithologic logs for the Zumaia and Ibaeta sections. Open circles denote unreliable data and crosses mark the position of samples that have provided no data. The position of chron C26 and correlation between both sections is shown. MPBE denotes the Mid-Paleocene Biotic Event and dashed lines correlate some distinct relatively thick carbonate beds. Numbering of the eccentricity (ca. 110 kyr) related E-cycles follows numbering for underlying strata that starts above the Cretaceous/Paleogene boundary and as reported by Dinarès-Turell et al. (2003). Numbering of the carbonate layers from the basic couplets of precession P-cycles arbitrarily starts at the Mid-Paleocene Biotic Event. From Dinarés-Turell et al. (2007).

Fig. 15. Magnetostratigraphy, main biostratigraphic events, lithology and cyclostratigraphy across the mid-Paleocene in the Zumaia section. MPBE denotes the Mid-Paleocene Biotic Event. Numbering of the eccentricity (ca. 110 kyr) related E-cycles follows numbering for underlying strata that starts above the Cretaceous/Paleogene boundary and as reported by Dinarès-Turell et al. (2003). Numbering of the carbonate layers from the basic couplets of precession P-cycles arbitrarily starts at the Mid-Paleocene Biotic Event. Biostratigraphic events represent first occurrences (FOs), otherwise they are indicated as first common occurrences (FCOs), first rare occurrence (FROs) or last common occurrences (LCOs). From Dinarès-Turell et al. (2007).

Fig. 16. Biostratigraphic correlation of the Zumaia section with South Tethys (Qreiya) and Danish sections. Calcareous nannofossil zones following the biozonation of Varol (1989). In North Sea log: (a)= Bryozoa Limestone, (b)= Calcisiltite, (c)= Lellinge Greensand, (d)= Kerteminde Marl, (e)= Æbelø Formation. From Bernaola et al. (2008). The paleomagnetic data for the North Sea below the FO of *N. perfectus* are of low quality and interpretations are uncertain.

Fig. 17. Summary of evaluation of the Zumaia section for holding the Selandian and Thanetian GSSPs in relation to the recommendations by the International Commission on Stratigraphy.

Medd. fra Dansk geol. Forening. København. Bd. 6 [1924]. 23. 35

Skema over det danske Paleocæn.				
Oligocæn	Rupélien		Septarieler	
			Lakune	
Paleocæn	Londinien		Stærkt farvede, fede Lerlag Lag med vulkansk Aske	Ca. 150 m
Paleocæn	Sélandien		Graa Lerlag Graa Mergellag Grønsandslag Konglomerat (lokalt)	Ca. 100 m
			Lakune	
Paleocæn	Danien	yngre	Kalksandskalk (lokal) Kokolitkalk, Bryozokalk, Koralkalk	Ca. 100 m
Paleocæn	Danien	ældre	Bryozokalk	Ca. 100 m
			Lakune	
			Cerithiumkalk	
			Lakune	
Senon	Maastrichtien		Skrivekridt	

Fig. 1

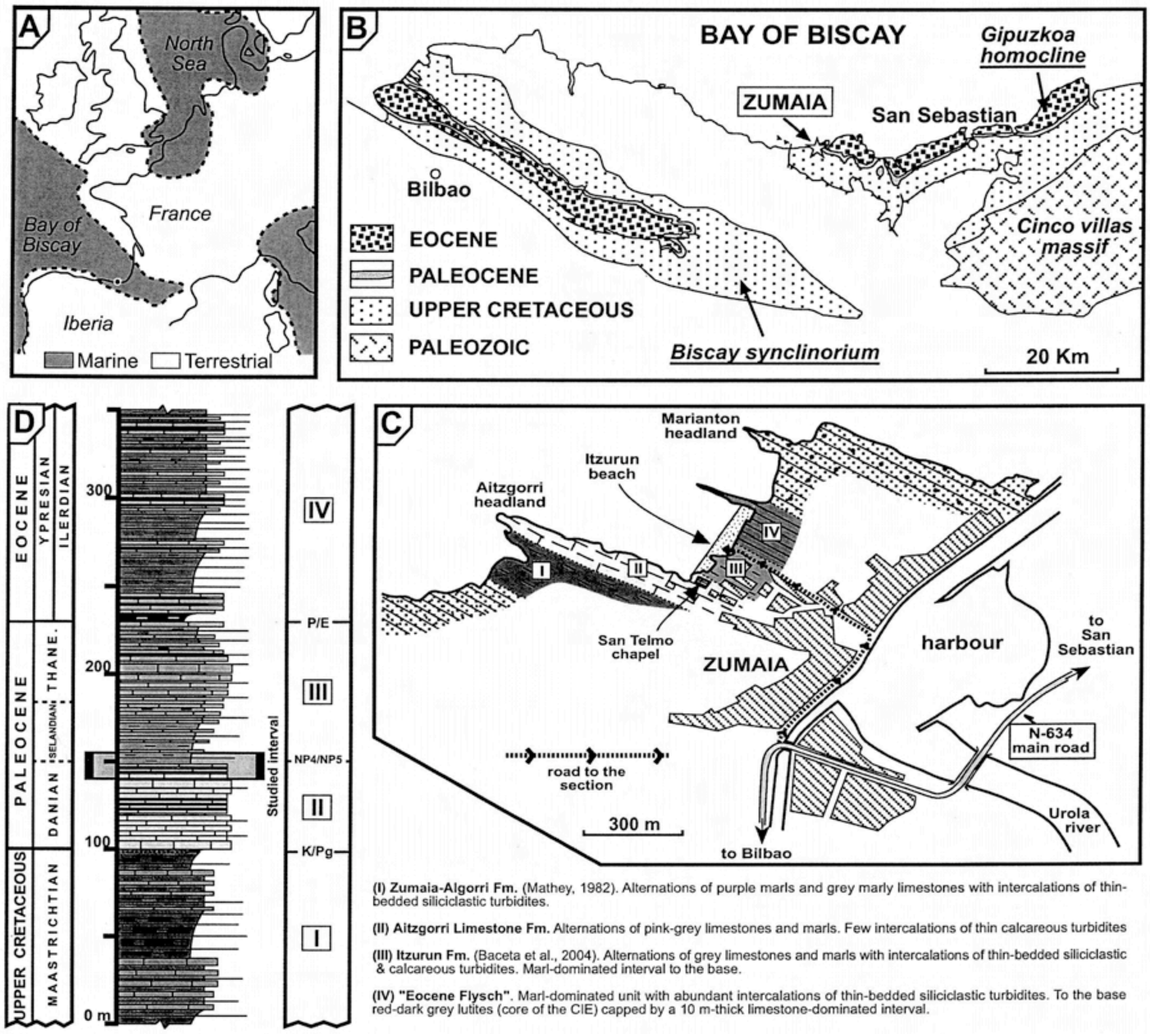

A
North Sea
France
Bay of Biscay
Iberia
Marine
Terrestrial
B
BAY OF BISCAY
Gipuzkoa homocline
ZUMAIA
San Sebastian
Bilbao
EOCENE
PALEOCENE
UPPER CRETACEOUS
PALEOZOIC
Cinco villas massif
Biscay synclinorium
20 Km
C
Marianton headland
Itzurun beach
Aitzgorri headland
I
II
III
IV
San Telmo chapel
ZUMAIA
harbour
to San Sebastian
N-634 main road
road to the section
300 m
to Bilbao
Urola river
D
UPPER CRETACEOUS
MAASTRICHTIAN
PALEOCENE
DANIAN
SELANDIAN
THANE.
EOCENE
YPRESIAN
ILERDIAN
0 m
100
200
300
Studied interval
K/Pg
NP4/NP5
P/E
(I) Zumaia-Algorri Fm. (Mathey, 1982). Alternations of purple marls and grey marly limestones with intercalations of thin-bedded siliciclastic turbidites.
(II) Aitzgorri Limestone Fm. Alternations of pink-grey limestones and marls. Few intercalations of thin calcareous turbidites
(III) Itzurun Fm. (Baceta et al., 2004). Alternations of grey limestones and marls with intercalations of thin-bedded siliciclastic & calcareous turbidites. Marl-dominated interval to the base.
(IV) "Eocene Flysch". Marl-dominated unit with abundant intercalations of thin-bedded siliciclastic turbidites. To the base red-dark grey lutites (core of the CIE) capped by a 10 m-thick limestone-dominated interval.

Fig. 2

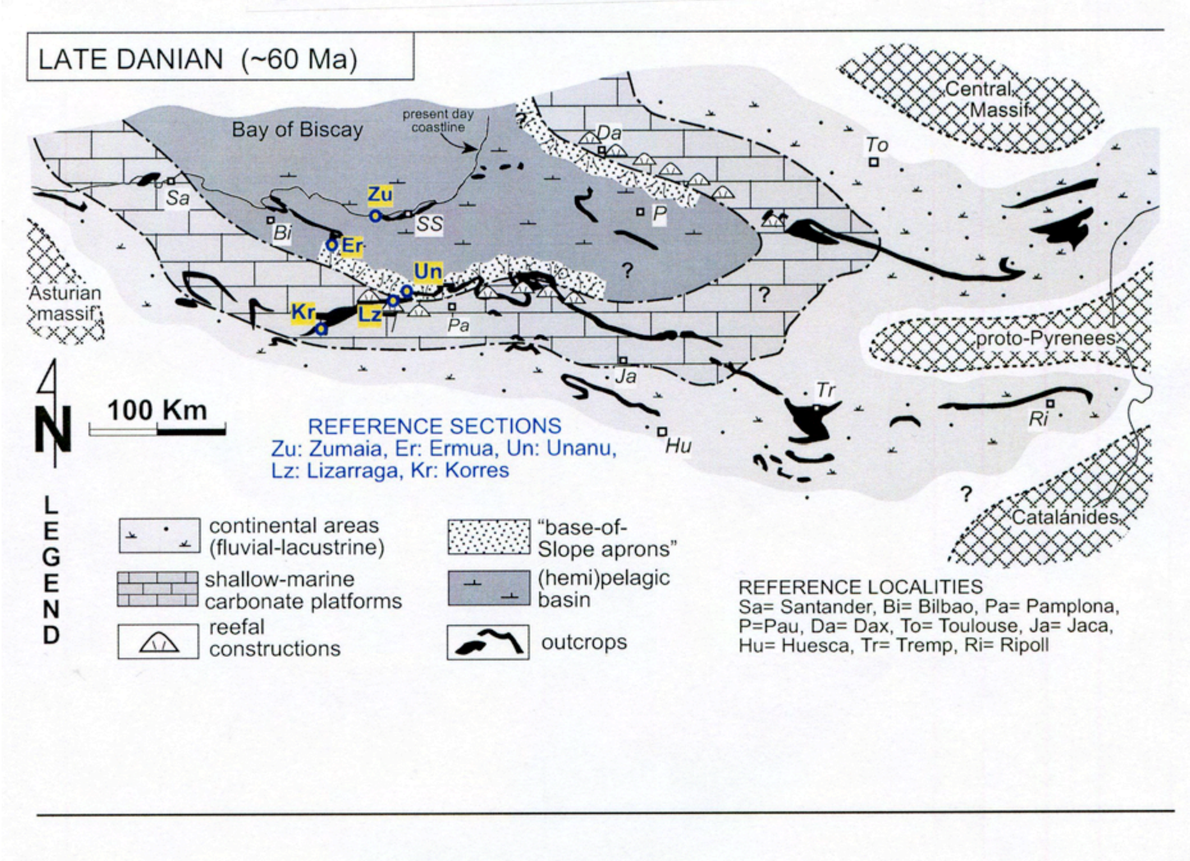

LATE DANIAN (~60 Ma)
Bay of Biscay
present day coastline
Central Massif
Asturian massif
proto-Pyrenees
Catalánides
Sa
Bi
SS
Zu
Er
Un
Kr
Lz
Pa
Da
P
To
Ja
Hu
Tr
Ri
100 Km
N
REFERENCE SECTIONS
Zu: Zumaia, Er: Ermua, Un: Unanu, Lz: Lizarraga, Kr: Korres
LEGEND
continental areas (fluvial-lacustrine)
shallow-marine carbonate platforms
reefal constructions
"base-of-Slope aprons"
(hemi)pelagic basin
outcrops
REFERENCE LOCALITIES
Sa= Santander, Bi= Bilbao, Pa= Pamplona, P=Pau, Da= Dax, To= Toulouse, Ja= Jaca, Hu= Huesca, Tr= Tremp, Ri= Ripoll

Fig. 3

Fig. 4

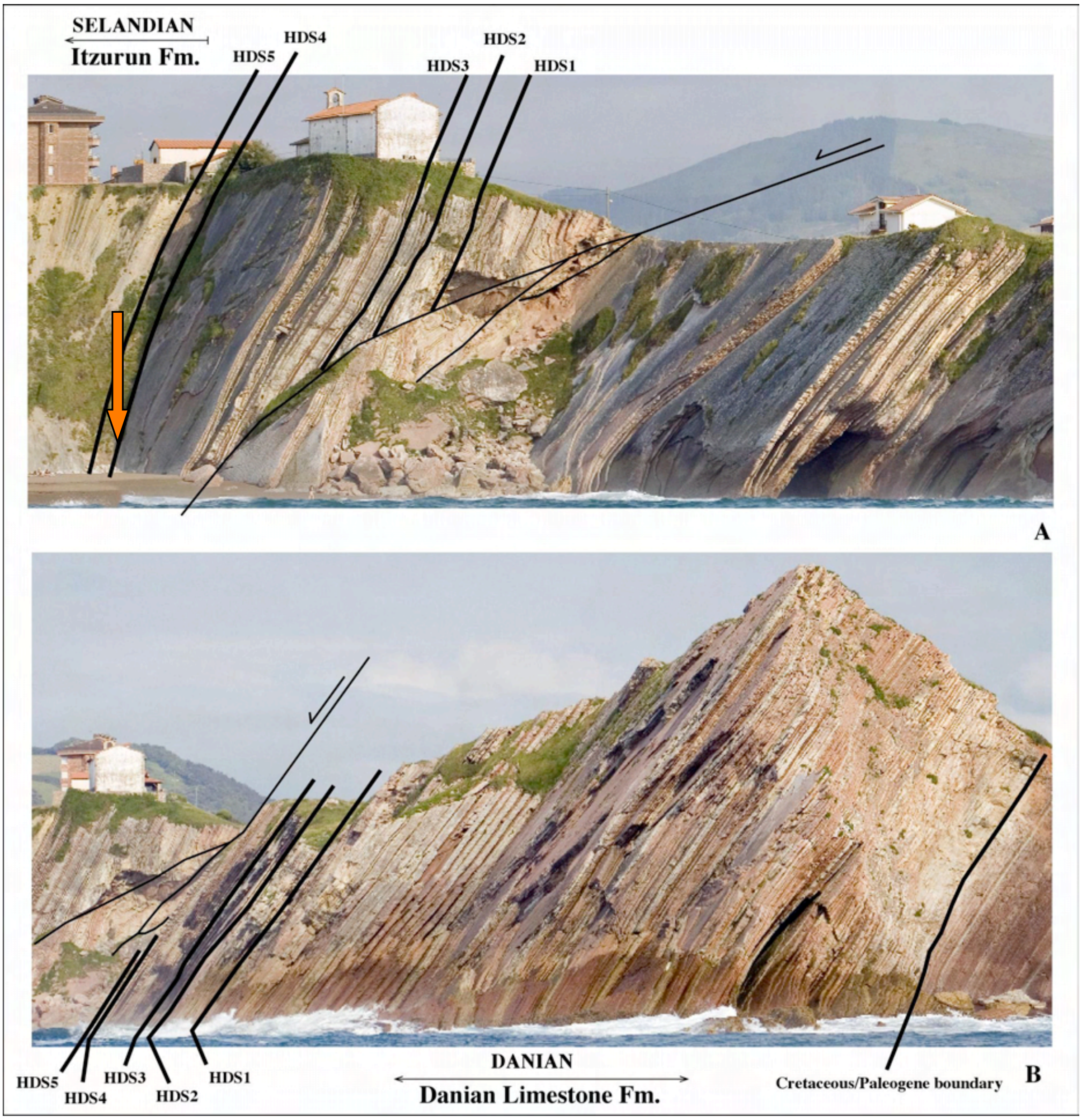
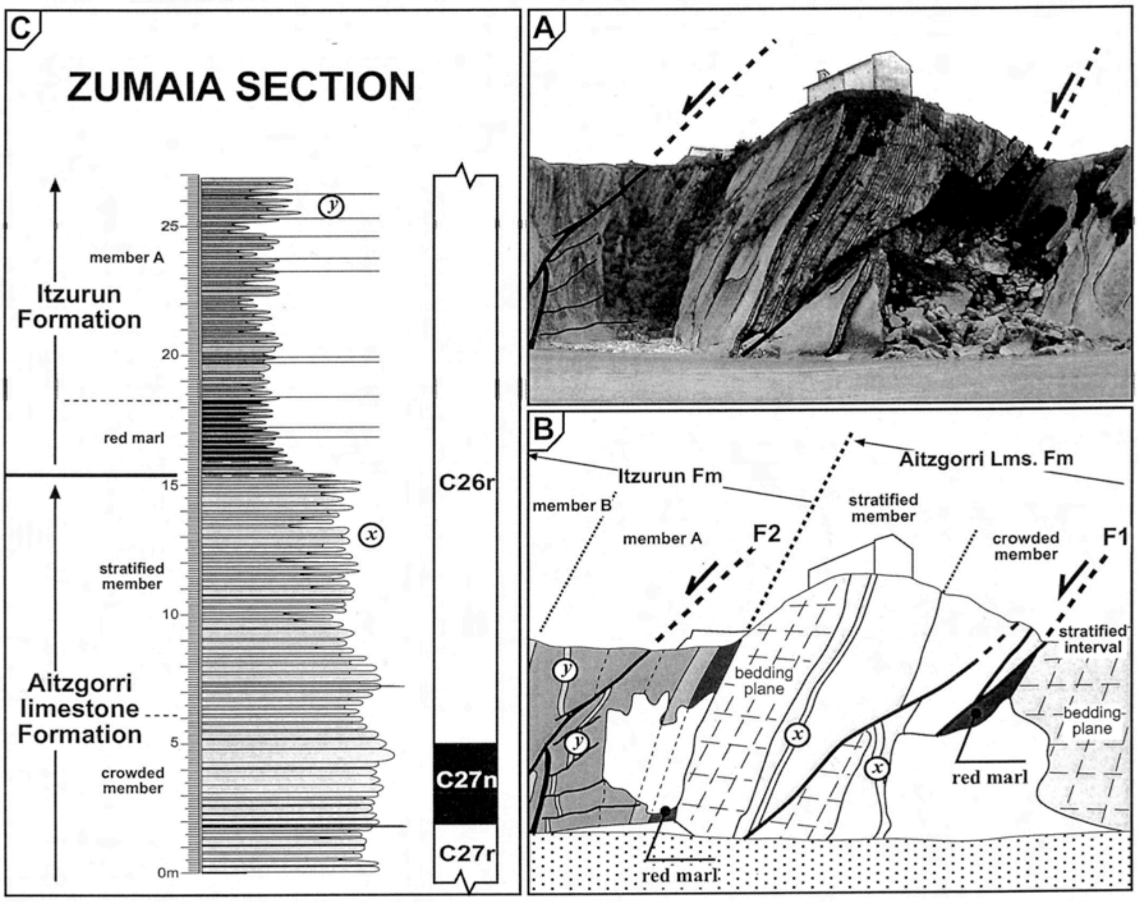

SELANDIAN
Itzurun Fm.
HDS5
HDS4
HDS3
HDS2
HDS1
A
HDS5
HDS4
HDS3
HDS2
HDS1
DANIAN
Danian Limestone Fm.
Cretaceous/Paleogene boundary
B

Fig. 5



C
ZUMAIA SECTION
member A
Itzurun Formation
red marl
stratified member
Aitzgorri limestone Formation
crowded member
0m
5
10
15
20
25
C26r
C27n
C27r
A
B
Itzurun Fm
Aitzgorri Lms. Fm
member B
member A
stratified member
crowded member
F2
F1
stratified interval
bedding plane
bedding-plane
red marl
red marl

Fig. 6

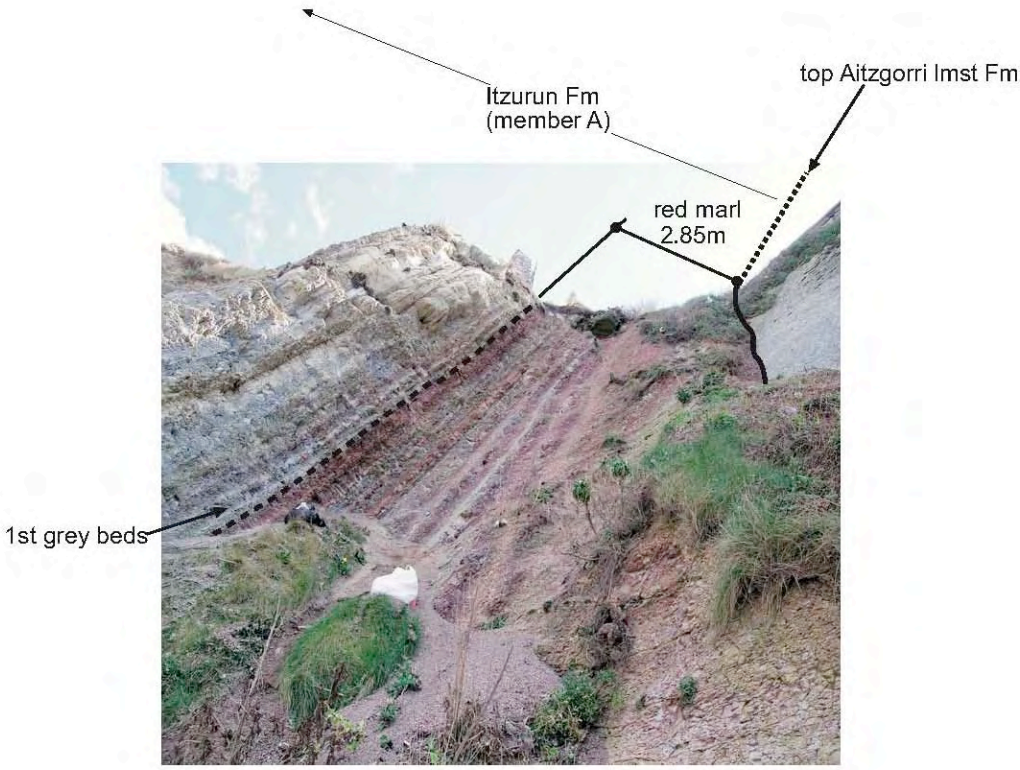

Itzurun Fm
(member A)
top Aitzgorri lmst Fm
red marl
2.85m
1st grey beds

Fig. 7

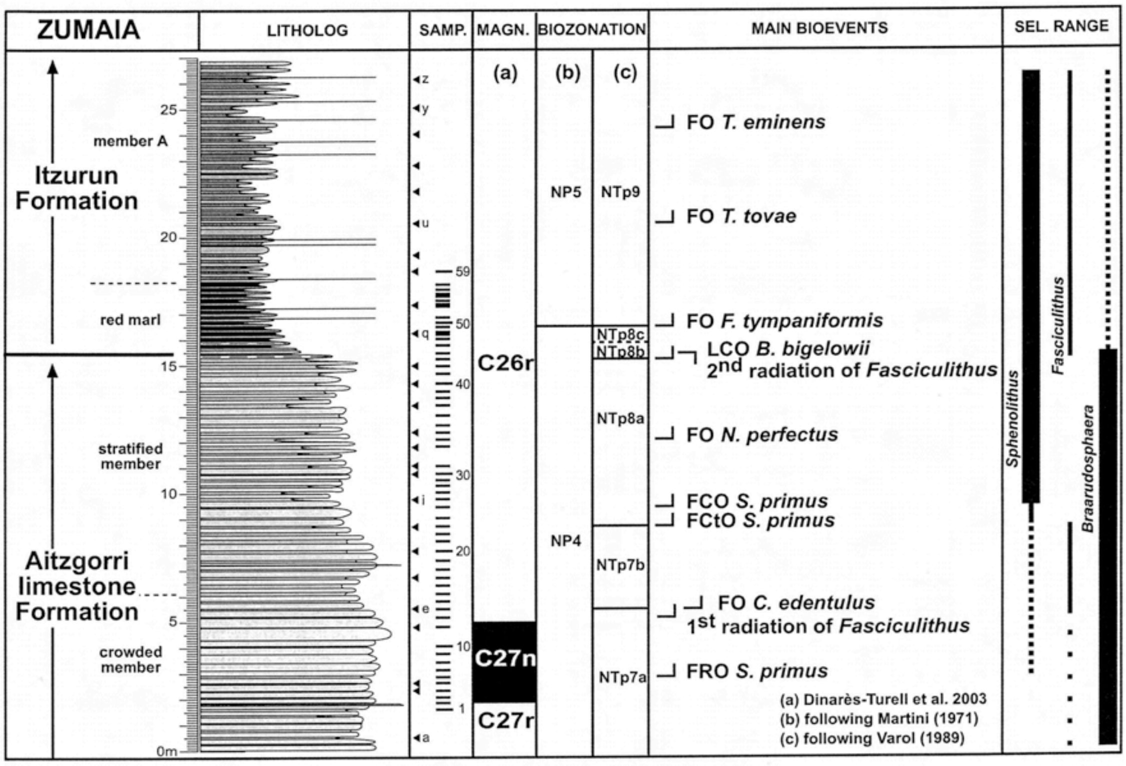

ZUMAIA
LITHOLOG
SAMP.
MAGN.
BIOZONATION
MAIN BIOEVENTS
SEL. RANGE
(a)
(b)
(c)
member A
Itzurun Formation
red marl
stratified member
Aitzgorri limestone Formation
crowded member
C26r
C27n
C27r
NP5
NP4
NTp9
NTp8c
NTp8b
NTp8a
NTp7b
NTp7a
FO T. eminens
FO T. tovae
FO F. tympaniformis
LCO B. bigelowii
2nd radiation of Fasciculithus
FO N. perfectus
FCO S. primus
FCtO S. primus
FO C. edentulus
1st radiation of Fasciculithus
FRO S. primus
(a) Dinarès-Turell et al. 2003
(b) following Martini (1971)
(c) following Varol (1989)
Sphenolithus
Fasciculithus
Braarudosphaera

Fig. 8

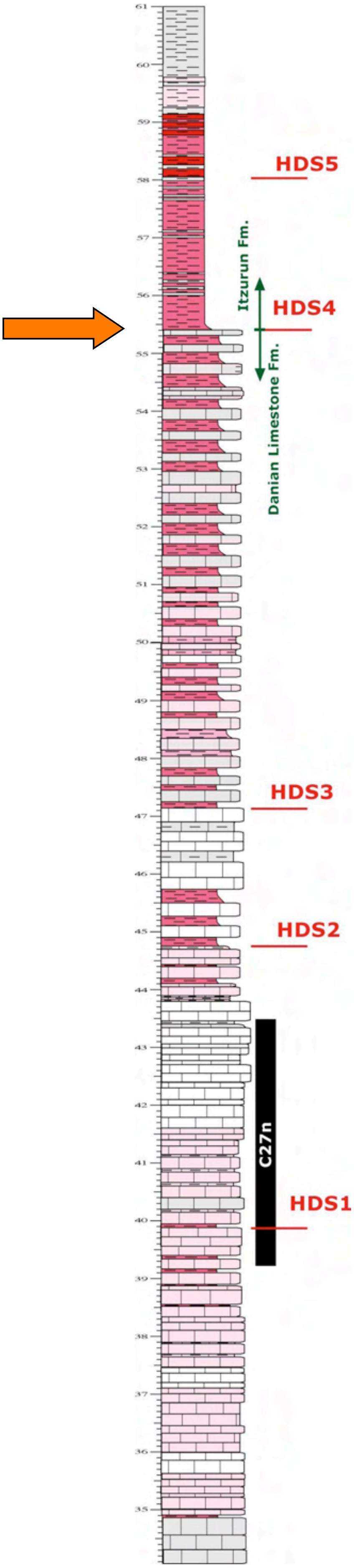

61
60
59
58
57
56
55
54
53
52
51
50
49
48
47
46
45
44
43
42
41
40
39
38
37
36
35
HDS5
Itzurun Fm.
HDS4
Danian Limestone Fm.
HDS3
HDS2
C27n
HDS1

Fig. 9

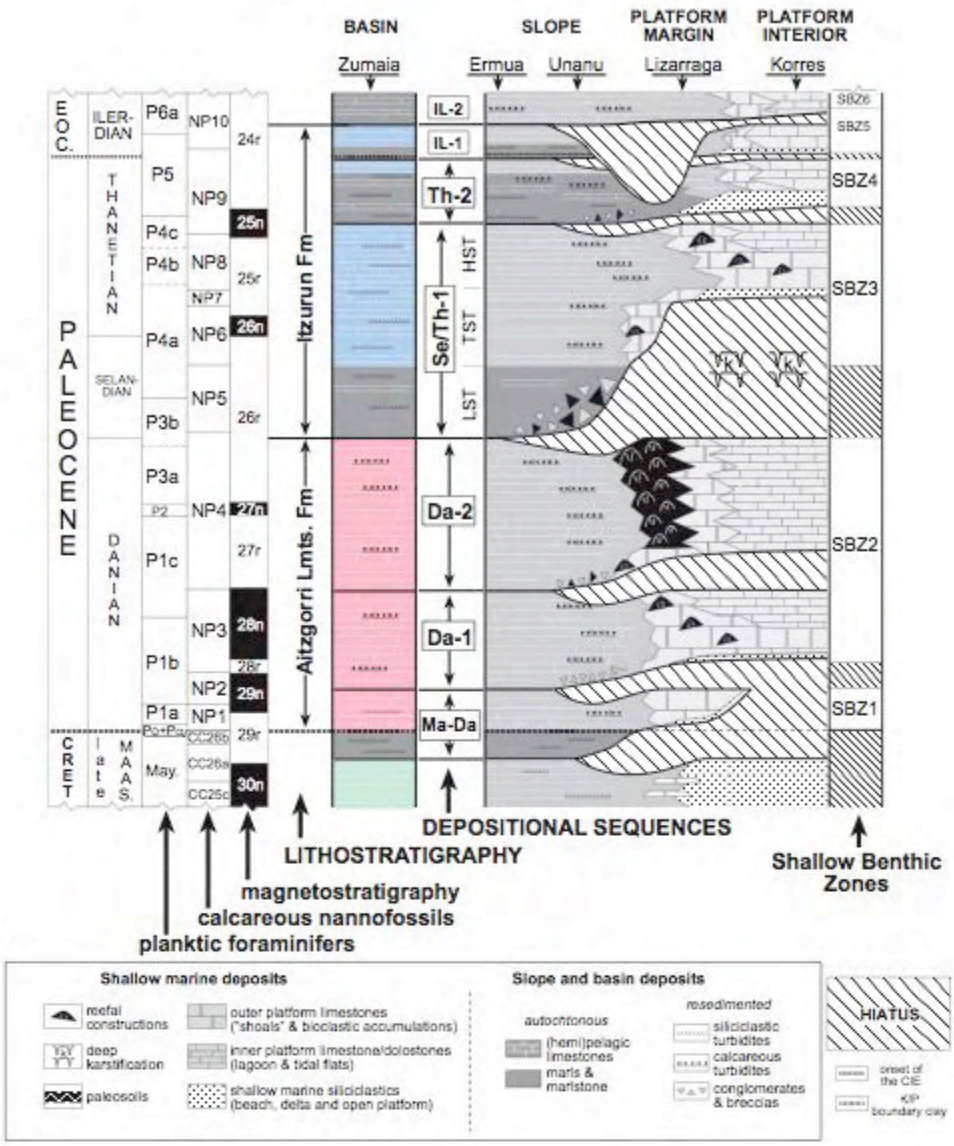

BASIN
SLOPE
PLATFORM MARGIN
PLATFORM INTERIOR
Zumaia
Ermua
Unanu
Lizarraga
Korres
EOC.
ILER-DIAN
THANETIAN
SELAN-DIAN
DANIAN
PALEOCENE
CRET
late
MAAS.
P6a
P5
P4c
P4b
P4a
P3b
P3a
P2
P1c
P1b
P1a
Po+Pa
May.
NP10
NP9
NP8
NP7
NP6
NP5
NP4
NP3
NP2
NP1
CC26b
CC26a
CC25c
24r
25n
25r
26n
26r
27n
27r
28n
28r
29n
29r
30n
Itzurun Fm
Aitzgorri Lmts. Fm
IL-2
IL-1
Th-2
Se/Th-1
HST
TST
LST
Da-2
Da-1
Ma-Da
SBZ6
SBZ5
SBZ4
SBZ3
SBZ2
SBZ1
DEPOSITIONAL SEQUENCES
LITHOSTRATIGRAPHY
magnetostratigraphy
calcareous nannofossils
planktic foraminifers
Shallow Benthic Zones
Shallow marine deposits
reefal constructions
deep karstification
paleosoils
outer platform limestones ("shoals" & bioclastic accumulations)
inner platform limestone/dolostones (lagoon & tidal flats)
shallow marine siliciclastics (beach, delta and open platform)
Slope and basin deposits
autochtonous
(hemi)pelagic limestones
marls & marlstone
resedimented
siliciclastic turbidites
calcareous turbidites
conglomerates & breccias
HIATUS
onset of the CIE
K/P boundary clay

Fig. 10

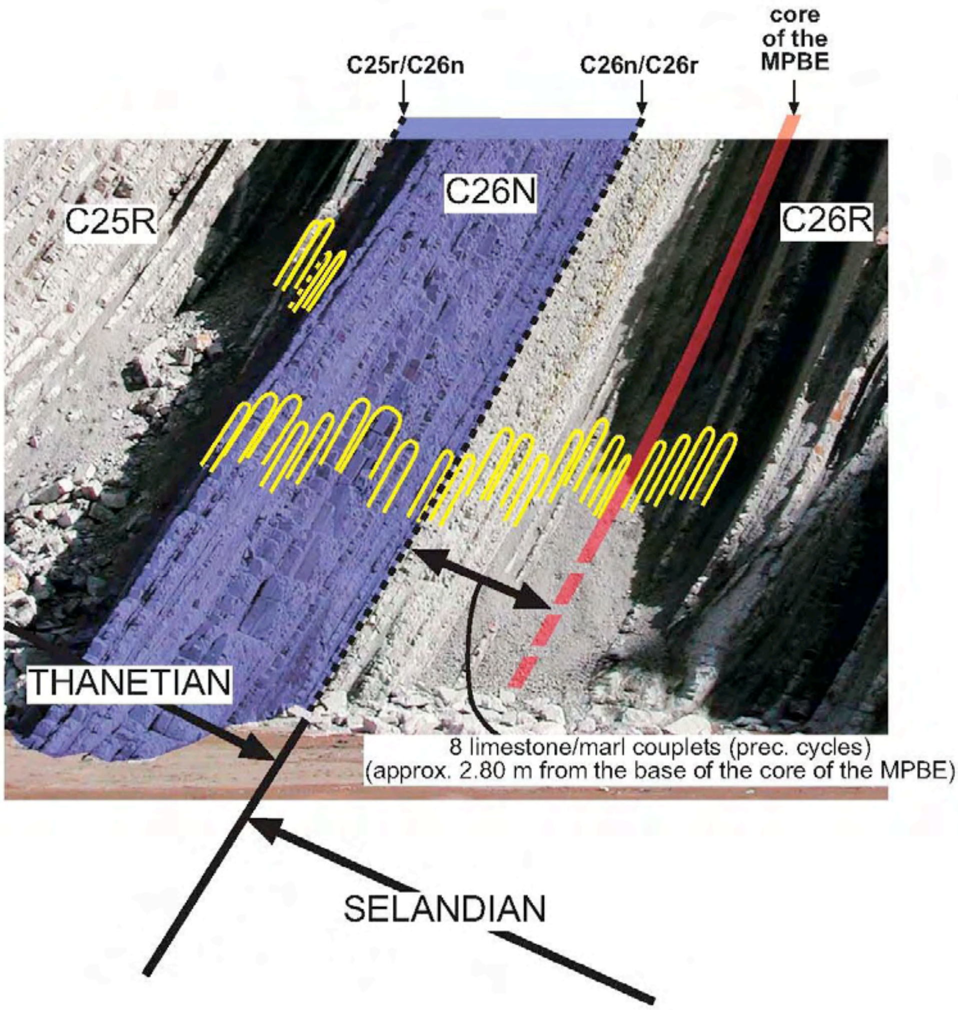

core
of the
MPBE
C25r/C26n
C26n/C26r
C25R
C26N
C26R
THANETIAN
8 limestone/marl couplets (prec. cycles)
(approx. 2.80 m from the base of the core of the MPBE)
SELANDIAN

Fig. 11

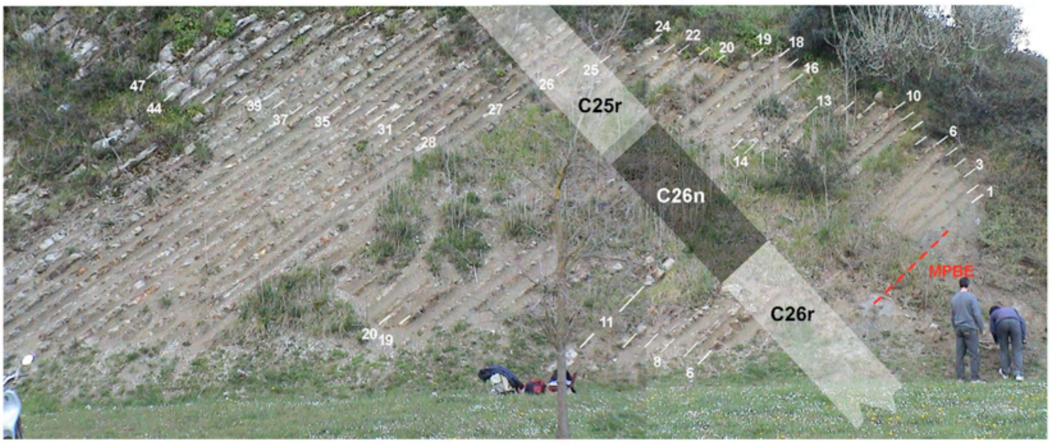
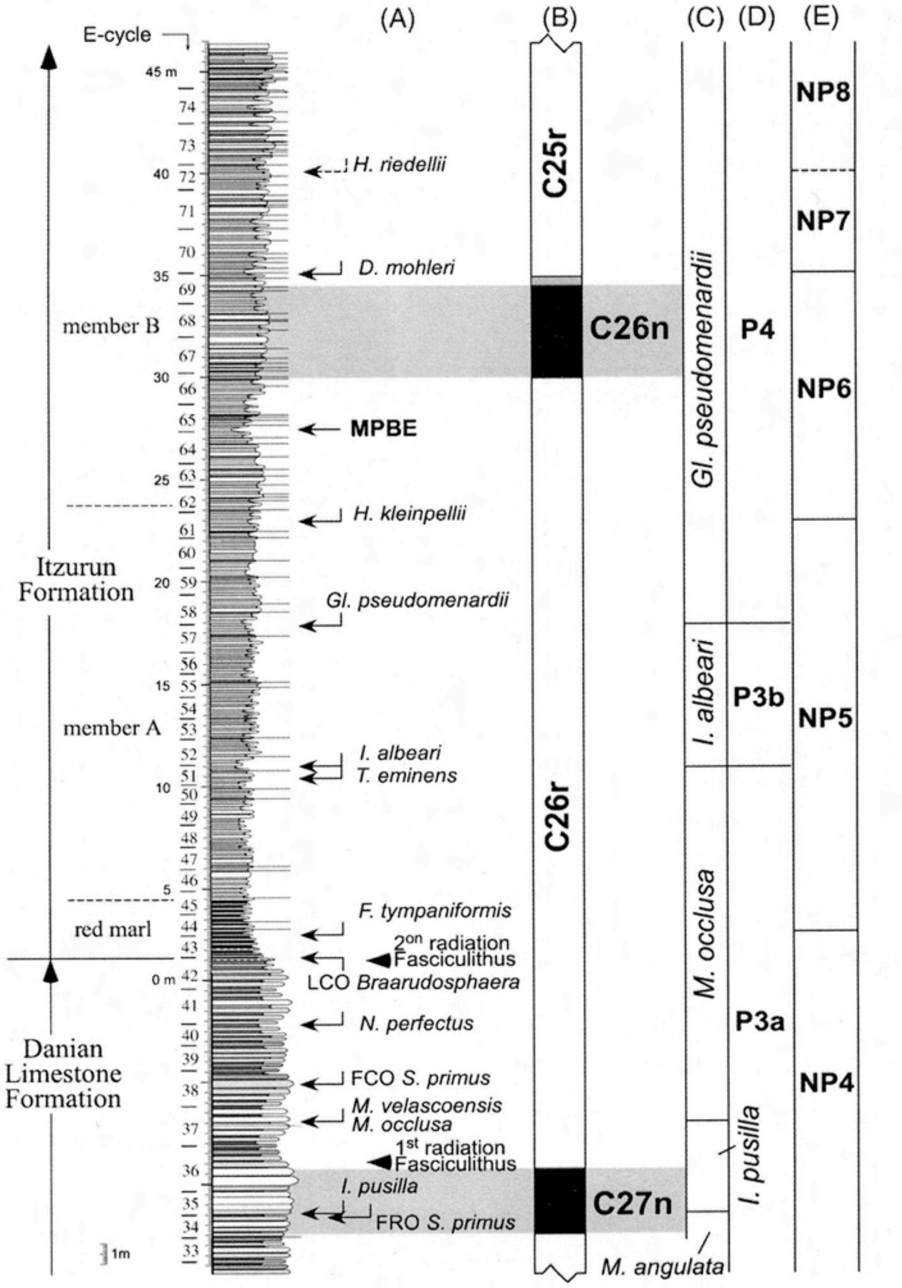
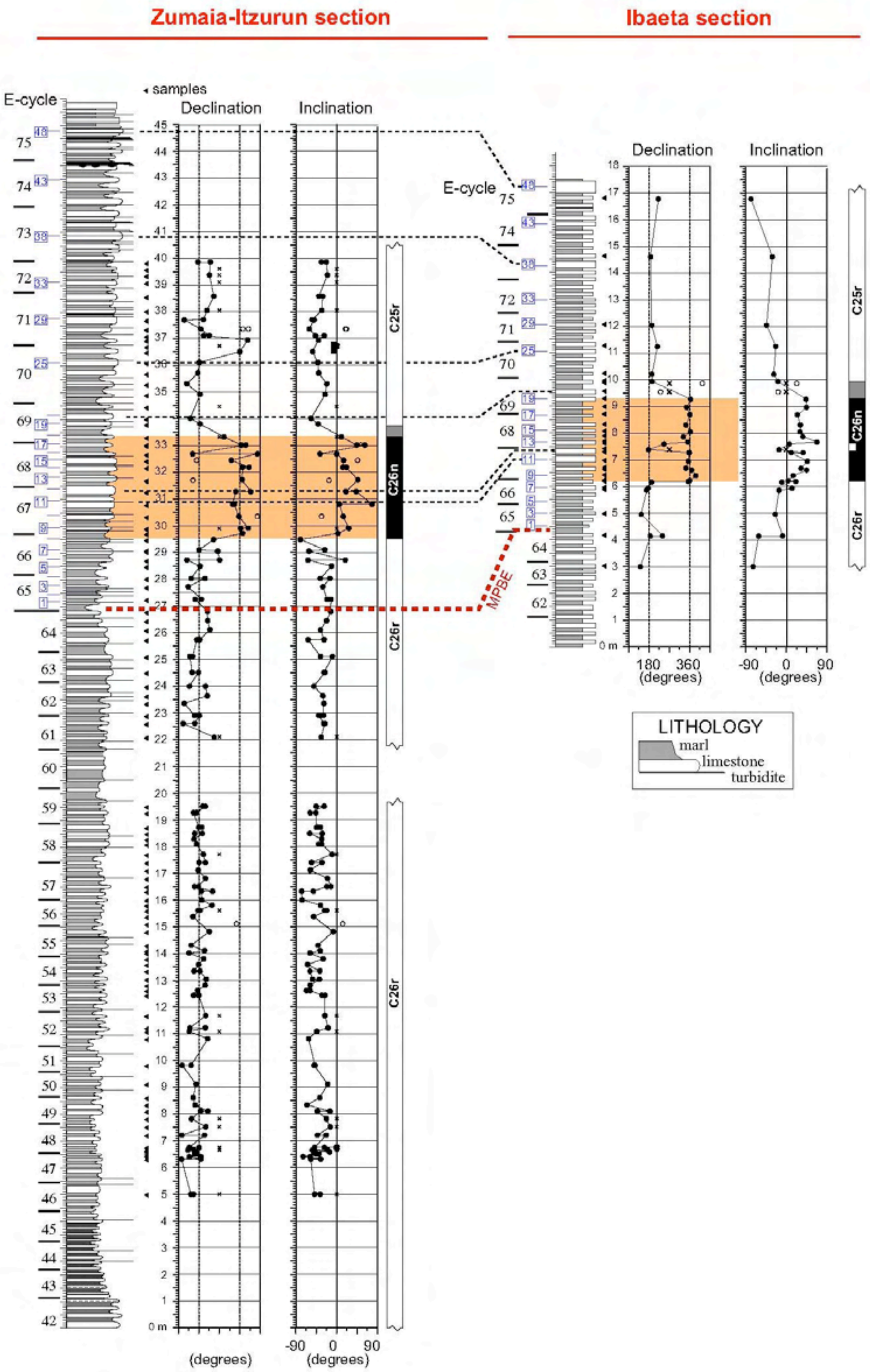

47
44
39
37
35
31
28
27
26
25
24
22
20
19
18
16
13
10
6
3
1
14
C25r
C26n
C26r
MPBE
20
19
11
8
5

Fig. 12



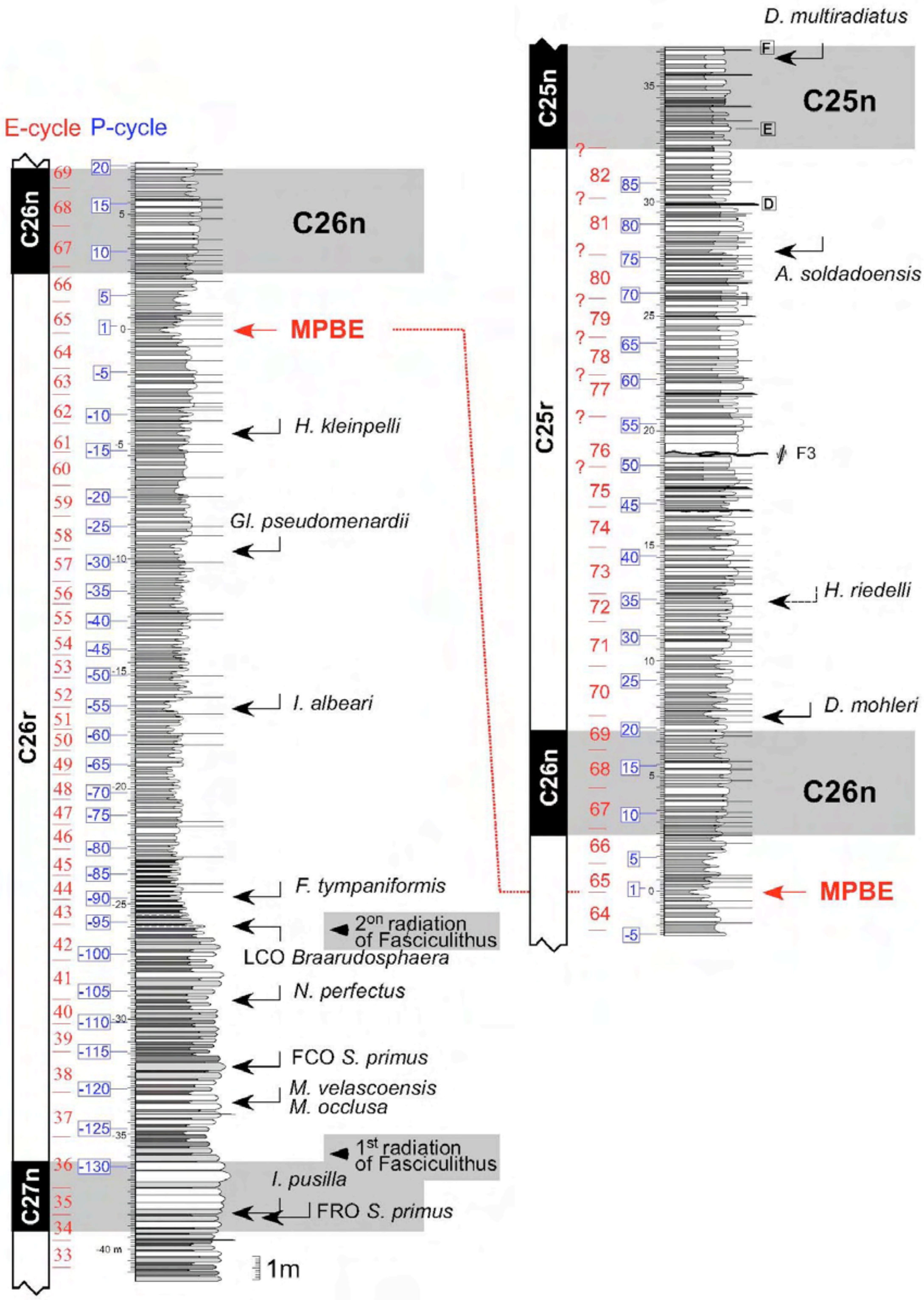
E-cycle
(A)
(B)
(C)
(D)
(E)
45 m
40
35
30
25
20
15
10
5
0 m
member B
Itzurun Formation
member A
red marl
Danian Limestone Formation
1m
H. riedellii
D. mohleri
MPBE
H. kleinpellii
Gl. pseudomenardii
I. albeari
T. eminens
F. tympaniformis
2on radiation Fasciculithus
LCO Braarudosphaera
N. perfectus
FCO S. primus
M. velascoensis
M. occlusa
1st radiation Fasciculithus
I. pusilla
FRO S. primus
C25r
C26n
C26r
C27n
Gl. pseudomenardii
I. albeari
M. occlusa
I. pusilla
M. angulata
P4
P3b
P3a
NP8
NP7
NP6
NP5
NP4

Fig. 13



Zumaia-Itzurun section
Ibaeta section
E-cycle
samples
Declination
Inclination
C25r
C26n
C26r
MPBE
LITHOLOGY
marl
limestone
turbidite
(degrees)

Fig. 14



E-cycle P-cycle
C26n
C26r
C27n
MPBE
H. kleinpelli
Gl. pseudomenardii
I. albeari
F. tympaniformis
2[nd] radiation of Fasciculithus
LCO Braarudosphaera
N. perfectus
FCO S. primus
M. velascoensis
M. occlusa
1[st] radiation of Fasciculithus
I. pusilla
FRO S. primus
1m
D. multiradiatus
C25n
C25r
A. soldadoensis
F3
H. riedelli
D. mohleri

Fig. 15

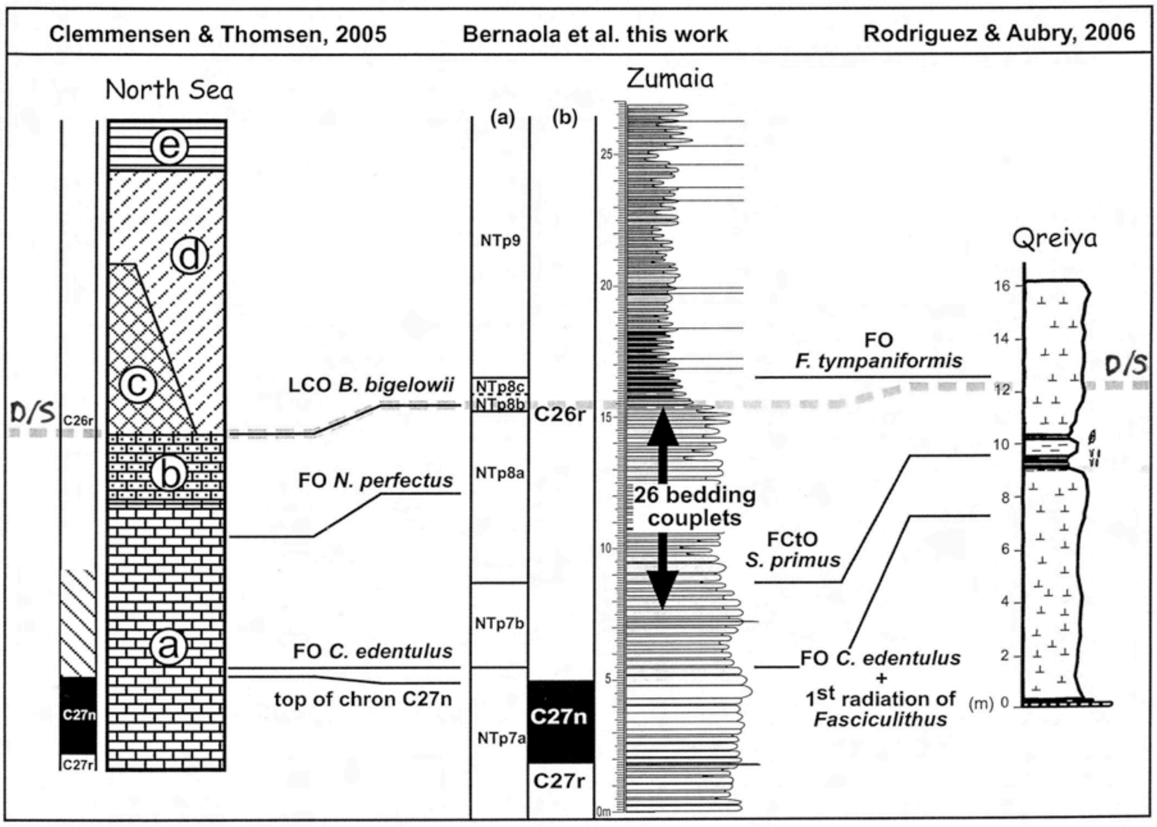

Clemmensen & Thomsen, 2005
Bernaola et al. this work
Rodriguez & Aubry, 2006
North Sea
Zumaia
Qreiya
(a)
(b)
D/S
C26r
C27n
C27r
NTp9
NTp8c
NTp8b
NTp8a
NTp7b
NTp7a
LCO B. bigelowii
FO N. perfectus
FO C. edentulus
top of chron C27n
26 bedding couplets
FO F. tympaniformis
FCtO S. primus
FO C. edentulus + 1st radiation of Fasciculithus
(m)

Fig. 16

Prerequisites to be fulfilled by a chronostratigraphic type-section	Zumaia
a) Exposure over an adequate thickness of sediments	The whole Paleocene is exposed
b) Continuous sedimentation	no gap detected
c) Rate of sedimentation	1,5 cm/kyr (Paleocene~150m)
d) Freedom from metamorphism and strong diagenetic alteration	YES
e) Abundance and diversity of well preserved fossils	YES
f) Freedom from vertical facies changes	NO
g) Favorable facies for long range biostratigraphic correlation	Tethys YES Atlantic Ocean YES North Sea /type area YES
h) Amenability to radiometric dating	We don't know, but there is the possibility to absolute dating with cyclostratigraphy
i) Amenability to magnetostratigraphy	YES (Dinares-Turell et al, 2003; in press)
j) Amenability to chemostratigraphy	YES
k) Accessibility	Excellent
l) Free access	Yes, the institutions and the Geologic Interpretation Center of Zumaia are willing to collaborate
m) Permanent preservation of the site	Yes, the institutions and the Geologic Interpretation Center of Zumaia will preserve the site

Fig. 17