doi: 10.1111/j.1365-3121.2007.00784.x

Foraminiferal and $\delta^{13}C$ isotopic event-stratigraphy across the Danian–Selandian transition at Zumaya (northern Spain): chronostratigraphic implications

I. Arenillas,[1] E. Molina,[1] S. Ortiz[1] and B. Schmitz[2]

[1]*Departamento de Ciencias de la Tierra, Universidad de Zaragoza, E-50009 Zaragoza, Spain;* [2]*Department of Geology, University of Lund, SE-22362 Lund, Sweden*

ABSTRACT

The Zumaya section, northern Spain, is a suitable candidate to define the Global Stratotype Section and Point for the base of the Selandian Stage (Palaeocene) because of its excellent accessibility, exposure and stratigraphic continuity. Uncertainties exist, however, with regard to the stratigraphic horizon where to place the Danian/Selandian (D/S) boundary. Five potential stratigraphic horizons (HDS1 to HDS5) to define the D/S boundary have been identified at Zumaya, based on integrated stratigraphic studies that include quantitative planktic and benthic foraminiferal results, as well as $\delta^{13}C$ isotopic and lithological data. Two of these horizons (HDS2 and HDS4) placed in Zone C26r appear to have particularly good potential for serving as the D/S boundary marker, because they may represent significant global palaeoceanographic, palaeoclimatic and eustatic events.

Terra Nova, 20, 38–44, 2008

Introduction

An international working group of the International Subcommission on Palaeogene Stratigraphy is searching for a suitable section to define the Global boundary Stratotype Section and Point (GSSP) for the base of Selandian (Schmitz, 1994; Schmitz *et al.*, 1998). The Danian/Selandian (D/S) boundary must be defined in a well-documented continuous stratigraphic section for the stability of the Geological Time Scale. According to Remane *et al.* (1996), the boundary level must be chosen within a series of successive events, enabling good reliable approximate correlation in the absence of the primary marker.

Rosenkrantz (1924) defined the Selandian Stage on the eastern Sjaelland (near Copenhagen, Denmark) on the basis of a succession composed of conglomerates, greensands, marls, and clays that unconformably overlie the Danian limestones (Perch-Nielsen and Hansen, 1981; Berggren, 1994; Luterbacher *et al.*, 2004). The contact between the Danian and Selandian in Denmark is marked by a regional unconformity, characterized by a major lithological shift from greyish white, oxic limestone/chalk of the Danskekalk Fm., upper Danian, to suboxic, glauconitic green sand of the Lellinge Greensand Fm., lower Selandian, overlain by grey marl and clay of the Kerteminde Marl Fm., middle Selandian. This unconformity was correlated with the sequence boundary between cycles TA 1.3 and TA 1.4 (Hardenbol *et al.*, 1998) and it may have resulted from an eustatic sea-level fall (Haq *et al.*, 1988; Clemmensen and Thomsen, 2005).

The D/S boundary was correlated with the NP4/NP5 biozonal boundary of calcareous nannofossils (Perch-Nielsen and Hansen, 1981; Thomsen, 1994; Schmitz *et al.*, 1998). By convention, the D/S boundary was placed at the P2/P3 biozonal boundary of planktic foraminifera (Hansen, 1968; Berggren, 1994; Berggren *et al.*, 1995; Steurbaut *et al.*, 2000). Nevertheless, other interesting biohorizons have been identified across the Danian–Selandian (D–S) transition and proposed as potential D/S boundary levels. A *Morozovella* acme-horizon (MAH) at the lower part of P3 Zone by Berggren *et al.* (1995) was also proposed as a potential D/S boundary in the Caravaca (Spain) and Sidi Naseur (Tunisia) sections (Arenillas, 1996; Arenillas and Molina, 1997). An excursion of benthic foraminifera *Neoeponides duwi* assemblages (*N. duwi* event) in the lower part of P3 Biozone was identified in Egypt and Jordan, and related to a sea-level fall at the D/S boundary (Speijer, 2003).

The Zumaya section (northern Spain) is an excellent candidate to define the GSSP for the base of the Selandian Stage (Schmitz *et al.*, 1998; Bernaola *et al.*, 2006). It provides a link between the Danish sections and the expanded Tethyan sections in Egypt, Israel, Tunisia and southern Spain (Schmitz *et al.*, 1998). The aim of this study was the planktic and benthic foraminiferal and $\delta^{13}C$ isotopic event-stratigraphic analysis of the Zumaya section to identify potential (bio-) horizons where to place the D/S boundary and define its GSSP.

Material and methods

The Zumaya section (42°18.00'N/2°15.30'W) is an excellent outcrop located to the northwest of the village of Zumaya (Basque Country, northern Spain). The Palaeocene sediments extend from the Aitzgorri headland (Cretaceous/Palaeogene) to the access of the San Telmo or Itzurun beach (Palaeocene/Eocene), and the D–S transition occurs along the cliffs of the beach (Fig. 1). The D–S succession at Zumaya spans the upper part of the Danian Limestone Formation and the lower part of the Itzurun Formation

Correspondence: Ignacio Arenillas, Departamento de Ciencias de la Tierra (Palaeontología), Universidad de Zaragoza, 50009 Zaragoza, Spain. Tel.: +34 976 762 475; fax: +34 976 761 106; e-mail: ias@unizar.es

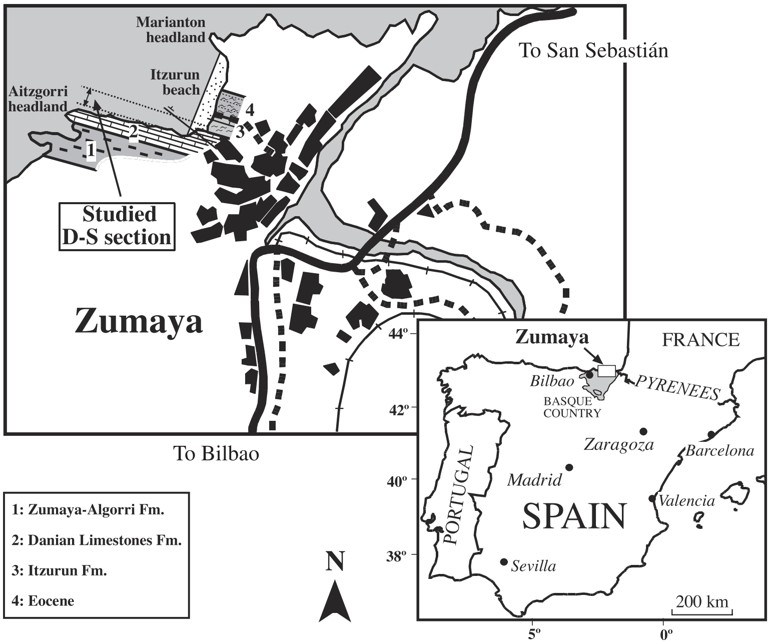

Fig. 1 Geographical and geological location of the Zumaya section (Norhern Spain).

(Apellániz *et al*., 1983; Baceta *et al*., 2004). A prominent lithological shift occurs between Danian Limestone and Itzurun Fms, about 56 m above the Cretaceous/Palaeogene boundary at Zumaya, from greyish limestone-reddish marly limestone couplets to red marls.

Thirty-six samples across the critical D–S succession were collected at Zumaya for micropalaeontological analysis at about 1 m spacing, and seventy for isotopic analysis at 0.25–0.5 m spacing. The studied stratigraphic interval spans the uppermost 20 m of the Danian Limestone Fm. and the lowermost 8 m of the Itzurun Fm. The micropalaeontological samples were taken preferably in marly beds. These samples were processed using the standard disaggregating technique employing diluted H_2O_2. The remaining more lithified samples were processed using a disaggregation technique with a solution of 80% acetic acid. All samples were sieved into 63–106 μm and ≥106 μm size fractions. For the quantitative studies, a representative split of more than 300 planktic foraminiferal specimens from ≥106 μm size fraction was picked from each sample, using an Otto splitter. The analyses for stable carbon isotopic composition ($\delta^{13}C$) were studied on whole-rock samples. These analyses were carried out with a VG Prism Series II mass spectrometer attached to an Isocarb automated carbonate preparation system. The values are expressed as per mil differences with respect to the PDB standard.

Palaeobathymetry

The D–S transition at the Zumaya section contains abundant organically cemented (*Hyperammina, Saccammina*, *Rhabdammina*, *Recurvoides*, *Trochamminoides Paratrochamminoides*) and calcareous-cemented (*Arenobulimina*, *Clavulinoides*, *Dorothia*, *Marssonella*, *Remesella*) agglutinated foraminifera. They are flysch-type taxa typical of relatively quiet terrigeneous environments, suggesting a minimum water depth of lower-middle bathyal. Based on agglutinated foraminifera, Kaminski and Gradstein (2005) included the Zumaya section in the Slope-type biofacies of Kuhnt *et al.* (1989), corresponding to deep-water and low-middle latitude agglutinated foraminifera.

Benthic foraminiferal assemblages are also characterized by taxa typical of deep-bathyal environment, such as *Bulimina trinitatensis*, *Cibicidoides hyphalus*, *Cibicidoides velascoensis*, *Gyroidinoides globosus*, *Stensioeina beccariiformis*, *Nuttallides truempyi*, *Osangularia velascoensis*, *Nuttallinela florealis*, *Gaudyrina pyramidata* or *Spiroplectammina spectabilis*. Most of them are typical of the Velasco-type fauna (Berggren and Aubert, 1975). These data suggest that the D–S sediments at the Zumaya section were deposited in a middle-lower slope (900–1100 m depth), in agreement with Pujalte *et al.* (1995) and Kuhnt and Kaminski (1997).

The lithological shift from the grey-pink limestones of the upper part of the Danian Limestone Fm. to the red-marls of the basal part of the Itzurun Fm. at Zumaya has been correlated with a prominent initial Selandian sea-level fall and an unconformity in the Danish stratotype area (Pujalte *et al*., 1995; Baceta *et al*., 2004). Nevertheless, benthic foraminiferal data do not indicate any sea-level change across the lithological shift. This apparent contradiction may be because of the palaeobathymetry of the Zumaya section being too deep that the benthic foraminiferal assemblages were affected (Ortiz, 2006).

Biostratigraphy

Figure 2 shows planktic foraminiferal zonations proposed for the D–S transition in lower and middle latitudes. The D–S transition was initially divided into the *Acarinina uncinata*, *Morozovella angulata* and *Igorina pusilla* Zones (Bolli, 1966; Toumarkine and Luterbacher, 1985; Canudo and Molina, 1992); the first occurrence data (FODs) of these taxa are the index-biohorizons used to place the lower boundaries of these biozones, and the FOD of *Luterbacheria pseudomenardii* is the upper boundary of the *I. pusilla* Zone. The P-zonation by Blow (1979) included two biozones: P2, equivalent to the *A. uncinata* Zone, and P3, equivalent to the *M. angulata* and *I. pusilla* Zones. Berggren *et al*. (1995) and Berggren and Pearson (2005) subdivided the P3 into two subzones: P3a and P3b, being the FOD of *Igorina albeari* the P3a/P3b boundary. Arenillas and Molina (1995, 1997) used the FODs of *Morozovella crosswicksensis* and *Igorina albeari* to subdivide the P3 by Berggren *et al*. (1995) into three biozones: *M. angulata, M. crosswicksensis* and *I. albeari* Zones. As Olsson *et al*. (1999) considered *M. crosswicksensis*

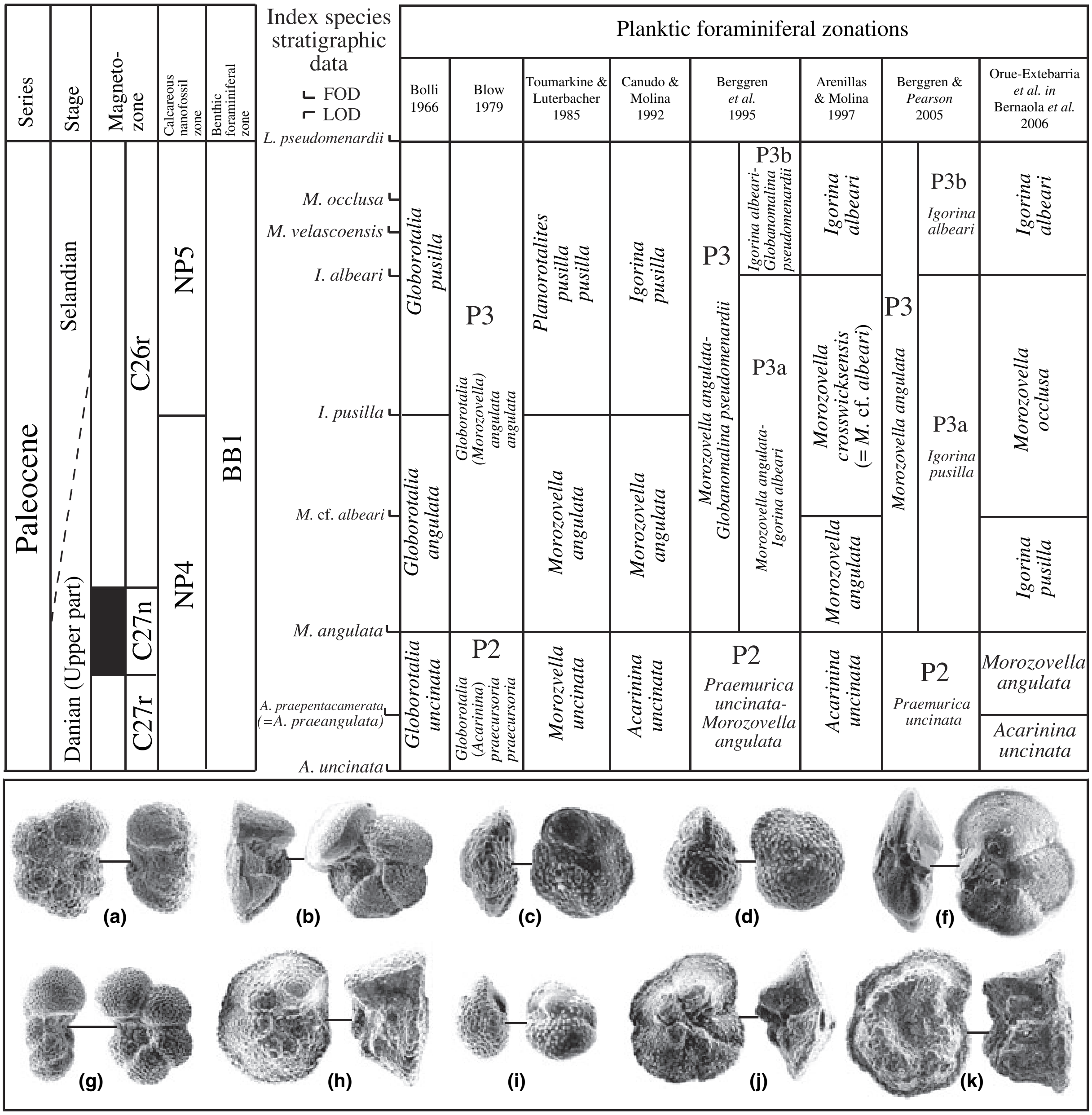

Fig. 2 Comparison of the planktic foraminiferal zonations proposed for the D–S transition in lower and middle latitudes. Significant planktic foraminiferal species in D–S biostratigraphy: (a) *Acarinina uncinata*; (b) *Morozovella angulata*; (c) *Morozovella* cf. *albeari* [*M. crosswicksensis* according to Blow (1979) and Arenillas (1996)]; (d) *Igorina albeari*; (f) *Luterbacheria pseudomenardii*; (g) *Acarinina trinidadensis*; (h) *Morozovella conicontruncata*; (i) *Igorina pusilla* [according to Toumarkine and Luterbacher (1985) and Arenillas (1996)]; (j) *Morozovella occlusa*; (k) *Morozovella velascoensis*.

to be a junior synonymous of *Morozovella occlusa*, the lowermost Selandian *crosswicksensis*-type specimens according to Blow (1979) and Arenillas (1996) are considered as *Morozovella* cf. *albeari* in Figs 2–4.

Figure 3 shows the stratigraphic positions at Zumaya of the biozones proposed by some of the above-mentioned authors. Previous correlations between biozones and magnetostratigraphic data from Zumaya were shown by Molina and Arenillas (1998) and Arenillas and Molina (2000), but the Fig. 3 shows a new correlation with the updated magnetostratigraphic data by Dinarès-Turell *et al.* (2003) based on lithostratigraphic criteria. Several index-species have taxonomic-type problems and their biostratigraphic distribution is, therefore, debatable (Arenillas, 1996; Olsson *et al.*, 1999; Bernaola *et al.*, 2006). As there are taxonomic problems still unsolved, the quantitative distribution (abundance curves) of planktic -and benthic- foraminiferal groups (genera and assemblages) is probably more significant for identifying biohorizons where to place the D⁄S boundary.

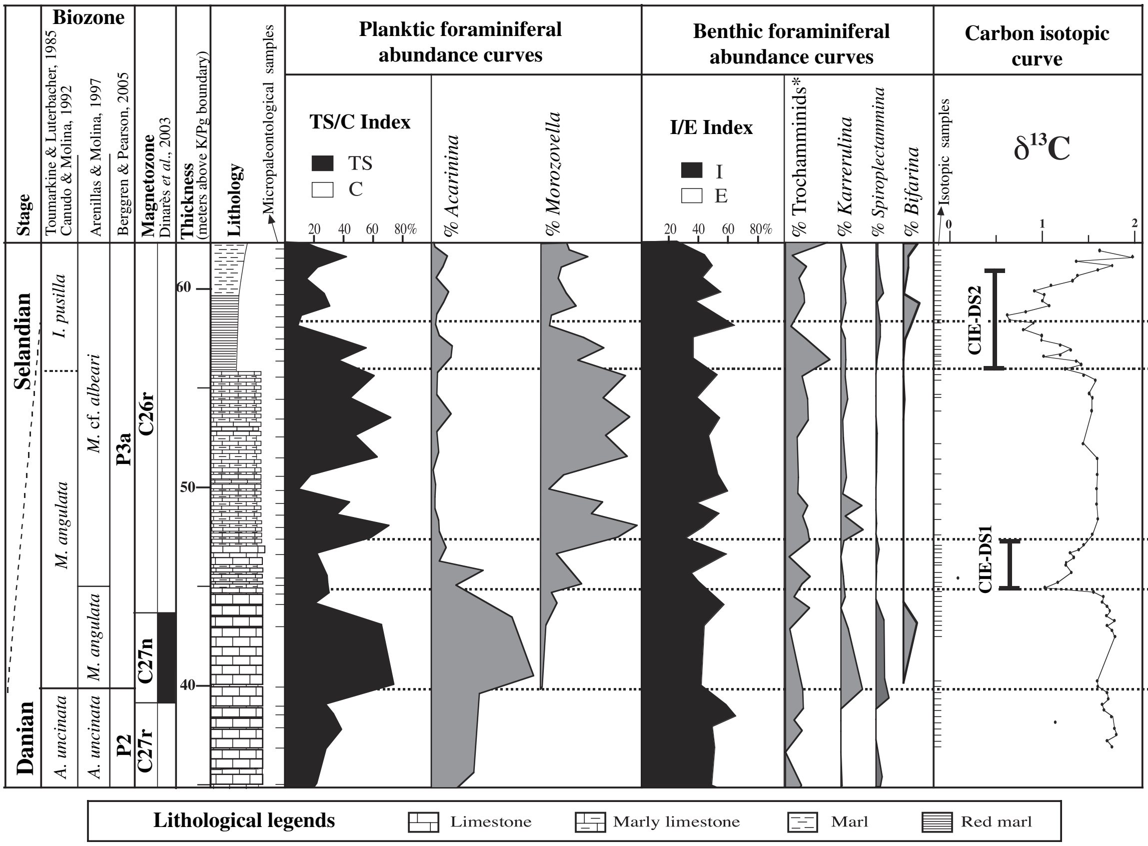

Fig. 3 Planktic and benthic foraminiferal quantitative distribution (abundance curve) and $\delta^{13}C$ isotopic curve across the Danian–Selandian transition at the Zumaya section. TS, % tropical–subtropical planktic foraminifera; C, % cosmopolitan planktic foraminifera; I, % infaunal benthic foraminifera; E, % epifaunal benthic foraminifera. The index TS/C is the percentage of specimens of tropical/subtropical planktic foraminifera with respect to the total, i.e. TS/C = 100 × [TS/(TS + C)]. Its turnovers approximately reflect the variations of the temperature at the ocean surface, which is linked to the local climatic temperature. The I/E index is the percentage of specimens of infaunal benthic foraminifera with respect to the total, i.e. I/E = 100 × [I/(I + E)]. Its turnovers in the D–S stratigraphical record approximately reflect the variations of some palaeoenvironmental parameters, such as the nutrient supply to the sea-floor and the bottom sea-water oxygenation.

Foraminiferal and isotopic event-stratigraphy

A quantitative analysis of the planktic and benthic foraminiferal assemblages across the D–S transition allows the identification of significant quantitative-biohorizons that may correspond to potential bioevents for defining the D/S boundary. Several planktic and benthic foraminiferal groups have been quantitatively analysed at Zumaya. The D–S planktic foraminiferal genera can be grouped into tropical-subtropical (TS, *Praemurica, Morozovella, Acarinina* and *Igorina*) and cosmopolitan (C, *Parasubbotina*, *Subbotina*, *Eoglobigerina*, *Globanomalina*, *Luterbacheria* and *Chiloguembelina*), according to Premoli Silva and Boersma (1988) and Olsson *et al.* (1999) among others. The D–S benthic foraminifera can be grouped into infaunal (I, *Clavulinoides*, *Karrerulina*, *Bifarina*, *Gyroidinoides beisseli*) and epifaunal (E, *Recurvoides*, *Osangularia*, *Stensioeina beccariiformis*, *Nuttallides trümpyi*) ecomorphotypes according to Corliss and Chen (1988), and Jones and Charnock (1985) among others. These groups are mainly genera and assemblages whose quantitative distributions allow palaeoceanographic and palaeoclimatic variations to be inferred.

Figure 3 shows turnovers of planktic (index TS/C) and benthic foraminiferal (index I/E) assemblages across the D–S transition at Zumaya, as well as the quantitative distribution (relative abundance) of planktic *Morozovella* and *Acarinina*, and benthic *Karrerulina, Bifarina, Spiroplectammina* and trochamminids. Figure 3 also shows the $\delta^{13}C$ isotopic curve across the D–S transition at Zumaya. Two carbon isotopic excursions (CIE) were identified at Zumaya: CIE-DS1 spans 2.5 m (from meter 45 to meter 47.5) and CIE-DS2 spans of about 5 m (from meter 56 to meter 66).

The analysis of the quantitative stratigraphic distribution (at marly beds) of planktic and benthic foraminiferal groups and the $\delta^{13}C$ stratigraphy (at limestone beds) has allowed us to identify five stratigraphic horizons at Zumaya corresponding to significant local events (Fig. 3):

1 HDS1 occurs at meter 40 (lower part of the C27n), is characterized by increases in *Acarinina* and *Karr-*

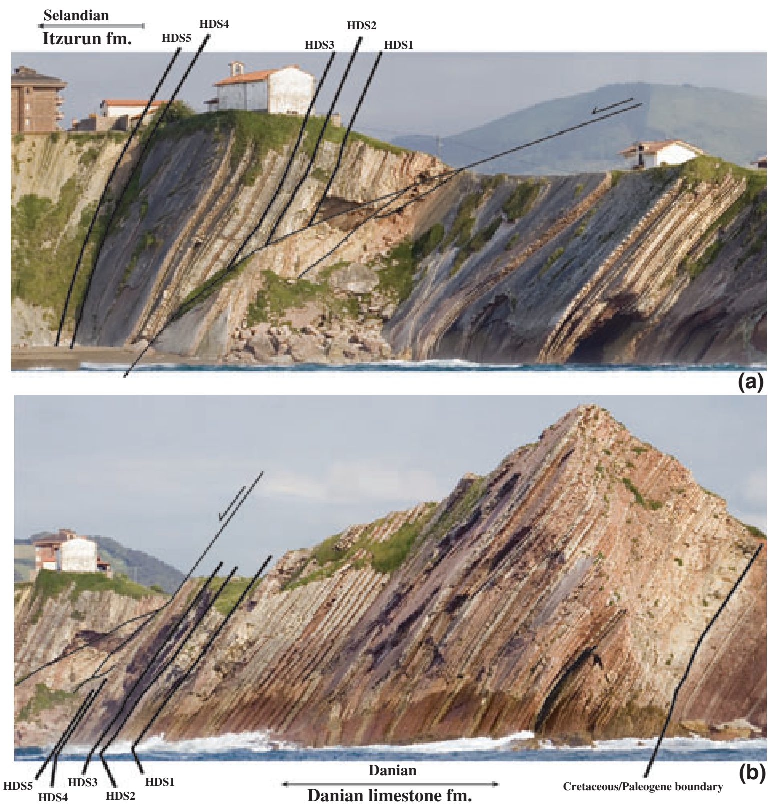

Fig. 4 Panoramic photographs of the Danian and Danian–Selandian transition at Zumaya. a: stratigraphical positions of the horizons HSD1 to HSD5 in the upper block of a normal fault that affects the D–S transition (the samples of grey and red marls of the Itzurun Fm. were taken here). b: stratigraphical positions of the Cretaceous/Palaeogene boundary and the horizons HSD1 to HSD5 in the lower block of the fault (the samples of pink-grey limestones and marls of the Danian Limestone Fm. were taken here).

erulina and *Spiroplectammina*, and corresponds to the lower boundary of the *Morozovella angulata* Zone; some authors usually place the D/S boundary at this biohorizon, i.e. at the P2/P3 biozonal boundary (Berggren, 1994; Berggren *et al.*, 1995; Steurbaut *et al.*, 2000).

2 HDS2 occurs at meter 45 (lower part of the C26r), is characterized by a negative $\delta^{13}C$ excursion (base of CIE-DS1) and an increase in *Morozovella* (MAH), and may correspond to the lower boundary of the *Morozovella* cf. *albeari* Zone.

3 HDS3 occurs at meter 47.5 (lower part of the C26r), is characterized by an increase in *Karrerulina* and maxima values in percentage of *Morozovella*, and coincides with a lithological shift from white limestone – greyish marly limestone couplets to pink or greyish limestone – reddish marly limestone couplets.

4 HDS4 occurs at meter 56 (middle part of the C26r), may correspond to the lower boundary of *Igorina pusilla* Zone, and is characterized by a prominent lithological shift (from grey limestone - reddish marl couplets to red marls of the depositional sequence boundary DS-P2/DS-P3), a negative $\delta^{13}C$ excursion (base of CIE-DS2), a slight decrease in *Morozovella*, and increases in trochaminids and *Spiroplectammina*.

5 HDS5 occurs at meter 58.5 (middle part of the C26r), is characterized by minimal $\delta^{13}C$ values in the CIE-DS2, a relevant lithological shift (from red marls to grey marls), minima values in percentage of *Morozovella* and maxima values in percentage of *Bifarina*.

The five stratigraphic horizons described above are potential candidate levels to define the D/S boundary at Zumaya. Nevertheless, these potential levels should be further studied to test whether they represent global events that can be used for worldwide correlation. HDS2 and HDS4 are probably the better horizons to place the D/S boundary at Zumaya, because they include multiparameter criteria, which may help in global chronocorrelation.

The slight increase in the TS/C index value at HSD2 is mainly caused by a significant increase in *Morozovella* (Fig. 3). This horizon coincides with the negative $\delta^{13}C$ excursion at the base of CIE-DS1, suggesting a decline in biological productivity, a sea level fall or the release of CH_4 from oceanic methane hydrates. Significant increases in *Morozovella* (MAH) in coincidence with the *M. angulata/M.* cf. *occlusa* zonal boundary have also been identified in Tethyan sections (Arenillas, 1996; Arenillas and Molina, 1997; Guasti *et al.*, 2006). Both stratigraphic markers (MAH and base of CIE-DS1) suggest a possible hyperthermal global event and episode, which mainly affected the ocean surface. Except for a slight decrease in the I/E index, no relevant change in the benthic foraminiferal assemblages has been identified. Nevertheless, it may correspond to the '*N. duwi* event' in the middle part of the calcareous nannofossil NP4 Biozone identified in Egypt and Jordan by Speijer (2003).

HDS4 coincides with a prominent lithological shift (from greyish limestone – reddish marly limestone couplets to red marls) that corresponds to the boundary between the Danian Limestone and Itzurun Fms. at Zumaya (Fig. 4). Scarce and dubious specimens of *I. pusilla* have been identified here, suggesting that the base of the *I. pusilla* Zone by Toumarkine and Luterbacher (1985) corresponds to the HDS4 at Zumaya. HDS4 may coincide with the calcareous nannofossil NP4/NP5 zonal boundary, although Schmitz *et al.* (1998) recognized the FOD of the index-species *Fasciculithus tympaniformis* 1 m above. The slight decreases in *Morozovella* and TS/C and I/E indices, and increases in trochaminids and *Spiroplectammina*, suggest an apparent decrease in the local climatic and surface oceanic temperature, and a possible increase in the bottom sea-water oxygenation. The second negative $\delta^{13}C$ excursion (base of CIE-DS2) suggests a significant decline in the local biological productivity or a sea level fall. As the sea level falls more, 12-C rich organic detritus from near shore environments affects the $\delta^{13}C$. The CIE-DS2 may also be caused by a release of CH_4 from oceanic methane hydrates, although this hypothesis seems to contradict the progressive decrease in *Morozovella* and TS/C index at Zumaya. HDS4 coincides with the depositional sequence boundary DS-P2/DS-P3 by Pujalte *et al.* (1995, 1998) and the boundary between the cycles 1.4/2.1 by Haq *et al.* (1988), related to a eustatic sea-level fall. For this reason, some authors relate this stratigraphic horizon to the relative sea-level fall at the base of the Selandian stratotype (base of the Lellinge Greensand Fm.) and propose to place the D/S boundary at this level of the Zumaya section (Arenillas, 1996; Schmitz *et al.*, 1997, 1998).

In conclusion, HDS2 in the lower part of C26r and HDS4 in the middle part of the C26r appear to be the best candidates as potential D/S boundary levels, because they may represent significant global events, which are easy to recognize and chronocorrelate in the stratigraphic record. Nevertheless, the identification and correlation of these horizons at other worldwide sections are necessary before choosing and deciding on the most appropriate criterion for definition of the D/S boundary.

Post-scriptum

At the recent meeting of the Palaeocene Working Group (Zumaya, Spain, June 2007), a decision was reached by unanimous (but informal) vote to place the D/S (GSSP) at the lithological boundary between the 'Danian Limestone' and the Itzurun Formation (~56m level) in the beach section at Zumaya, Spain. This is Horizon/Level HDS4 in this paper. This level is ~1.1 m below the FAD of the calcareous nannoplankton taxon *Fasciculithus tympaniformis* and essentially coincident with the 2nd radiation of the fasciculiths and the regional, but temporary, disappearance of braarudosphaerids. This recommendation will now be submitted to the voting members of the International Subcommission on Palaeogene Stratigraphy (ISPS) for approval; pending approval it will be forwarded to the International Commission on Stratigraphy (ICS) for ratification.

Acknowledgements

We thank Hanspeter Luterbacher, Xavier Orue-Etxebarria, William A. Berggren, Richard K. Olsson and Robert Speijer for the review of the manuscript. We thank Asier Hilario, Director of the Algorri geological center of Zumaia, for providing us with panoramic photographs of the Zumaya section taken from a ship. This research was funded by the Spanish Ministerio de Educación y Ciencia (project CGL2004-00738) and by the Aragonian Departamento de Educación y Ciencia (DGA group E05).

References

Apellániz, E., Lamolda, M.A. and Orue-Etxebarria, X., 1983. Posición estratigráfica de las "Calizas del Danés", País Vasco. *Rev. Esp. Micropal.*, **15**, 447–455.

Arenillas, I., 1996. *Los foraminíferos planctónicos del Paleoceno-Eoceno inferior: Sistemática, Bioestratigrafía, Cronoestratigrafía y Paleoceanografía.* PhD thesis, Prensas Universitarias de Zaragoza, Spain.

Arenillas, I. and Molina, E., 1995. Análisis cuantitativo de los foraminíferos planctónicos de Paleoceno en Zumaya: implicaciones paleoambientales y eventos paleoceanográficos. *Geogaceta*, **17**, 23–26.

Arenillas, I. and Molina, E., 1997. Análisis cuantitativo de los foraminíferos planctónicos del Paleoceno de Caravaca (Cordilleras Béticas): Cronoestratigrafía, bioestratigrafía y evolución de las asociaciones. *Rev. Esp. Pal.*, **12**, 207–232.

Arenillas, I. and Molina, E., 2000. Reconstrucción paleoambiental con foraminíferos planctónicos y Cronoestratigrafía del tránsito Paleoceno-Eoceno de Zumaya (Guipúzcoa). *Rev. Esp. Micropal.*, **32**, 283–300.

Baceta, J.I., Pujalte, V., Serra-Kiel, J., Robador, A. and Orue-Etxebarria, X., 2004. El Maastrichtiense final, Paleoceno e Ilerdiense inferior de la Cordillera Pirenaica. In: *Geología de España* (J.A. Vera, ed.), pp. 308–313. Soc. Geol. Esp, ITGME, Madrid.

Berggren, W.A., 1994. In defense of the Selandian age/stage. *GFF*, **116**, 44–46.

Berggren, W.A. and Aubert, J., 1975. Paleocene benthonic foraminiferal biostratigraphy, paleobiogeography and paleoecology of Atlantic-Tethyan regions: midway-type fauna. *Palaeogeogr, Palaeoclimatol. Palaeoecol.*, **18**, 73–192.

Berggren, W.A. and Pearson, P.N., 2005. A revised tropical to subtropical Paleogene planktonic foraminiferal zonation. *J. Foram. Res.*, **35**, 279–298.

Berggren, W.A., Kent, D.V., Swisher, C.C. and Aubry, M.P., 1995. A revised Paleogene Geochronology and Chronostratigraphy. *Soc. Econ. Paleont. Min. Spec. Publ.*, **54**, 129–212.

Bernaola, G., Baceta, J.I., Payros, A., Orue-Etxebarria, X. and Apellaniz, E. (eds.), 2006. The Paleocene and lower Eocene of the Zumaia section (Basque Basin). Climate and Biota of the Early Paleogene 2006. *Post conference Field Trip Guidebook*, Bilbao, Spain.

Blow, W.H., 1979. *The Cainozoic Globigerinidae* (E.J. Brill, ed.), pp. 1413. Leiden, the Netherlands.

Bolli, H.M., 1966. Zonation of Cretaceous to Pliocene marine sediments based on Planktonic foraminifera. *Bol. Inf. Asoc. Venez. Geol. Min. Petrol.*, **9**, 1–34.

Canudo, J.I. and Molina, E., 1992. Bioestratigrafía con foraminíferos planctónicos del Paleógeno del Pirineo. *Neues. Jahrb. Geol. Paläontol. Abh.*, **186**, 97–135.

Clemmensen, A. and Thomsen, E., 2005. Palaeoenvironmental changes across the Danian-Selandian boundary in the North Sea Basin. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **219**, 351–394.

Corliss, B.H. and Chen, C., 1988. Morphotype patterns of Norwegian Sea deep-sea benthic foraminifera and ecological implications. *Geology*, **16**, 716–719.

Dinarès-Turell, J., Baceta, J.I., Pujalte, V., Orue-Etxebarria, X., Bernaola, G. and Lorito, S., 2003. Untangling the Palaeocene climatic rhythm: an astronomically calibrated Early Palaeocene magnetostratigraphy and biostratigraphy at Zumaia (Basque basin, northern Spain). *Earth Planet. Sci. Lett.*, **216**, 483–500.

Guasti, E., Speijer, R.P., Brinkhuis, H., Smit, J. and Steurbaut, E., 2006. Paleoenvironmental change at the Danian-Selandian transition in Tunisia: Foraminifera, organic-walled dinoflagellate cyst and calcareous nannofossil records. *Mar. Micropal.*, **59**, 210–229.

Hansen, H.J., 1968. On the biostratigraphical age of the lower Selandian of Denmark. *Dansk Geol. Foren. Meddelel.*, **18**, 277–284.

Haq, B.U., Hardenbol, J. and Vail, P.R., 1988. Mesozoic and Cenozoic chronostratigraphy and cycles of sea level change. *Soc. Econ. Paleont. Min. Spec. Publ.*, **42**, 71–108.

Hardenbol, J., Thierry, J., Farley, M.B., Jacquin, T., De Graciansky, P.C. and

Vail, P.R., 1998. Mesozoic and Cenozoic sequence chronostratigraphic framework of European basins. *Soc. Econ. Paleont. Min. Spec. Publ.*, **60**, 3–13.

Jones, R.W. and Charnock, M.A., 1985. "Morphogroups" of agglutinated foraminifera. Their life positions and feeding habits and potential applicability in (paleo)ecological studies. *Rev. Palèobiol.*, **4**, 311–320.

Kaminski, M.A. and Gradstein, F.M., 2005. Atlas of Paleogene cosmopolitan deep-water agglutinated foraminifera. *Grzybowski Found. Spec. Publ.*, **10**, 1–547.

Kuhnt, W. and Kaminski, M.A., 1997. Cenomanian to Lower Eocene deep-water agglutinated foraminifera from the Zumaya section, northern Spain. *Ann. Soc. Geol. Polon.*, **67**, 257–270.

Kuhnt, W., Kaminski, M.A. and Moullade, M., 1989. Deep-water agglutinated benthic foraminiferal assemblages of the upper Cretaceous North Atlantic and its marginal seas. *Geol. Rundsch.*, **78**, 1121–1140.

Luterbacher, H.P., Ali, J.R., Brinkhuis, H., Gradstein, F.M., Hooker, J.J., Monechi, S., Ogg, J.G., Powell, J., Rol, U., Sanfilippo, A. and Schmitz, B., 2004. The Paleogene period. In: *A Geologic Time Scale 2004* (F. Gradstein, J. Ogg and A. Smith, eds), pp. 384–408. Cambridge University Press, Cambridge.

Molina, E. and Arenillas, I., 1998. The Paleogene of Zumaya section: chronostratigraphy and planktic foraminifera. In: *Libro Guía 24 Congr. Europeo Micropal* (M.A. Lamolda, ed), pp. 93–97.

Olsson, R.K., Hemleben, C., Berggren, W.A. and Huber, B.T., 1999. Atlas of Paleocene planktonic foraminifera. *Smithson. Contrib. Paleobiol.*, **85**, 1–252.

Ortiz, S., 2006. *Análisis de eventos del Paleógeno con foraminíferos bentónicos. Taxonomía, reconstrucción paleoambiental y aplicación cronoestratigráfica.* PhD thesis, Universidad de Zaragoza, Spain.

Perch-Nielsen, K. and Hansen, J.M., 1981. Selandian. Bull. D'Information Géol. *Bassin Paris.*, **2**, 219–230.

Premoli Silva, I. and Boersma, A., 1988. Atlantic Eocene planktic foraminiferal historical biogeography and paleohydrographic indices. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **67**, 315–356.

Pujalte, V., Baceta, J.I., Dinarès-Turell, J., Orue-Etxebarria, X., Parès, J.M. and Payros, A., 1995. Biostratigraphic and magnetostratigraphic intercalibration of late Maastrichtian and Paleocene depositional sequences from the deep-water Basque basin, W Pyrenees, Spain. *Earth Planet. Sci. Lett.*, **136**, 17–30.

Pujalte, V., Baceta, J.I., Orue-Etxebarria, X. and Payros, A., 1998. Paleocene strata of the Basque Country, western Pyrenees, norther Spain: facies and sequence development in a deep-water starved basin. In: *Mesozoic and Cenozoic Sequence Stratigraphy of European Basins* (P.C. de Graciansky *et al.*, eds). SEPM Spec. Publ., **60**, 311–325.

Remane, J., Bassett, M.G., Cowie, J.W., Gohrbandt, K.H., Lane, R., Michelsen, O. and Naiwen, W., 1996. Revised guidelines for the establishment of global chronostratigraphic standards by the International Commission on Stratigraphy. *Episodes*, **19**, 77–81.

Rosenkrantz, A., 1924. De københavnske Grønsandslag og deres Placering i den danske Lagrække (med et Skema over det danske Paleocæn). *Medd. Danks Geol. For.*, **6**, 22–39.

Schmitz, B., 1994. The Paleocene Epoch – stratigrpahy, global change and events. *GFF*, **116**, 39–41.

Schmitz, B., Asaro, F., Molina, E., Monechi, S., Von Salis, K. and Speijer, R., 1997. High-resolution iridium, $\delta^{13}C$, $\delta^{18}O$, foraminifera and nannofossil profiles across the latest Paleocene benthic extinction event at Zumaya, Spain. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **133**, 49–68.

Schmitz, B., Molina, E. and Von Salis, K., 1998. The Zumaya section in Spain: a possible global stratotype section for the Selandian and Thanetian Stages. *Newsl. Stratigr.*, **36**, 35–42.

Speijer, R.P., 2003. Danian-Selandian sea-level change and biotic excursion on the southern Tethyan margin (Egypt). *GSA Special Paper*, **369**, 275–290.

Steurbaut, E., Dupuis, C., Arenillas, I., Molina, E. and Matmati, M.F., 2000. The Kalaat-Senan section in the Central Tunisia: a potential reference-section for the Danian/Selandian boundary. *GFF*, **122**, 158–160.

Thomsen, E., 1994. Calcareous nannofossil stratigraphy across the Danian-Selandian boundary in Denmark. *GFF*, **116**, 65–67.

Toumarkine, M. and Luterbacher, H.P., 1985. Paleocene and Eocene planktic foraminifera. In: *Plankton Stratigraphy* (H.M. Bolli, J.B. Saunders and K. Perch-Nielsen, eds), pp. 88–153. Cambridge University Press, Cambridge.

Received 21 December 2006; revised version accepted 28 November 2007