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Marine Micropaleontology 67 (2008) 1–29

MARINE  
MICROPALEONTOLOGY

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## Danian/Selandian boundary criteria and North Sea Basin–Tethys correlations based on calcareous nannofossil and foraminiferal trends in SW France

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Received 30 April 2007; received in revised form 22 August 2007; accepted 23 August 2007

### Abstract

High-resolution calcareous nannofossil and foraminiferal investigations of the Bidart and Loubieng outcrop sections allow to define a time-calibrated sequence of 47 bio-events within the Danian/Selandian (D/S) boundary interval (61.2–59.7 Ma) of Aquitaine (SW France). The D/S boundary, as originally defined in Denmark (start of clastic sedimentation at the base of the Lellinge Greensand Formation), is marked by the end of the acme of the nannofossil family braarudosphaeraceae. This bio-event, dated at 59.9 Ma, has also been identified at the lithological change from limestone-dominated (Lasseube Formation) to marly sedimentation (Latapy Member of the Pont-Labau Formation) in SW Aquitaine and at the base of the red marls of the Itzurun Formation at Zumaia (Spain), recently designated as Global Stratotype Section and Point (GSSP) for the D/S boundary. This implies contemporaneity of this lithological shift throughout Europe and a GSSP proposal, which is consistent with the original boundary definition. The braarudosphaeraceae-event is believed to be due to the interruption of freshwater influx, probably related to a sudden decrease in precipitation. It is located at the top of nannofossil zone NP4 and within planktonic foraminiferal zone P3b and bracketed between the lowest occurrence (LO) of *Morozovella velascoensis* (below) and the LO of *Fasciculithus tympaniformis* (above). It is coincident with the LO of *Bomolithus elegans*, the LCsO (Cs = consistent) of *Fasciculithus janii* and the LO of *Subbotina velascoensis*. The D/S boundary as originally defined is 400 k.y. posterior to a major discontinuity, recorded throughout the Tethyan Realm (Tunisia, Egypt) and up to now erroneously considered to correspond to the D/S boundary. This break in sedimentation, dated at 60.3 Ma and coinciding with the P3a/P3b boundary, is due to a major sea-level fall. It is correlated with sedimentation changes in the Aquitaine–Zumaia area (start of development of marly interbeds) and in the North Sea Basin (transition Bryozoan limestone–Calcsiltite in Denmark; transition shallow marine Mons Formation–continental Hainin Formation in Belgium). The Loubieng section supplements the Zumaia section. Because of its rich and well-preserved fossil content and continuous sedimentation it constitutes an excellent auxiliary section for the D/S boundary.

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**Keywords:** Danian/Selandian boundary; calcareous nannofossils; foraminifera; France; North Sea Basin–Tethys correlations

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## 1. Introduction

The Danian/Selandian (D/S) transition is supposed to correspond to the first out of six short episodes of extreme warming, called hyperthermals, which occurred in the early Paleogene (Thomas and Zachos, 2000). They are superimposed on a long-term global warming trend, extending from the Mid-Paleocene into the Early Eocene (Zachos et al., 2001). The causes and biotic consequences of the Mid-Paleocene Hyperthermal (MPH) are currently under study. Major faunal changes have been recorded within the D/S boundary interval in the North Sea Basin (Clemmensen and Thomsen, 2005) and in the Tethyan Realm (Egypt: Speijer, 2003; Tunisia: Steurbaut et al., 2000; Guasti et al., 2005, 2006; Van Itterbeeck et al., 2007), but their exact relations and timing are uncertain through lack of a high-resolution integrated stratigraphic framework.

The abrupt shift from carbonate to siliciclastic sedimentation marking the D/S boundary in Denmark (Thomsen and Heilmann-Clausen, 1985; Thomsen, 1994) and Belgium (Steurbaut, 1998) has been linked to the uplift of the Scotland-Shetland Platform, initiating

a massive input of siliciclastic sediments in the North Sea Basin (Clemmensen and Thomsen, 2005). In Denmark, the type region of the Danian and Selandian Stages, this lithological shift seems to coincide with major biotic changes, including a decline in the abundance of the nannofossil taxon *Braarudosphaera*, an increase in percentage of planktonic foraminifera and substantial quantitative changes in benthic foraminifera (Clemmensen and Thomsen, 2005) and dinoflagellate cysts (Heilmann-Clausen, 1985, 1994; Stouge et al., 2000). Although these bio-events offer good opportunities for interregional correlation, estimation of the age of the lithofacies shift through magnetobiochronologic calibration remains problematic. The standard Late Danian and Early Selandian planktonic foraminiferal and calcareous nannofossil zones, through which the age estimation is calibrated, cannot be identified in the North Sea Basin, because of paucity or absence of the relevant index species.

A similar lithological shift from carbonates to marls has been recorded in the Zumaia section in northern Spain (Fig. 1). This lithological change, characterised by red marl-limestone couplets abruptly passing upwards

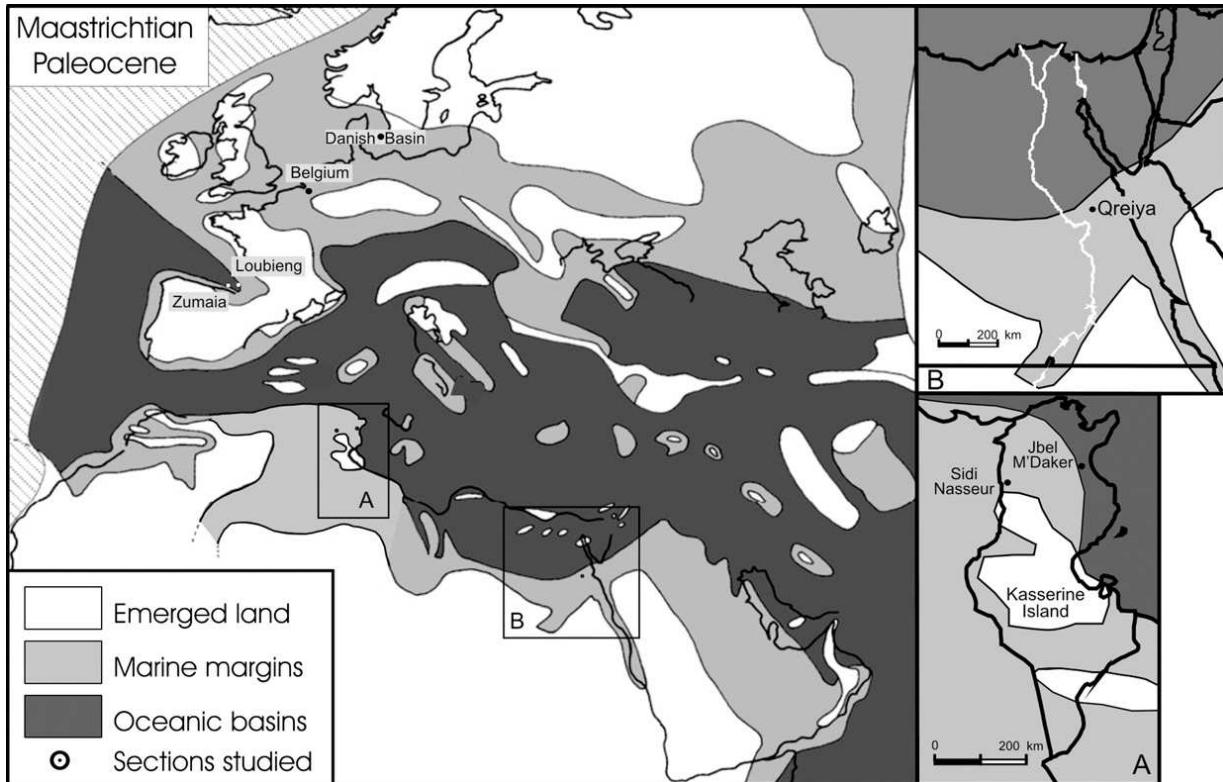


Fig. 1. Location of the Danian/Selandian boundary sections discussed here, superimposed on the paleogeographic situation in Europe and northern Africa around the Maastrichtian–Paleocene transition (modified after Gheerbrandt and Rage, 2006). Tunisia (A) and Egypt (B) are shown in more detail.

into 3.4 m thick red marl, is one of the most prominent at Zumaia (Schmitz et al., 1998). It is located in the upper part of nannofossil zone NP 4 (75 cm below the lowest occurrence of *Fasciculithus tympaniformis*, defining the base of NP5) and marked by a sharp decrease in *Braarudosphaera bigelowii*, a nannofossil taxon known to bloom in coastal hyposaline conditions (Bukry, 1974). The drastic decrease in *Braarudosphaera* at the base of the red marl (boundary between the Danian Limestone Formation and the Itzurun Formation according to Baceta et al., 2006) has been upheld in a current nannofossil study by Bernaola and Nuño-Arana (2006). The LO of *F. tympaniformis*, however, was relocated at about 2.5 m above the lithological boundary.

Analogous reddish marl-limestone successions have been mentioned from the southwestern part of the Aquitaine Basin, e.g. at Bidart and Loubieng (Peybernès et al., 2000; Sztrákos, 2005b; Sztrákos and Steurbaut, 2007) (Fig. 2). The Loubieng quarry, located 300 m east of the crossing of road N 647 Orthez-Navarrenx with road D 110 Loubieng-Sauvelade exposes the most complete Danian/Selandian boundary section of Aquitaine, but was not studied in much detail up to now. Sztrákos and Steurbaut (2007) recently reviewed its stratigraphy and discussed previous investigations, which often seemed to have led to erroneous interpretations. The higher parts of the

Selandian are continuously exposed in the Gan-Rébénacq road section, 60 km southeast of Loubieng (Steurbaut and Sztrákos, 2002).

Further southward into the Tethys area sedimentation conditions are completely different (Fig. 1). During most of the Danian and Selandian, from c 63 Ma to 58.5 Ma, monotonous sequences developed on the northwestern margin of the Arabian-Nubian shield in Egypt (Said, 1962), as well as in the Tunisian trough in the western part of the southern Tethys (Steurbaut et al., 2000). Abrupt sedimentation shifts occurred simultaneously in both areas, marked by omission surfaces overlain by special lithologies: a purplish brown marl bed, laminated and rich in fish debris within the hemipelagic Dakhla Formation in Egypt (Sprong et al., in press) and complex channel systems with glauconite infill within the marly El Haria Formation in Tunisia (Steurbaut et al., 2000). The latter, believed to coincide with the P2/P3a planktonic foraminiferal zonal boundary (lowest occurrence of *Morozovella angulata*, according to Molina in Steurbaut et al., 2000) and falling within nannofossil zone NP 4 (Steurbaut et al., 2000), was equated with the D/S boundary, following the interpretation of Berggren et al. (1995). However, in recent investigations (Guasti et al., 2006; Van Itterbeeck et al., 2007; Sprong et al., in press) it was suggested that the lithological break correspond to the P3a/P3b boundary, using the lowest occurrence of slightly keeled *Igorina* as zonal boundary criterion.

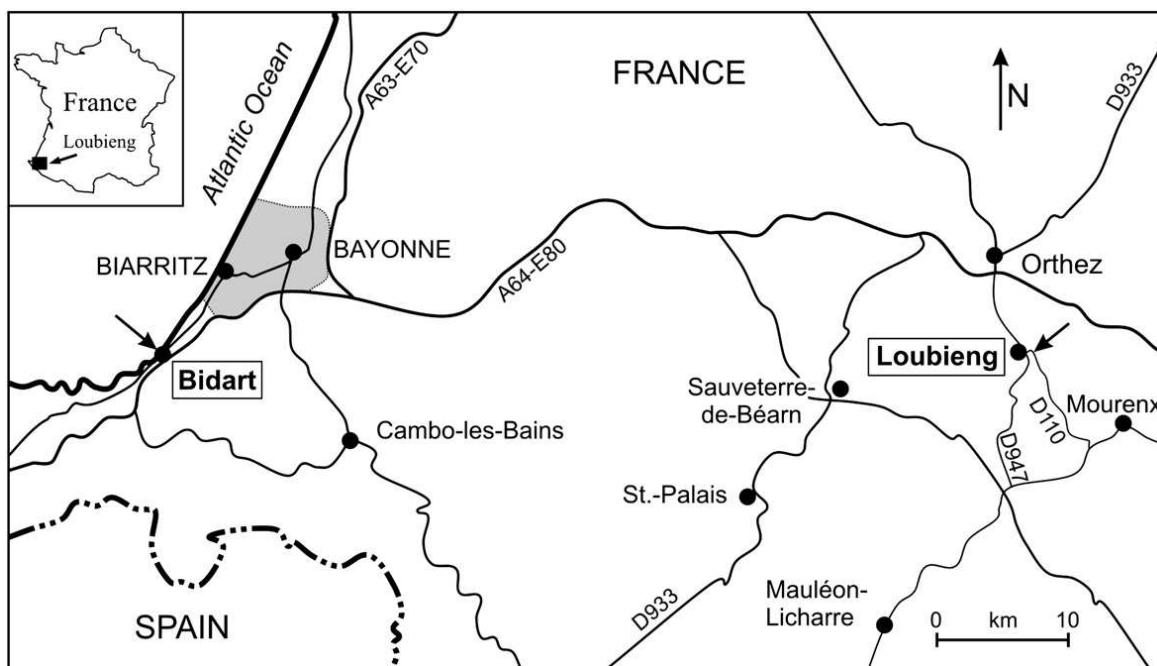


Fig. 2. Map with the location of the Bidart and the Loubieng outcrop sections in SW Aquitaine (France).

Despite the recent release of numerous new microfossil data (essentially ostracods and benthic foraminifera), the relation of this major event with the D/S boundary in the type area remains unclear.

Here, we aim at clarifying existing Late Danian and Early Selandian correlation problems between the North Sea Basin and the Tethys through the study of the Loubieng and Bidart outcrops in the Aquitaine Basin, integrating lithology, foraminifera and calcareous nanofossil records. The data from the North Sea Basin are based on Varol (1989), Steurbaut (1998) and Clemmensen and Thomsen (2005), the Tethys data are from Tunisian (Steurbaut et al., 2000; Guasti et al., 2005; 2006; Van Itterbeek et al., 2007) and Egyptian sections (Speijer, 2003; Sprong et al., in press).

## 2. The Bidart and Loubieng sections: geological setting and lithostratigraphy

The Bidart section, a 60 m long and several tens of m high cliff south of Biarritz in the extreme SW of Aquitaine (Fig. 2, IGN map Bayonne-Biarritz, 1244E;  $x \sim 282.650$ ,  $y \sim 3125.400$ ), includes a series of essentially whitish and pink limestones from late Cretaceous to Late Danian age. The succession, the lower part of which is interrupted by faults or slumping structures, has been documented by Sztrákos and Steurbaut (2007). The topmost 15 m, consisting of undisturbed limestones with several tiny marl beds and belonging to the Lasseube Formation, is re-discussed here (Fig. 3).

The Loubieng quarry is located in the North-Pyrenean Tectonic Zone ( $43^{\circ} 25' 37.19''$  N,  $0^{\circ} 44' 41.04''$  W; IGN map Orthez, 1444E;  $x=350.400$ ,  $y=3129.900$ ), which westwards of Pau is fractured into several tectonic units. It sits on the northern limb of a syncline, the centre of which covers the Sauvelade village, and belongs to the Sauvelade tectonic unit (Rocher et al., 2000; Serrano et al., 2001; Sztrákos et al., 2003). The Loubieng section consists of several faulted blocks marked by small displacements (throw of a few meters) along normal faults (Rocher et al., 2000, Fig. 6G). The lower part of the section belongs to the upper part of the Lasseube Limestone or Lasseube Formation (Sztrákos et al., 1997; Sztrákos and Steurbaut, 2007) (Fig. 4). It forms the quarry front and consists of an alternation of limestone beds (20 to 40 cm thick) and tiny marl intercalations. The marls with tiny sand and calcarenite intercalations, overlying the quarry front are included in the Latapy Member, which in Western Aquitaine represents the lowermost unit of the Pont-Labau Formation (Sztrákos, 2005b).

The rhythmicity within the Lasseube Formation is fairly constant, despite some thickness differences. It

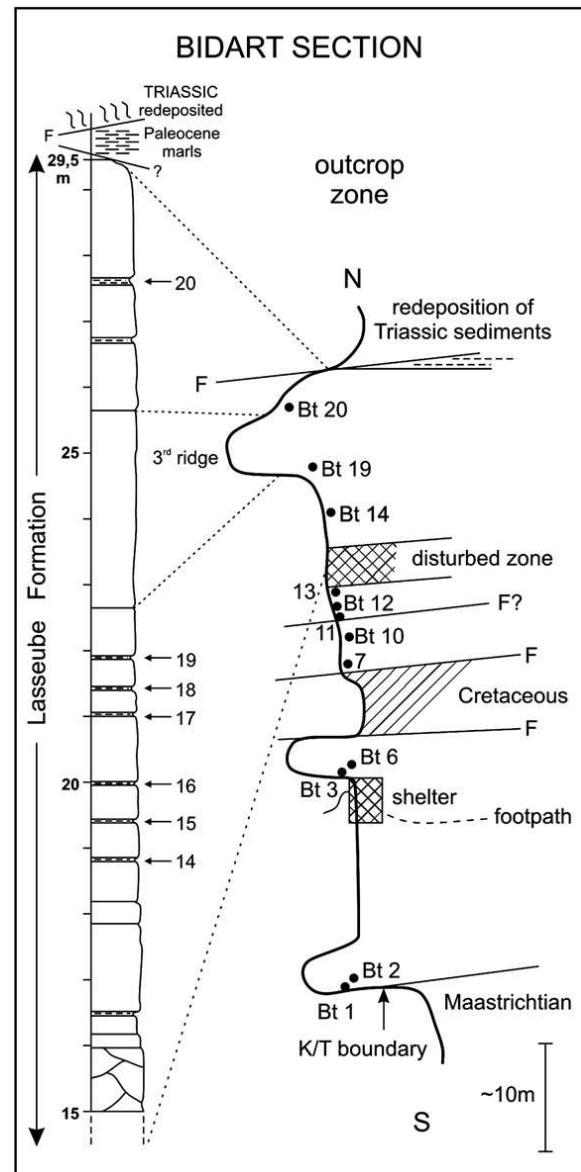


Fig. 3. The Bidart outcrop section, with location of the major stratigraphic units, details of the lithological succession and location of samples.

is disrupted at six levels, marked by special lithologies, labelled in ascending order A to F. These marker beds are excellent reference levels, which can easily be followed throughout the quarry (Figs. 4 and 5). Marker bed A, at the base of the quarry, consists of a 1 to 2 m thick calcareous conglomerate. Beds B and C are bioclastic calcareous grainstones, with a thickness of about 0.6 m. D includes a series of folded limestones ( $\sim 1.5$  m), due to slumping, whereas E is a massive conglomeratic and bioclastic limestone ( $\sim 0.8$  m). F ( $\sim 0.2$  m) is the highest

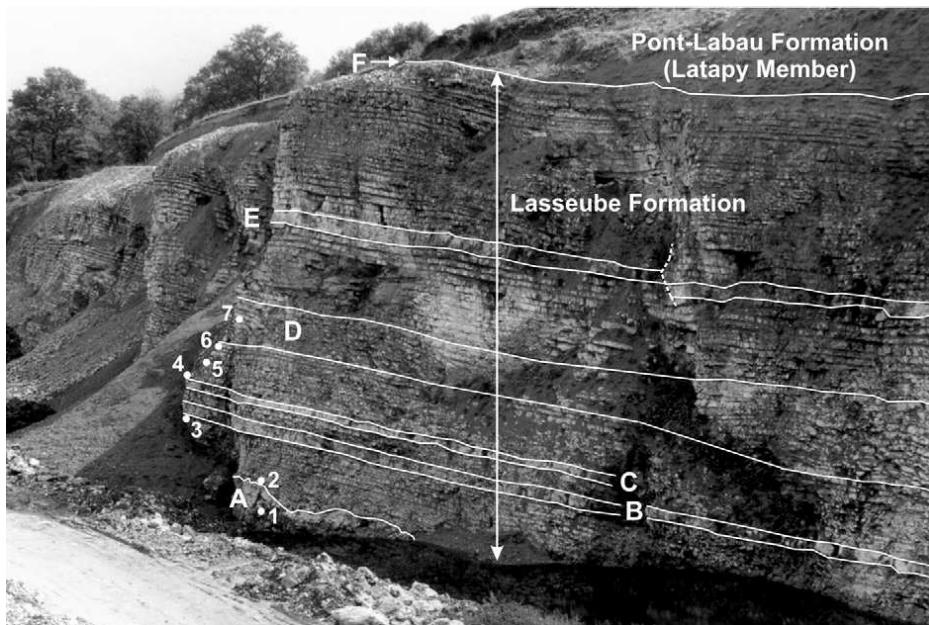


Fig. 4. Lithological succession and position of samples in the eastern sector of the Loubieng quarry (anno, 2002).

limestone bed recorded, overlying 0.25 m of reddish marl (Fig. 6). It is overlain by the Latapy Member, including grey highly bioturbated clays, which up-section pass into homogenous grey bioturbated marls.

### 3. Materials and methods

The Loubieng quarry was logged and sampled in September 2002 by K. Sztrákos (details in Sztrákos and Steurbaut, 2007). The lowermost seven samples (labelled L1 to L7) have been collected along the eastern edge of the main quarry front (see Fig. 4). They come from thin marly levels within an essentially lithified interval, except for sample 1, which originates from a soft calcareous pebble within the basal conglomerate A. The remainder of the sample set (L8 to L32) was taken along the western edge, from the base of a small platform upward (Figs. 4 and 5). E. Steurbaut collected a series of additional samples (labelled bis) in that part of the section in April 2006 (Fig. 6).

In September 2002 K. Sztrákos also carried out the stratigraphical logging and sampling of the Bidart section (details in Sztrákos and Steurbaut, 2007). The uppermost 7 samples (Bt14 to Bt20) from the most northern undisturbed part of the section are discussed in the present paper (Fig. 3).

Samples for foraminiferal analysis were processed following standard micropaleontological procedures. Quantitative analyses are based on estimations using

the following 3 categories: r (rare) = a few specimens, c (common) = a few tens of specimens and f (frequent) = over fifty specimens (Table 2). The taxonomy adopted here is that from Berggren and Norris (1997) and Olsson et al. (1999), the biozonation is from Berggren et al. (1995), taking into account the modifications by Berggren and Pearson (2005).

Qualitative and quantitative calcareous nannofossil investigation was carried out using standard procedures as described in Steurbaut and King (1994). About two square centimeters of glass-slide have been examined for each sample, using a Zeiss light microscope at 1000 $\times$  or 1250 $\times$  magnification. The best-preserved and richest associations have been examined with a Scanning Electron Microscope at the Royal Belgian Institute of Natural Sciences (RBINS). Martini's (1971) standard Paleogene calcareous nannofossil zonation (traditionally abbreviated to NP zones) and the high-resolution low latitude zonation of Varol (1989) are applied here. The taxonomy is essentially from Perch-Nielsen (1985), taken into account subsequent modifications by Varol (1992: *Sullivana*).

The calcareous nannofossil material is stored in the collections of the RBINS (Brussels, Belgium). The sieved residues from the foraminiferal investigation (including the figured foraminifera) are temporarily kept in the collections of Sztrákos (see address above), but from 2008 on, will be permanently stored in the collections of the "Muséum de Paris".

## 4. Results

### 4.1. Calcareous nannofossils

#### 4.1.1. Biozonation

The Late Danian and Early Selandian nannofossil associations in SW France (Loubieng and also Bidart) are difficult to link up with Martini's (1971) standard calcareous nannoplankton zonation because of the latitudinal asynchronous distribution of the marker species *Ellipsolithus macellus*. The latter, the lowest occurrence (LO) of which defines the base of Martini's Zone NP4, seems to be a thermophile taxon with a temperature-controlled dispersal. It is consistently and commonly present in the Tethyan Realm from the base of NP4 onward (Steurbaut et al., 2000; Guasti et al., 2006), dated as 62.2 Ma (Berggren et al., 1995), but is supposed to enter the North Sea Basin only several

million years later. This assumption is based on its common occurrence in various Ypresian NP11 associations (~53 Ma) of Western Europe (Aubry, 1983; Steurbaut, 1991; Bignot, 1994; Steurbaut and King, 1994), after a period of extreme rarity throughout the Paleocene (recorded from the Herne Bay section only, dated as NP8 at ~57 Ma, Aubry, 1983; Steurbaut, 1998). Its presence in the Danian of the North Sea Basin, based on the identification of 2 specimens from Denmark (Perch-Nielsen, 1979, reconfirmed in Perch-Nielsen and Hansen, 1981) is regarded with caution, as it has never been reported subsequently in that time interval (Van Heck and Prins, 1987; Varol, 1989; Steurbaut, 1998; Lottaroli and Catullo, 2000; Clemmensen and Thomsen, 2005).

The low latitude zonation of Varol (1989) allows much more refined interpretations of the nanno-associations, NP4 being subdivided into 7 zones-

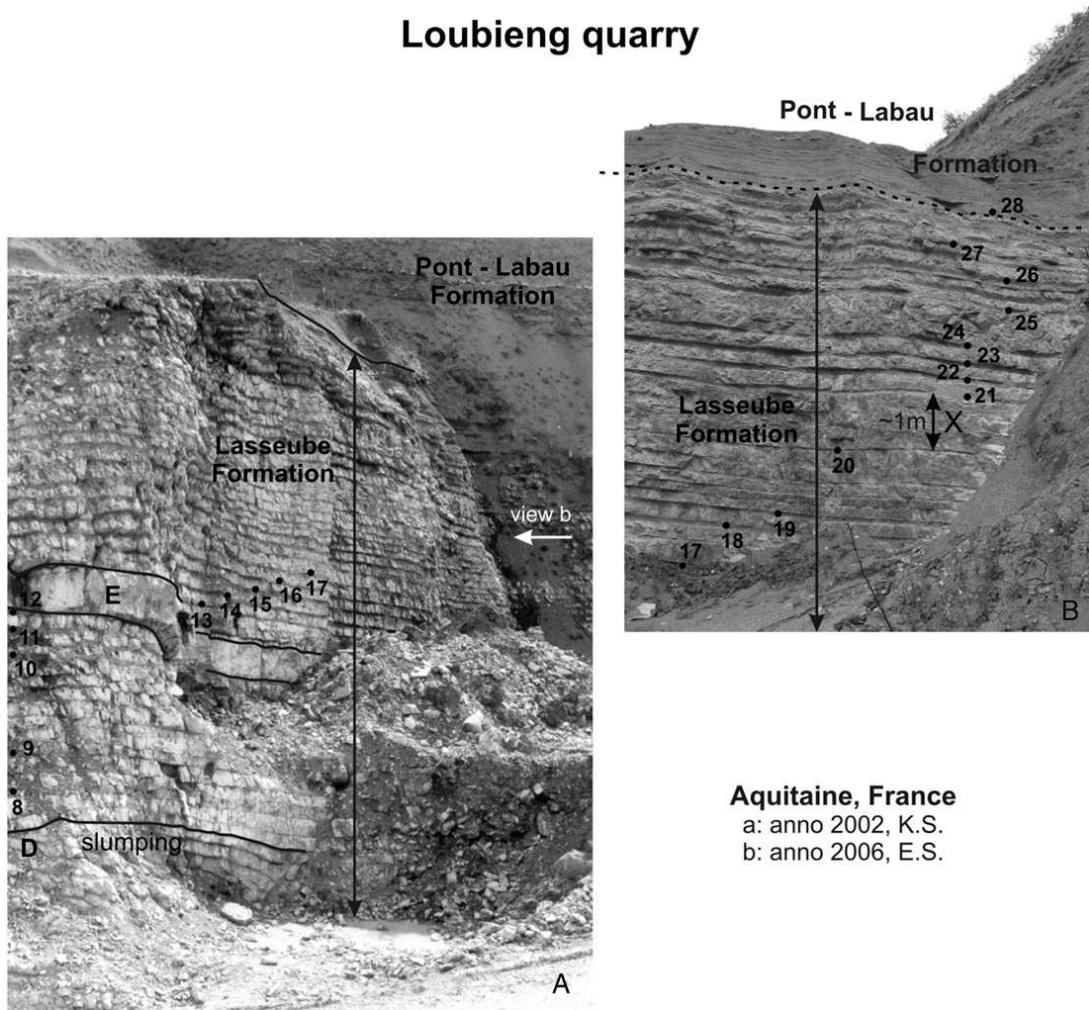


Fig. 5. Lithological succession and position of samples in the western sector of the Loubieng quarry.

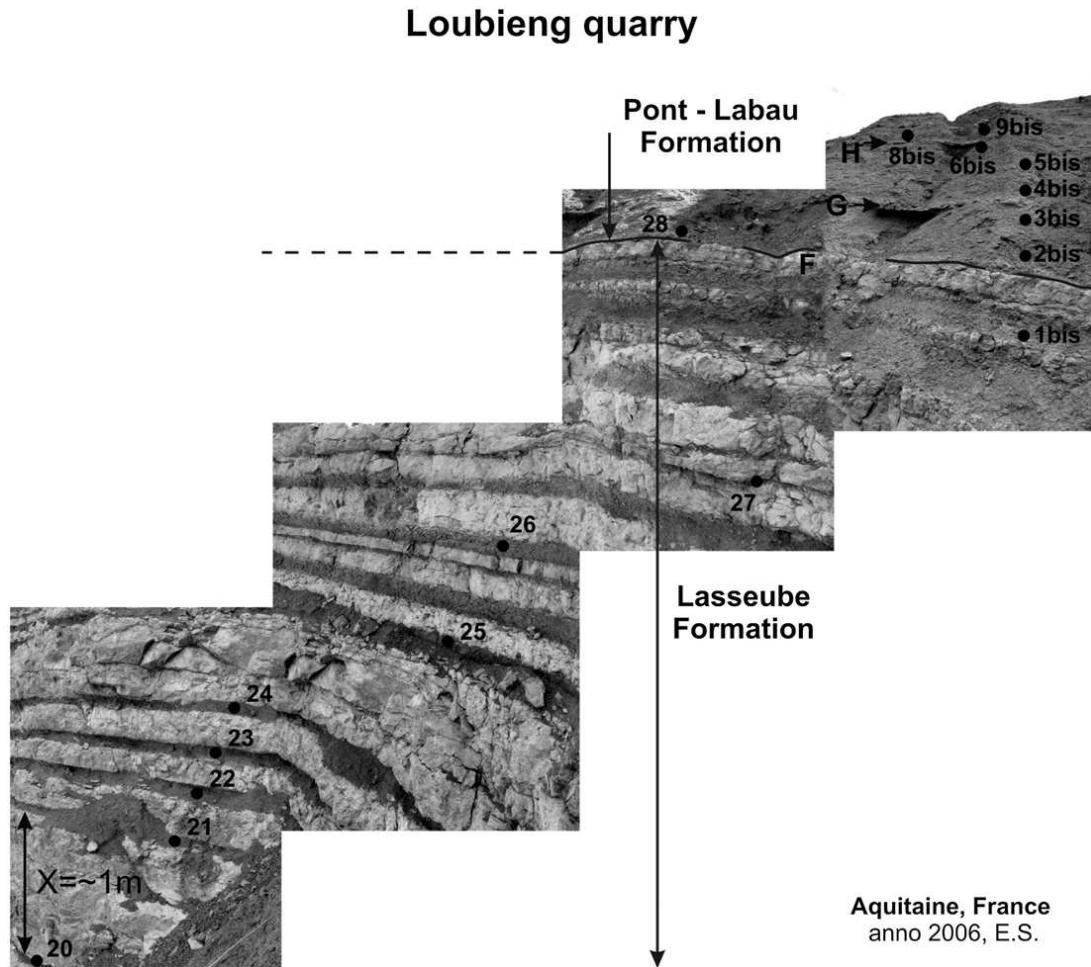


Fig. 6. Detailed lithology of the upper Lasseube Formation and the lower Pont-Labau Formation in the western sector of the Loubieng quarry (anno, 2006).

subzones. This zonation is easily correlated with Martini's zonation as the First Appearance Datum (FAD) of *E. macellus* and the FAD of *Fasciculithus tympaniformis*, respectively defining the base and the top of NP4, are used as zonal boundary markers in both zonations.

The lowest occurrence (LO) of *E. macellus* and the HO of *Neochiastozygus imbriei*, defining Varol's NTp5B/NTp5C and NTp6/NTp7 zonal boundaries respectively, are coinciding in the Aquitaine Basin (both recorded in sample Bt17) (Table 1). Comparison of other nannofloral and microfaunal components in the different areas studied indicates that this coincidence is not due to the presence of a major hiatus. It just results from the considerably time lag between the initial appearance of *E. macellus* in the Tethyan Realm (62.2 Ma) and its earliest occurrence in the Aquitaine Basin (estimated at 60.95 Ma). This time lag approx-

imates 1.25 m.y., applying the time scale of Berggren et al. (1995).

Varol's zonation seems to be applicable to the Aquitaine Basin as all its relevant index taxa are recognised in the nanno-associations of Bidart and Loubieng. However, identification and calibration of Varol's zones are not so straightforward as might be thought, because most of these index taxa are very rare in the lower part of their range (e.g. *Chiasmolithus edentulus*, *Sphenolithus primus*, see below) or are represented by small atypical specimens (*Chiasmolithus edentulus*). There is no discrepancy between the distribution of the marker species in the Aquitaine Basin and the Turkish Kokaksu Section, used as reference section in Varol's zonation, if the term "first occurrence" is not used in its strict sense, the record of the very first, often isolated specimen (LO), but in a broader context, the start of the consistent (LCsO) or common occurrence (LCO) of the

Table 1

A time-calibrated sequence of calcareous nannofossil and planktonic foraminiferal events in the Danian/Selandian boundary interval in SW Aquitaine (ages after Berggren et al., 1995; Berggren and Pearson, 2005)

Events	Planktonic foraminifera		Calcareous nannofossils		Location	Age in Ma	
	Nr	Nature	Taxon	Nature	Taxon		
E1		LCsO	<i>Praemurica uncinata</i>			Bt 14	(61.2)
E2		LO		LO	<i>Neochiastozygus imbriei</i>	Bt 14	
E3		LO	<i>Morozovella angulata</i>			Bt 16	61.0
E4				LO	<i>Ellipsolithus macellus</i>	Bt 17	(62.2)*
E5				HO	<i>Neochiastozygus imbriei</i>	Bt 17	
E6		LO	<i>Morozovella conicotruncata</i>			Bt 18	60.9
E7		HCO	<i>Praemurica inconstans</i>			Bt 19	
E8		HCO	<i>Praemurica uncinata</i>			Bt 20	
E9				LO	<i>Sphenolithus primus</i>	L 1	60.6
E10				LO	<i>Fasciculithus magnus</i>	L 2	
E11				LO	<i>Fasciculithus magnicordis</i>	L 3	
E12				LO	<i>Chiasmolithus edentulus</i>	L 4	(60.7)*
E13				HO	<i>Fasciculithus magnus</i>	L 4	
E14		LO	<i>Acarinina strabocella</i>			L 6	60.5
E15		HO	<i>Praemurica inconstans</i>			L 7	
E16		HO	<i>Morozovella preeangulata</i>			L 8	
E17		LCO	<i>Morozovella angulata</i>			L 10	
E18				LCsO	Small <i>Fasciculithus</i> spp.	L 10	
E19				LCsO	<i>Chiasmolithus edentulus</i>	L 10	
E20				LCsO	<i>Sphenolithus primus</i>	L 12	
E21				LO	<i>Neochiastozygus perfectus</i>	L 12	
E22				LO	<i>Ellipsolithus distichus</i>	L 12	
E23				LO	<i>Fasciculithus vertebratoides</i>	L 12	
E24		LO	<i>Igorina albeari</i>			L 17	60.0
E25		LO	<i>Morozovella apanthesma</i>			L 17	
E26				HO	<i>Fasciculithus magnicordis</i>	L 19	
E27		LO	<i>Morozovella velascoensis</i>			L 26	60.0
E28				LO	<i>Fasciculithus billii</i>	L 27	
E29				LO	<i>Fasciculithus involutus</i>	L 27	
E30				LO	<i>Fasciculithus janii</i>	L 27	
E31				LO	<i>Fasciculithus ulii</i>	L 1 bis	
E32				HCO	<i>Braarudosphaera bigelowii</i>	L 1 bis	59.9
E33		LO	<i>Subbotina velascoensis</i>			L 28	
E34				LO	<i>Bomolithus elegans</i>	L 28	
E35				LO	<i>Toweius</i> sp. 1	L 28	
E36				LO	Large <i>Neochiastozygus perfectus</i>	L 28	
E37				LCsO	<i>Fasciculithus janii</i>	L 28	
E38		HO	<i>Morozovella conicotruncata</i>			L 28	
E39		HCO	<i>Parasubbotina varianta</i>			L 29	
E40				LO	<i>Ellipsolithus bollii</i>	L 29	
E41				LO	<i>Toweius tovae</i>	L 31	
E42				LO	<i>Fasciculithus pileatus</i>	L 31	
E43				LO	<i>Scapholithus apertus</i>	L 31	
E44				LCsO	<i>Fasciculithus involutus</i>	L 31	
E45		HO	<i>Morozovella angulata</i>			L 31	
E46				LCO	<i>Fasciculithus pileatus</i>	L 32	
E47				LO	<i>Fasciculithus tympaniformis</i>	L 32	59.7

species. In Aquitaine, the LCO of *C. edentulus* coincides with the LO of small *Fasciculithus* spp. (both in L10) and precedes the LCsO of *S. primus* (L12) just as in Varol's zonation sequence. However, in the Aquitaine Basin the first few *C. edentulus* (interval L4 to L9) and *S. primus* (L1) are known from older levels, implying that isolated

specimens can be recorded earlier, below Varol's so-called "first appearance" levels.

The upper part of the Bidart section (Bt14–Bt20) is attributed to Varol's interval NTp6–NTp7A, because of the presence of *E. macellus*, the presence of *N. imbriei* (up to Bt17) and the absence of *Fasciculithus*. This

interval corresponds to the lower middle part of Martini's NP4 (Fig. 8).

The lower part of the Lasseube Formation in the Loubieng quarry (covering samples L1 to L9), although almost completely devoid of the NP4 marker species *E. macellus* (1 specimen in L8) was definitely deposited during Biochon NP4. It contains isolated specimens of *C. edentulus* (1 specimen in L4) and of *Sphenolithus primus* (a few specimens in L1 to L4) and is attributed to zone NTp7A because of the absence of *N. imbriei* and the absence of small *Fasciculithus* spp. (e.g. *F. varolii* n. sp.). The presence of *S. primus* and the large *F. magnus* suggests that it is slightly younger than the top of the Bidart section. The remainder of the Lasseube Formation and the major part of the exposed Latapy Member also belong to NP4. This upper NP4 interval can be subdivided into 4 subzones on the basis of the LCO of *C. edentulus*, coinciding with the LO of *F. varolii* (sample L10), the LCsO of *Sphenolithus primus* (L12), the LO of *Fasciculithus ulii* (L1bis) and the LO of *Fasciculithus pileatus* and the LCsO of *F. involutus* (L31), marking the lower boundaries of Varol's NTp7B, NTp8A, B and C respectively (Fig. 8). The LO of *Fasciculithus tympaniformis*, defining the base of Varol's NTp9 and Martini's NP5 was identified in the topmost sample of the Latapy Member (L32).

#### 4.1.2. Nannofossil evolution and major lineages

The nannofossil record at Bidart and Loubieng is marked by a series of first occurrences, indicating that the Mid-Paleocene calcareous nannofossil renewal, defined by Aubry (1998) as an essentially increase in generic diversification, is not a minor phenomenon as originally thought. In a time span of about 0.9 million years 4 genera emerge in the fossil record, in chronological order *Sphenolithus*, *Fasciculithus*, *Toweius* and *Pontosphaera* with a total of 19 species occurrences (Table 1). Disappearances are less frequent and essentially on the specific level (*Neochiastozygus eosaepe*s, *N. imbriei*, *F. magnus*, etc.).

**4.1.2.1. *Sphenolithus*.** *S. primus*, the oldest representative of the genus, first appears in sample L1, slightly predating the LO of the genus *Fasciculithus* (L2). It is poorly represented in the lowermost part of its range (a few specimens in interval L1–L4). Its consistent presence from L12 onward (1 to 2% of the association) is considered to represent the NTp7B–NTp8 boundary. After a short abundance peak in the upper part, but not the top of NP 4 (L24–L26: between 12% and 25%), its number decreases again to normal proportions (1 to 3%) (Fig. 7).

**4.1.2.2. *Fasciculithus*.** The Danian–Selandian transition at Loubieng is a primary source for unraveling the early evolutionary history of the genus *Fasciculithus*. The origin of the genus is unclear, but phylogenetic relationships with *Markalius* (Perch-Nielsen, 1977, 1981) or *Biantholithus* (Aubry, 1998) are the most successful among the postulated hypotheses. The first *Fasciculithus* species encountered at Loubieng is *F. magnus* (L2). It occurs in a thin interval (L2–L4) and is generally accompanied by the much rare *F. magnicordis* (L3–L4). The range of *F. magnus* is generally very short and can easily be overlooked. In Tunisia it has been recorded at the top of Zone NTp6 in the Aïn Settara section (Van Itterbeeck et al., 2007). The small form *F. varolii* is the next representative in the *Fasciculithus* sequence. It co-occurs with *F. chowii* in sample L10. The latter, pinpointed in many sections in Turkey, Spain and Tunisia, announces the start of the consistent occurrence (LCO) of the genus *Fasciculithus* throughout the Tethyan Realm. It represents the first diversification event of the genus, which slightly postdates the LO of *Acarinina strabocella*, estimated at 60.5 Ma. The second diversification event, marked by the LOs of *F. billii*, *F. involutus* and *F. janii*, has been identified in sample L27. It is slightly prior to the LO of *F. ulii* (L1 bis), dated at 59.9 Ma. Between the first and second diversification event, the number of *Fasciculithus* specimens decreases from around 3% (L10 to L12) to almost nil (from L24 onward). Important *Fasciculithus* events within this interval are: the LO of *F. vertebratoides* n. sp. (L12) and the HO of *F. magnicordis* (L19). The third event, pinpointed in sample L28, is a merely quantitative phenomenon, corresponding to the start of a bloom of *Fasciculithus* (increase from ~0.5% to 3% of the total number of nannofossils). These high species diversity and high quantitative percentages are consistently present in the overlying samples (L29 to L32) and seems to be characteristic of the top of NP4 and the base of NP5. *F. involutus* is consistently present from the top of NP4 onward (L31). The LO of *F. tympaniformis*, defining the base of NP5 (L32), seems to coincide with a substantial rise in *F. pileatus* (from less than 0.5% to 2.5%).

**4.1.2.3. *Toweius*.** The small *Toweius* forms have not systematically been identified on the specific and the generic level. They were grouped into the taxon Prinsiaceae, because of the rather poor quality of some of the nannofossil assemblages, hampering the identification and the exact estimation of the distribution of the species. *T. pertusus* is present in L12, although its LO is difficult to pinpoint because of preservation problems. A large form (*Toweius* sp. 1) was recorded in L28, two

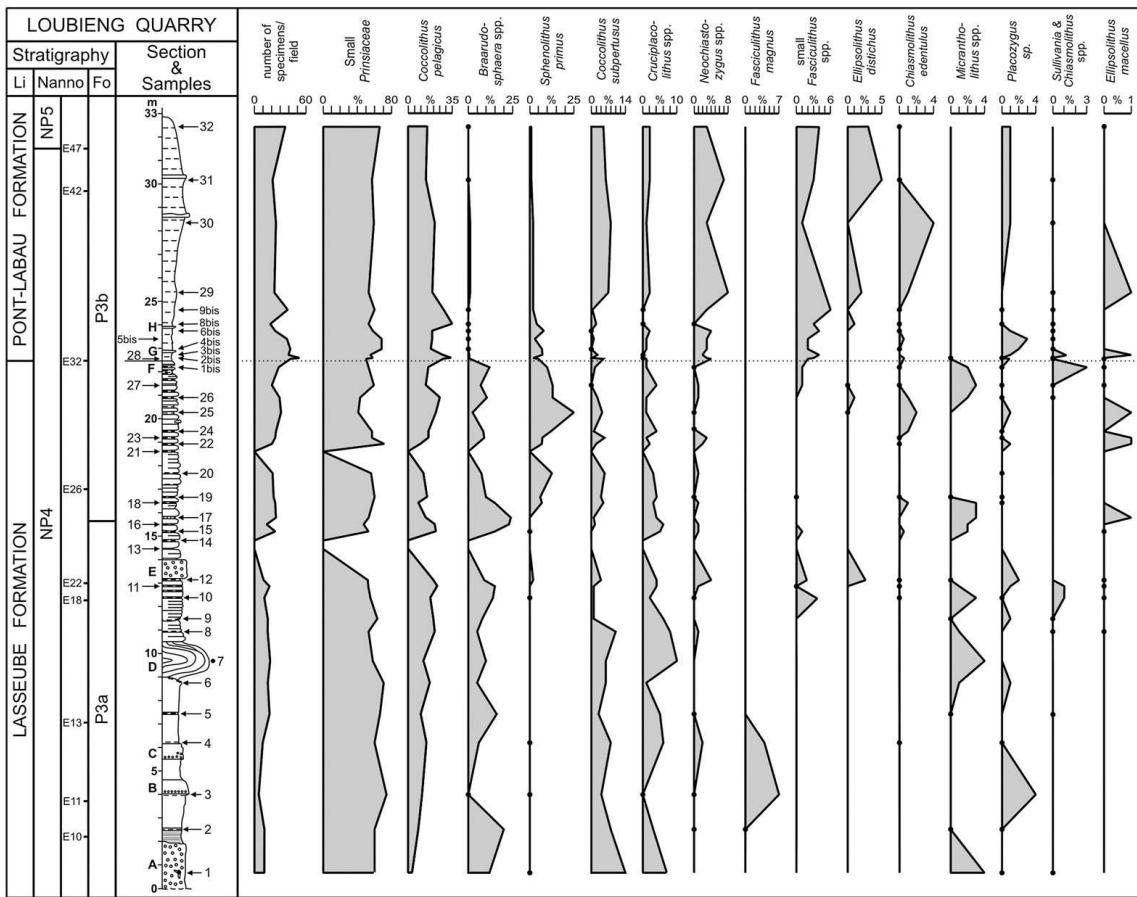


Fig. 7. Quantitative calcareous nannofossil distribution across the Danian/Selandian boundary in the Loubieng quarry (●=present, but not found in counts).

others (*Toweius* sp. 2 and *T.* sp 3) in the overlying samples L2bis to L8bis, whereas the large *Toweius tovae* is consistently present from L31 upward. Apparently, the major diversification event of the genus *Toweius* took place around 59.8 Ma, during late Biochron NP4. *Toweius eminens* has not been recognised, indicating that the top of the Loubieng section predates its first appearance, known to occur in the middle of the Latapy Member (Steurbaut and Sztrákos, 2002).

**4.1.2.4. *Pontosphaera*.** This taxon is extremely rare in the Danian–Selandian transition of the Aquitaine Basin. Its first and only representative (one single specimen) is recorded from L29.

**4.1.2.5. *Chiasmolithus edentulus*.** Small isolated specimens have been observed at the base of the Loubieng section (2 specimens in L4). It is consistently present from L10 onward, although in low numbers.

**4.1.2.6. *Neochiastozygus perfectus*.** The biostratigraphical relevant species *N. perfectus*, first recorded in L12, is represented by rather small specimens in the lower part of its range ( $L_{max}=7\text{ }\mu\text{m}$ ). Larger forms ( $L_{min}=8.5\text{ }\mu\text{m}$ ) make their entry in L28.

#### 4.1.3. Paleoenvironmental changes

Braarudosphaeraceae are consistently represented in the upper Bidart section and in the Loubieng section (Fig. 7). The genus *Braarudosphaera*, including *B. alta*, *B. bigelowii* and *B. discula*, remains abundant throughout the Lasseube Formation, although with a series of fluctuations. Its distribution pattern is marked by high values (12 to 20%) in interval Bt14–L2. It presents a slight decrease (5 and 10%) in interval L3–L9, a sudden increase in interval L10–L19 (15% to 24%) and a return to about 10% in the top of the Lasseube Formation (L24 to L1bis) (Fig. 7). A sharp and major decrease in abundance is recognised at the base of the Pont-Labau Formation (Latapy Member) (from 10% to less than 1%). *Micrantholithus* is less abundant in the studied interval. It is not continuously present in the Lasseube Formation, never exceeding more than 3%. It is absent in the Latapy Member.

As Braarudosphaeraceae are known to prefer hyposaline coastal waters (Bukry, 1974; Moshkovitch and Ehrlich, 1982), changes in their abundance patterns indicate major fluctuations in water mass parameters (essentially paleosalinity). The almost complete disappearance of Braarudosphaeraceae at the boundary between the Lasseube Formation and the Pont-Labau

Formation (Latapy Member) points to a sudden return to normal salinity, after a substantial long period of hyposaline conditions. Apparently, the Loubieng area was suddenly deprived of freshwater influence. This suggests a major decrease in precipitation or landward shift of the coastline, related to a major sea-level rise.

#### 4.2. Foraminifera

##### 4.2.1. Planktonic foraminiferal zonation

The planktonic foraminiferal zonation of Berggren et al. (1995) (consisting of the traditionally abbreviated P zones) is applicable to the Danian and Selandian of the Aquitaine Basin, without any special adaptation. *Morozovella angulata*, the lowest occurrence (LO) of which defines the P2/P3a boundary, is recorded in sample Bt16 (Table 2). *Igorina albeari* is only rarely and inconsistently represented. Its LO, defining the P3a/P3b boundary, is recorded in sample L17. Not a single specimen of *Globanomalina pseudomenardii* was encountered, suggesting that the top of the Loubieng section is still within P3b.

##### 4.2.2. Major biostratigraphic markers

All the foraminiferal taxa recorded in the upper Bidart and the Loubieng sections, planktonic as well as benthic, have been listed and figured by Sztrákos (2005a), as part of a general study of the lower Paleogene foraminifera of southern Aquitaine. Their distribution reveals strong diversification of the planktonic groups during Late Danian and Early Selandian time, marked by rapid evolution within the muricate and photosymbiotic lineages *Acarinina*, *Morozovella* and *Igorina*, and disappearance of *Praemurica* (Table 2). The planktonic foraminiferal associations are marked by a series of appearances (LO, LCsO and LCO) and disappearances (HO), which seem to have a substantial biostratigraphic potential. The events (16 in total), their position and age are summarised in Table 1. The LO of *Morozovella velascoensis*, dated at 60.0 Ma, which is major correlative event within the Tethyan realm is slightly prior to the second diversification within the genus *Fasciculithus*.

Changes within the benthic faunas are less conspicuous. According to Sztrákos (2005a) only three species among the benthic foraminifera have biostratigraphic interest in the D/S boundary interval of Aquitaine (*Tritaxilina cubensis* and *Thalmanitta madrugaensis* already present at the base of the Loubieng section, and *Svenia bulbosa*, first appearing in L28). However, these are too rare and too inconsistently present at Loubieng in order to allow biostratigraphic resolution.

Table 2  
Quantitative planktonic foraminiferal distribution across the Danian/Selandian boundary in SW Aquitaine

#### 4.2.3. Abundance patterns

The planktonic foraminiferal faunas of the studied sections are dominated by 4 genera, two of which, *Subbotina* and *Parasubbotina*, are abundantly present throughout the entire interval. The quantitative distribution of the other two genera, *Praemurica* and *Moro-*

*zovella*, allows the Danian/Selandian boundary interval of S Aquitaine to be subdivided into three major planktonic foraminiferal assemblages (Fig. 8). The lowermost *Praemurica* assemblage, occurring in the upper part of the Bidart section, is characterised by common to frequent occurrences of *P. uncinata* and

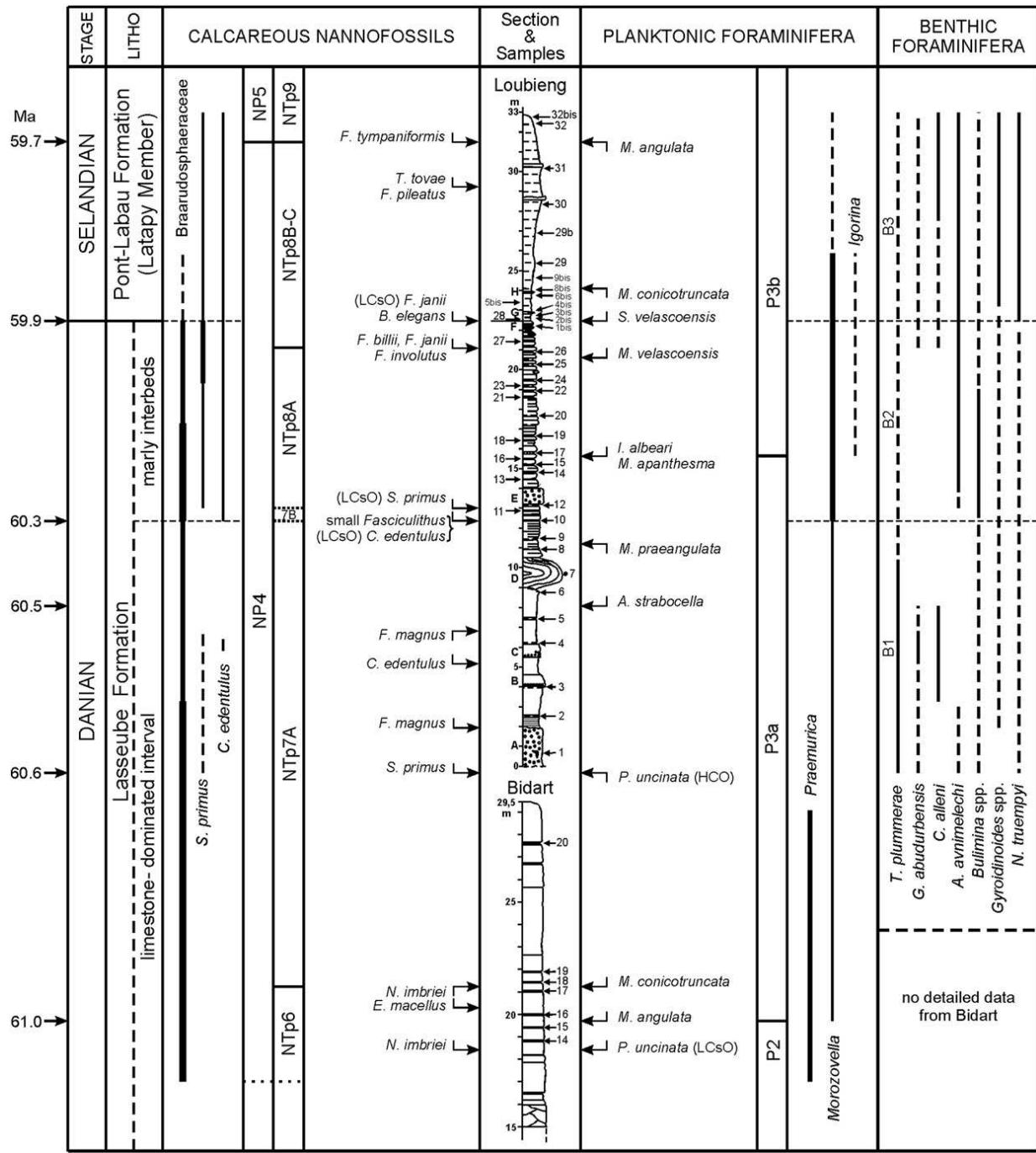


Fig. 8. Integrated stratigraphy of the Danian/Selandian boundary interval in SW Aquitaine with positioning of the major calcareous nannofossil and foraminiferal events.

*P. inconstans*, and contains rare *Morozovella*. The middle mixed *Subbotina*–*Parasubbotina* assemblage is recorded in the lower part of the Loubieng section. It is dominated by both nominative genera and contains only rare *Morozovella* and almost no *Praemurica* (a few specimens in lowermost sample L1). The upper *Morozovella* assemblage is dominated by *Morozovella*, *Subbotina* and *Parasubbotina*, with almost equal proportions, and is completely devoid of *Praemurica* (except for a few reworked specimens). The other surface dwelling taxa, such as *Acarinina* and *Igorina* are poorly represented in S Aquitaine. *Acarinina* is inconsistently recorded in the Loubieng section and only be very low numbers. *Igorina* is restricted to the upper part of this section, and occurs only inconsistently and rarely. Both have not been recorded in the Bidart section. The deeper water taxon *Globanomalina* is present in most of the samples. It is recorded in very low quantities, except for sample Bt18, where it is quite common.

Most of the benthic foraminifera range throughout the studied section, including the mesobathyal forms *Stensioeina beccariiformis* and *Osangularia velascoensis*. A few specimens show substantial abundance differences, allowing a three-fold subdivision of the benthic foraminiferal fauna. The lowermost assemblage B1 and B2 are recorded in the Lasseube Formation. High numbers of *Textularia plummerae*, *Cibicidoides allenii* and *Gavelinella abudurbensis* mark assemblage B1 (Fig. 8). These taxa are rare or lacking in the overlying B2 assemblage (sample L10 and higher), which on the contrary is richer in *Bulimina* and in *Angulogavelinella avnimelechi*. The B3 assemblage, characteristic of the Latapy Member, shows a strong increase in *Gyroidinoides globosa* and *G. subangulata* and in the deepwater form *Nuttallides truempyi*.

#### 4.2.4. Paleoenvironmental interpretation

Subbotinids, known to prefer living within or below the termocline, are abundantly present throughout the studied interval. Their co-occurrence with rare globanomalinids, also deepwater dwellers, indicates the presence of deepwater settings in the D/S boundary interval in S Aquitaine. This is corroborated by the persistence of mesobathyal benthic foraminifera, such as *S. beccariiformis*, *O. velascoensis* and *N. truempyi*, throughout the interval.

The strong increase of morozovellids in the upper 10 m of the Lasseube Formation (from L10 onward), associated with slight differences in the benthic foraminiferal fauna (occurrence of B2 assemblage), suggests a shallowing of the paleoenvironment, although still within the bathyal range. The typical

representatives of the surface mixed-layer zone, such as the frequent morozovellids and the rare acarinids and igorinids, disappear at or in the lower part of the Pont-Labau Formation. This major change in planktonic foraminifera coincides with a substantial increase of the mesobathyal benthic form *N. truempyi*, referring to substantial deepening of the basin, with paleodepths below 600 m.

#### 4.3. Changes in cyclicity patterns

The Lasseube Formation represents a limestone-dominated stacking pattern, consisting of a series of limestone beds and thin marly intercalations. The proportion of marl in the marl/limestone couplets increases upward in the formation. The crowded bundles, limestone beds alternating with marly joints, dominate in the lower part of the formation (Figs. 5 and 8). Open bundles with clear marly interbeds develop in the upper part of the Lasseube Formation (from sample L10 on), with increasing thickness of the marly portion in upward direction. This limestone/marl cyclicity changes abruptly at the base of the overlying essentially marly Latapy Member, which marks the base of the Pont-Labau Formation in the Orthez area.

#### 4.4. Red-coloured beds

In the Loubieng quarry these beds are restricted to the upper part of the Lasseube Formation. They first appear in-between sample L17 and L18 and are irregularly alternating with grey-coloured beds up to the top of the Formation (Figs. 5 and 6). The uppermost red level occurs within the base of the Pont-Labau Formation, about halfway between stone levels F and G (Fig. 6). The red colour is probably due to the presence of oxidized Fe-bearing particles, introduced into the sedimentation system through aeolian or hydrological transport from an adjacent continental source.

### 5. Discussion

#### 5.1. The Late Danian–Early Selandian depositional history of S Aquitaine

Integration of micropaleontological and sedimentological data from the upper Bidart and the Loubieng outcrop sections reveals that the Late Danian–Early Selandian depositional history of S Aquitaine is marked by two significant geological events, which had substantial repercussions on the biotic and sedimentological evolution of the area. The first event (named

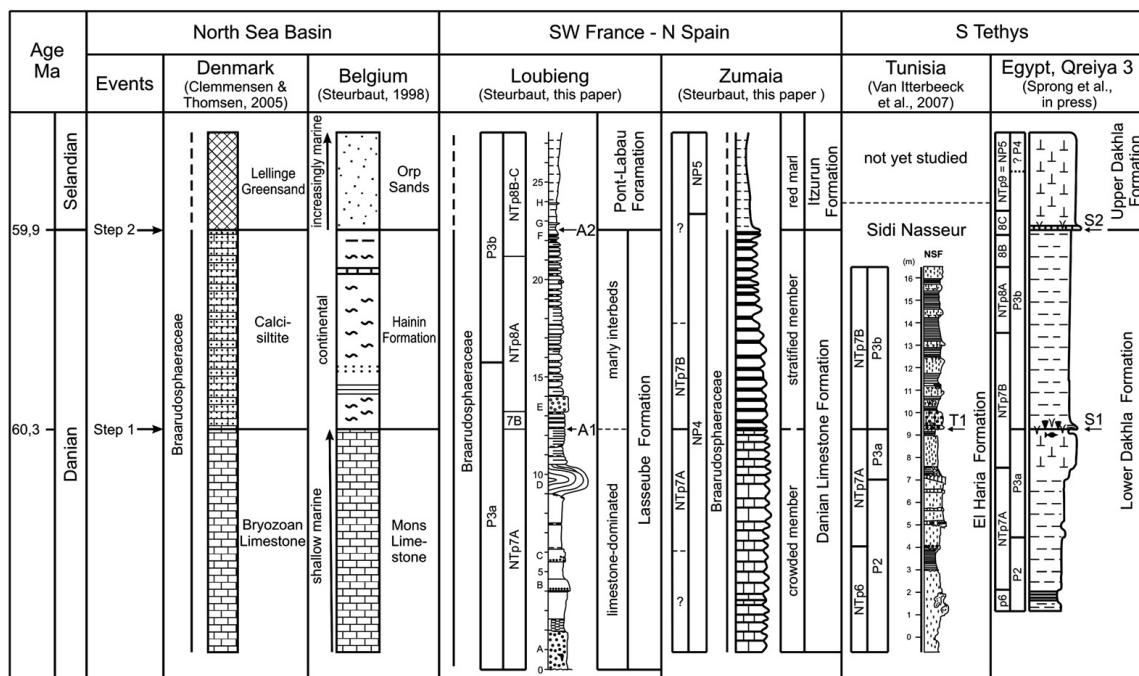


Fig. 9. North Sea Basin — Tethys correlations across the Danian/Selandian boundary.

Aquitaine 1 or A1) occurred in the upper part of the Lasseube Formation (base sample L10) at ca 60.3 Ma. It led to the increase in *Morozovella* and in braarudosphaerids, to the onset of a slight, but gradual influx of siliciclastics in the depositional area, resulting in the development of clear limestone-marl couplets and to the formation of red-coloured beds. These changes point to a shallowing sea-floor in the Loubieng area, although probably still within epibathyal depths, and to approach of the coastline (continental source). It points to regressive conditions. The second event, occurring 400 k.y. later (A2 at 59.9 Ma), had a much more pronounced effect, as shown by the disappearance of the typical limestone-marl cyclicity and its replacement by an almost exclusive siliciclastic sedimentation regime in greater part of S Aquitaine (Fig. 9). The disappearance of planktonic foraminifera of the surface mixed-layer zone, and the increase in mesobathyal benthic foraminifera indicate deepening of the Loubieng depocentre. The disappearance of braarudosphaerids witnesses the return of normal salinity, due to disconnection of the depocentre from freshwater sources as the coastline shifted substantially landward. All these changes suggest an abrupt reinforcement in subsidence in S Aquitaine, initiating a major transgressive pulse. It is coupled with an overwhelming influx of siliciclastic material due to increasing uplift in certain tectonically unstable sectors. Plate tectonic compression due to collision of the African and European plates seemed to have provoked major uplift in the central and eastern Pyrenees (Baceta et al., 2007) and substantial subsidence in adjacent northern areas (Steurbaut and Sztrákos, 2002; Sztrákos, 2005a).

This major transgressive A2 event at 59.9 Ma, clearly separating two different deposition systems (e.g. in the Orthez-Pau area, the Lasseube Formation and the Pont-Labau Formation), has since long been identified throughout the Aquitaine Basin (Gubler and Pomeyrol, 1946; Kieken, 1974). It has led to the traditional twofold subdivision of the Paleocene of Aquitaine, including a lower system, known as the Dano-Montian or Danian, and an upper system, termed Upper Paleocene, Thanetian or even Landenian (Kieken, 1974).

### 5.2. North Sea Basin–Tethys correlations (Fig. 9)

Global correlation of the D/S boundary interval has remained unsuccessful up to now because the major biostratigraphically significant microfossil groups, such as *Acarinina*, *Morozovella* and *Igorina*, among the planktonic foraminifera, and sphenolithaceae and fascilithaceae among the calcareous nannofossils, well-

known worldwide, including the Tethys, are not or only rarely recorded in this interval in the North Sea Basin. Moreover, through their endemic nature the biota in the latter are quite different from these in the surrounding world's oceans.

#### 5.2.1. North Sea Basin

Clemmensen and Thomsen (2005) concluded on the basis of a multidisciplinary investigation that the transformation of the Danish Basin from a carbonate to a siliciclastic basin across the Danian/Selandian boundary involved 4 steps. These steps correspond to substantial paleontological and lithological changes, as the result of sea-level fluctuations in the northeastern part of the North Sea Basin, which, according to these authors, seemed to be primarily of eustatic nature. A similar stepwise transformation has also been recognised in the Belgian Basin (Steurbaut, 1998), although its relation with other areas was not completely understood at that time. The recent release of new information from Denmark reveals that both the Danish Subbasin and the Belgian Subbasin underwent an analogous depositional history, allowing detailed inter-regional correlation (see Fig. 9).

The first step in this shifting depositional regime results from a considerable sea-level fall (~50 m). It led to the abrupt shift from bryozoan limestone to calcisiltite in Denmark and from shallow marine shelly limestone (the Mons Limestone) to fluviatile clays, lacustrine marls and limestones in West Belgium (Hainin Formation) and to continental multicoloured clays with lignitic lenses or fine sands in East Belgium (Opglabbeek Formation). In Denmark step 1 is associated with major biotic changes (decrease in planktonic foraminiferal proportions and increase in braarudosphaerids). The second step, corresponding to the Danian/Selandian boundary in its traditional concept, is characterised by the reinstallation of fully marine conditions, with the start of the deposition of the Lellinge Greensand or Kerteminde Marl in Denmark, depending on the position in the basin. Similar deposits accumulated simultaneously in NE Belgium, the transgressive glauconitic calcareous Orp Sands in the shallow areas and the Gelinden Marls in the somewhat deeper zones. In both subbasins there is a considerable increase in influx of land-derived material, probably originating from erosion of the same source area, the uplifted Scotland-Shetland landmass. The hypersaline Braarudosphaeraceae seem to disappear almost completely from the northeastern Danish part of the North Sea Basin at that particular point in time. The third step, marked by the replacement of in situ nannofossils by reworked

Cretaceous forms at the transition Lellinge Greensand–Kerteminde Marl in Denmark, has also been identified in Belgium, at the top of the Orp Sands. The fourth step, the abrupt shift from marl to non-calcareous or slightly calcareous clay, has not been recognised as such in Belgium because of fundamental differences (paleotemperature, paleodepth, circulation patterns, degree of isolation, etc.) between both subbasins. In Belgium this shift to non-calcareous sedimentation is much more gradual. A first decrease in carbonate is recognised at the boundary between the Gelinden Marl (white chalky marl with carbonate content between 80 and 90%) and the overlying Maaseik Clay (grey clayey marl with carbonate content around 60%). A second more conspicuous change is observed in the lower part of the overlying Waterschei Clay (carbonate content drops to 25%; Steurbaut, 1998).

### 5.2.2. Aquitaine Basin

The sea-level fall within the upper part of the Lasseube Formation (event A1) is correlated with step 1 in the North Sea Basin. This fall was not sufficiently large to provoke substantial differences of the bathyal depositional regime in western Aquitaine. It just led to considerable changes in planktonic and benthic life and in an increase in land-derived material. The transgressive event A2 is linked to step 2 in the North Sea Basin because of similar sedimentological (abrupt change in sedimentation pattern because of deepening and of major influx of land-derived material) and biotic (disappearance of braarudosphaeraceae) changes. Steps 3 and 4 have not been identified in the Aquitaine Basin.

### 5.2.3. Zumaia (N Spain)

The lithological stacking of the limestone/marl couplets in the D/S boundary interval at Zumaia is identical to that in the southern part of the Aquitaine Basin (see above, Section 4.3). There is an abrupt shift from a limestone-dominated unit (the so-called “crowded member” of Baceta et al., 2006) to a “stratified member” with clear marlstone intercalations at about 9.5 m below the top of the “Danian Limestone Formation”. This level is very close to the LO of small *Fasciculithus* spp. and therefore can be correlated with the same lithological event in the Aquitaine Basin (event A1). The contact between the Danian Limestone Formation and the marly base of the Itzurun Formation corresponds to major biotic changes, also recognised at event A2 in the Aquitaine Basin (abrupt decrease in braarudosphaerids, LCsO of *F. janii*). In both areas this lithologic junction is located at the top of NP4, between the bracketing events of the LO of *Morozovella*

*velascoensis* (below) and the LO of *Fasciculithus tympaniformis* (above).

### 5.2.4. Tunisia

The D/S boundary interval in Central and West Tunisia is marked by a marly depositional regime. It is interrupted by complex channel systems with glauconite infill in a single thin interval (level T1). This condensed interval with several short breaks in sedimentation is due to a considerable sea-level fall. It separates outer shelf (~150 m depth) from inner shelf deposits (~100 m depth) in the Sidi Nasseur section, close to Kalaat Senan (Guasti et al., 2006; Van Itterbeeck et al., 2007). It coincides with the entry of small *Fasciculithus* and the start of the common occurrence of *Morozovella* (including *M. angulata*). Because of similarity of biotic changes this major event, which was correlated with the D/S boundary by Steurbaut et al. (2000) and Guasti et al. (2006), adopting the recommendations of Berggren et al. (1995), must be equated with event A1 in the Aquitaine Basin. The latter, also related to a sea-level fall, is believed to be coeval with step 1 in the North Sea Basin. Thus, the major lithological event in Central Tunisia, coinciding with the P3a/P3b planktonic foraminiferal boundary according to Guasti et al. (2006), is definitely older and unrelated to the traditionally defined Danian/Selandian boundary. The subsequent steps 2 to 4, widely recognisable in the North Sea Basin, have not been identified in western Tunisia.

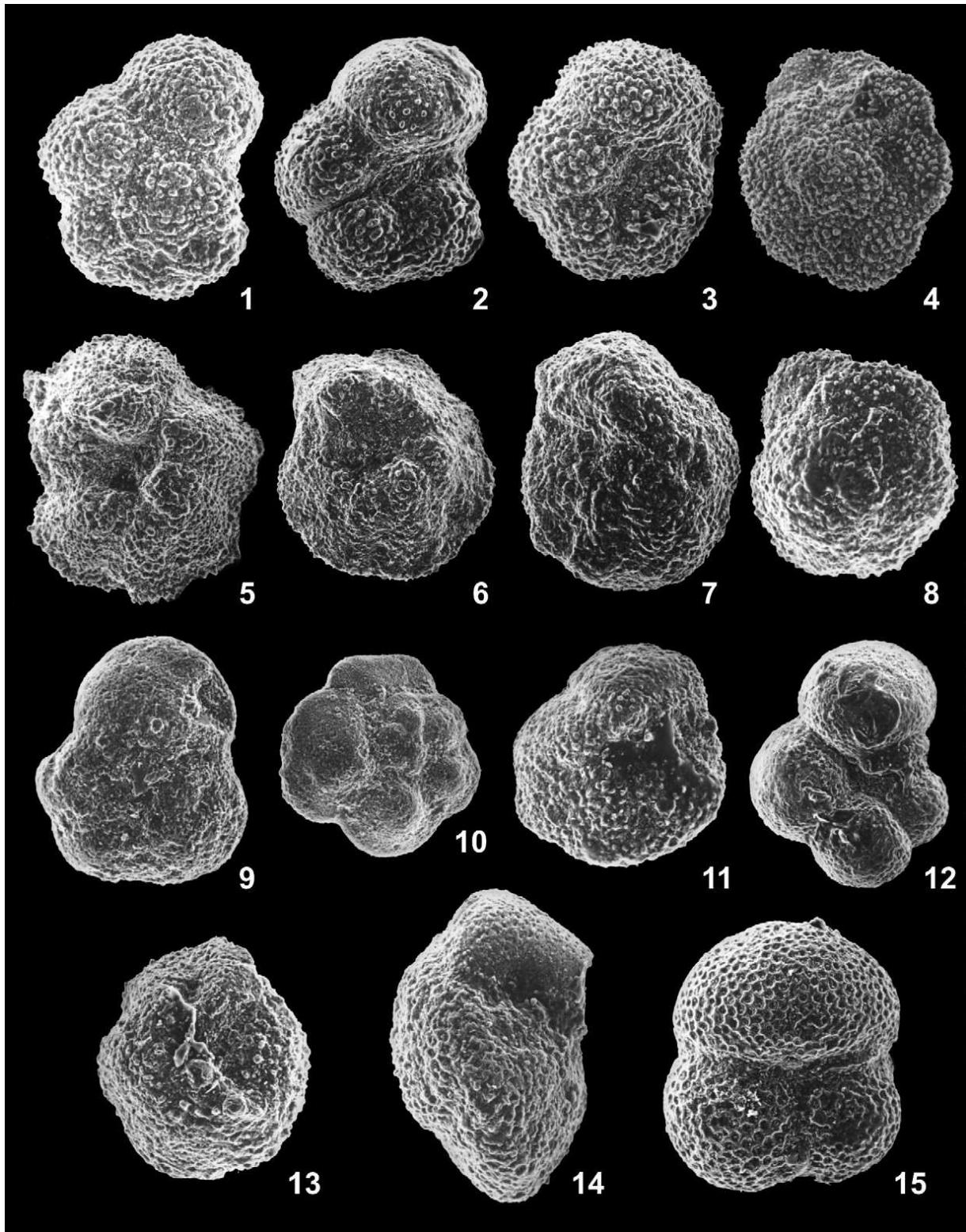
Sedimentation conditions are substantially different in East Tunisia (Fig. 1), as shown by the stratigraphic succession of the Jbel M'Daker (MDKB) section, a few km west of Enfidaville. The Danian is much more condensed and consists of an 8.2 m thick alternation of limestones and marls. It is unconformably overlain by grey marls and marly clays, of which the age was not well constrained up to now. Calcareous nannofossil investigation allowed for the first time detection of a major hiatus in that part of the Tunisian Basin, encompassing the late part of the Danian and the entire Selandian (interval from top of NP2 to base of NP6 is missing).

### 5.2.5. Egypt

The investigation of the Qreiya outcrop sections in Central Egypt reveals the presence of several omission surfaces in the top part of the essentially greyish shaly Lower Dakhla Formation, the lowermost of which (S1) seems to be consistent throughout the Nile Basin. Deep vertical and oblique bioturbations originate from this surface and penetrate in the underlying deposits (Fig. 9). Surface S1 is overlain by 8 cm of brownish heterogeneous

shale rich in fish debris and by 15 cm of dark brown laminated shale. The boundary between the grey shaly lower Dakhla Formation and the overlying beige-

coloured chalky marls of the upper Dakhla Formation is also marked by an omission surface (S2) with several bioturbations.



Speijer (2003) recorded a major paleoenvironmental shift at surface S1 in the Aweina section, marked by substantial changes in the foraminiferal assemblages. The dominant occurrence of *Neoeponides duwi* in the organic-rich layer, overlying surface S1, referred to as the “Neo-duwi event”, was believed to result from a 50 to 100 m shallowing of the depositional area. Speijer (2003) associated surface S1 with a sequence boundary and with the D/S boundary.

Preliminary studies of the nannofossil assemblages from the Egyptian sections led to the positioning of the first small *Fasciculithus* taxa (e.g. *F. chowii*). This lowest consistent occurrence (LCO) of *Fasciculithus* is recorded about 1.20 m below S1 (Sprong et al., in press). It is coinciding with the LCO of *Chiasmolithus edentulus* and with the start of rather frequent *Pontosphaera* spp. Identical associations have been recognised in West Tunisia at glauconitic level T1. The boundary between the shaly lower Dakhla Formation and the marly upper Dakhla Formation coincides with a major quantitative influx in calcareous nannofossils (doubling of number of specimens/mm<sup>2</sup>), characterised by the LCsO of *Fasciculithus janii* and the rare occurrence of *Toweius tovae*. It relates to a higher productivity within the sea surface layers and to a decrease in influx of siliciclastic material, which seems to point to a transgressive pulse. This boundary is coeval with the boundary between the Lasseube Formation and the Pont-Labau Formation in Aquitaine (event A2), dated as 59.9 Ma, being both bracketed between the LO of *Morozovella velascoensis* and the LO of *Fasciculithus tympaniformis*.

#### 5.2.6. Sea-level changes

The present sedimentological and micropaleontological investigation carried out along a N–S transect from North Sea Basin to southern Tethys has allowed deciphering of the amplitude, timing and nature of the depositional events, marking the Danian–Selidian transition. It shows that the 4 phases of sea-level change, identified in the D–S transition in the type area, are not all 4 primarily caused by eustacy, as previously thought (Clemmensen and Thomsen, 2005). On the

contrary, only the sea-level changes associated with steps 1 and 2 of Clemmensen and Thomsen (2005) have been consistently identified throughout the investigated area. Step 1, marked by a sea-level fall, is everywhere characterised by a discontinuity and substantial paleoenvironmental change, despite major latitudinal and paleobathymetric differences. It is interpreted as a major sequence boundary. Up to now, we do not know if this sea-level fall is a global phenomenon, as it has only been identified in the east Atlantic–North African realm, in basins with a common tectonic history. The sedimentological response to this plate tectonic event strongly diverges from area to area and is not equally pronounced. The shallow marine areas, such as the Belgian and the Danish Basins (complete change of depositional regime) were much more affected than the intermediate (Tunisia and Egypt, presence of discontinuity) and the deeper settings (Aquitaine and Zumaia). However, a 40 to 50 m sea-level drop seems to be compatible with the palaeoenvironmental data recorded along the studied transect, suggesting a major tectonic uplift pulse at ~60.3 million years ago in that part of the globe.

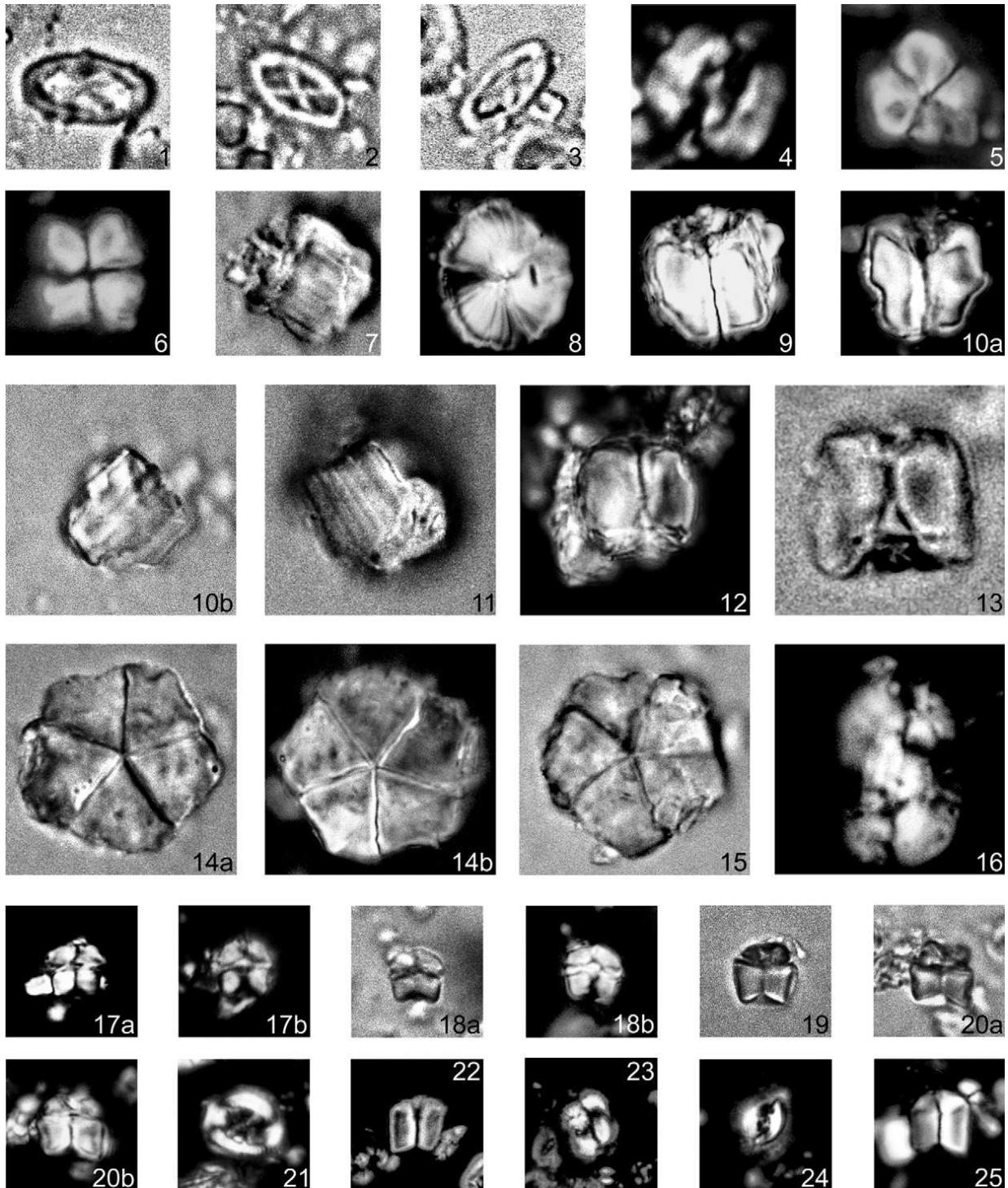
Step 2 of Clemmensen and Thomsen (2005), corresponding to a major shift from carbonate to siliciclastic depositional regime with major deepening of the sea-floor, has been recorded throughout the North Sea Basin, in Aquitaine and in N Spain, but seems not to have left any clear sedimentological imprint in the Tunisian areas. Recent investigations in Central Egypt provide evidence of a major change in depositional regime in the Nile Basin, coeval to the phenomena in the North Sea Basin, but of inverse nature, siliciclastics shifting to carbonates. Apparently, the paleoenvironmental shift, defining step 2, which coincides with the traditionally defined Danian/Selandian boundary and with the newly designated GSSP for this boundary (Zumaia), appears to be detectable on a widespread scale (global?). The micropaleontological and sedimentological data point to a major transgression, of which the origin is not well understood up to now. The sudden almost complete disappearance of the hyposaline braarudosphaeraceae in different basins throughout

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Plate I. 1, *Acarinina strabocella* (Loeblich and Tappan, 1957), Loubieng L6, ×200. 2, *Acarinina strabocella* (Loeblich and Tappan, 1957), Loubieng L29b, ×154. 3, *Morozovella praeangulata* (Blow, 1979), Bidart Bt16, ×171. 4, *Morozovella angulata* (White, 1928), Bidart Bt16, ×114. 5, *Morozovella conicotruncata* (Subbotina, 1947), Loubieng L7, ×114. 6, *Morozovella velascoensis* (Cushman, 1925), Loubieng L28, ×97. 7, *Morozovella apanthesma* (Loeblich and Tappan, 1957), Loubieng L17, ×142. 8, *Igorina albeari* (Cushman and Bermudez, 1949), Loubieng L29, ×200. 9, *Globanomalina compressa* (Plummer, 1927), Bidart Bt14, ×142. 10, *Globanomalina ehrenbergi* (Bolli, 1957), Bidart Bt17, ×114. 11, *Igorina albeari* (Cushman and Bermudez, 1949), Loubieng L17, ×171. 12, *Parasubbotina varianta* (Subbotina, 1953), Loubieng L29b, ×114. 13, *Igorina pusilla* (Bolli, 1957), Loubieng L17, ×171. 14, *Igorina pusilla* (Bolli, 1957), Loubieng L29, ×200. 15, *Subbotina velascoensis* (Cushman, 1925), Loubieng L28, ×142.

Europe at the D/S boundary is believed to be due to the interruption of freshwater influx, related to major climatic changes (probably a substantial decrease in precipitation). The difference in sedimentological signature between Europe (carbonates to siliciclastics) and

Egypt (siliciclastics to carbonates), originates from a different tectonic history. Plate tectonic compression in the Pyrenean area, due to collision of the W European and African plates, caused uplift in the central and eastern Pyrenees and major influx of siliciclastics in



northern (Aquitaine) and southern (N Spain) adjacent areas. Similar movements seem to have occurred in the northern North Sea Basin with uplift of the Scotland-Shetland landmass, related to the opening of the Northern Atlantic. The hypersaline braarudosphaeraceae are virtually absent in the southern Tethys (Tunisia and Central Egypt) indicating normal salinity conditions throughout the D/S boundary interval. The transgressive event, associated with step 2 in that area, coincides with the deepening of the basin and the decrease in land-derived siliciclastics.

The third step, marked by a major influx of Cretaceous nannofossils, is a phenomenon that seems to be restricted to the North Sea Basin. It is related to inversion of various local Cretaceous subbasins during the early Selandian, which in most places led to erosion of several hundred metres of chalk. As it has no correlative in more southern areas, it seems to be a regional, tectonic North Sea Basin-related event.

Step 4 corresponds to a rather abrupt change from marl to clay sedimentation in the Danish Subbasin, suggested to have occurred in the later part of the early Selandian (Clemmensen and Thomsen, 2005). It is believed to result from the installation of colder and acidic sea-bottom conditions, due to increasing water depth and restricted water circulation. In Belgium the transition from marl to clay occurred in two steps. The first step corresponds to a 25% reduction of the carbonate content, which took place during the late Selandian, dated at 58 to 58.5 Ma. The second, marked by a further 40% reduction of carbonate content occurred in the early Thanetian at ~57.5 Ma. Apparently there is a general shift from marls to clays in the North Sea Basin, although not simultaneously throughout the Basin. Step 4 as defined in the Danish Subbasin seems to be a local phenomenon.

### 5.3. The Loubieng section in light of the recent D/S boundary decisions

The present investigation has shown for the first time that the original D/S boundary criteria, defined in the type area of Denmark as a major influx in siliciclastics and a drastic decrease in braarudosphaeraceae proportions, cannot be identified outside the European basins and that the major lithological and paleoenvironmental shift in the Tethys area is not coeval with the D/S boundary in the type area, as previously thought (Steurbaut et al., 2000; Speijer, 2003; Van Itterbeek et al., 2007). This shift, coinciding with the P3a/P3b planktonic foraminiferal boundary and resulting from a tectonically induced sea-level fall (major sequence boundary), is 400 k.y. older. It is marked by the start of the consistent occurrence of small *Fasciculithus* spp. and by the replacement of a *Praemurica*-dominated by a *Morozovella*-dominated planktonic foraminiferal association. As these biotic phenomena are recorded on a widespread scale (except North Sea Basin) they might help in the global correlation of the D/S boundary interval and the positioning of the sequence boundary, 400 k.y. prior to the D/S boundary in the type area.

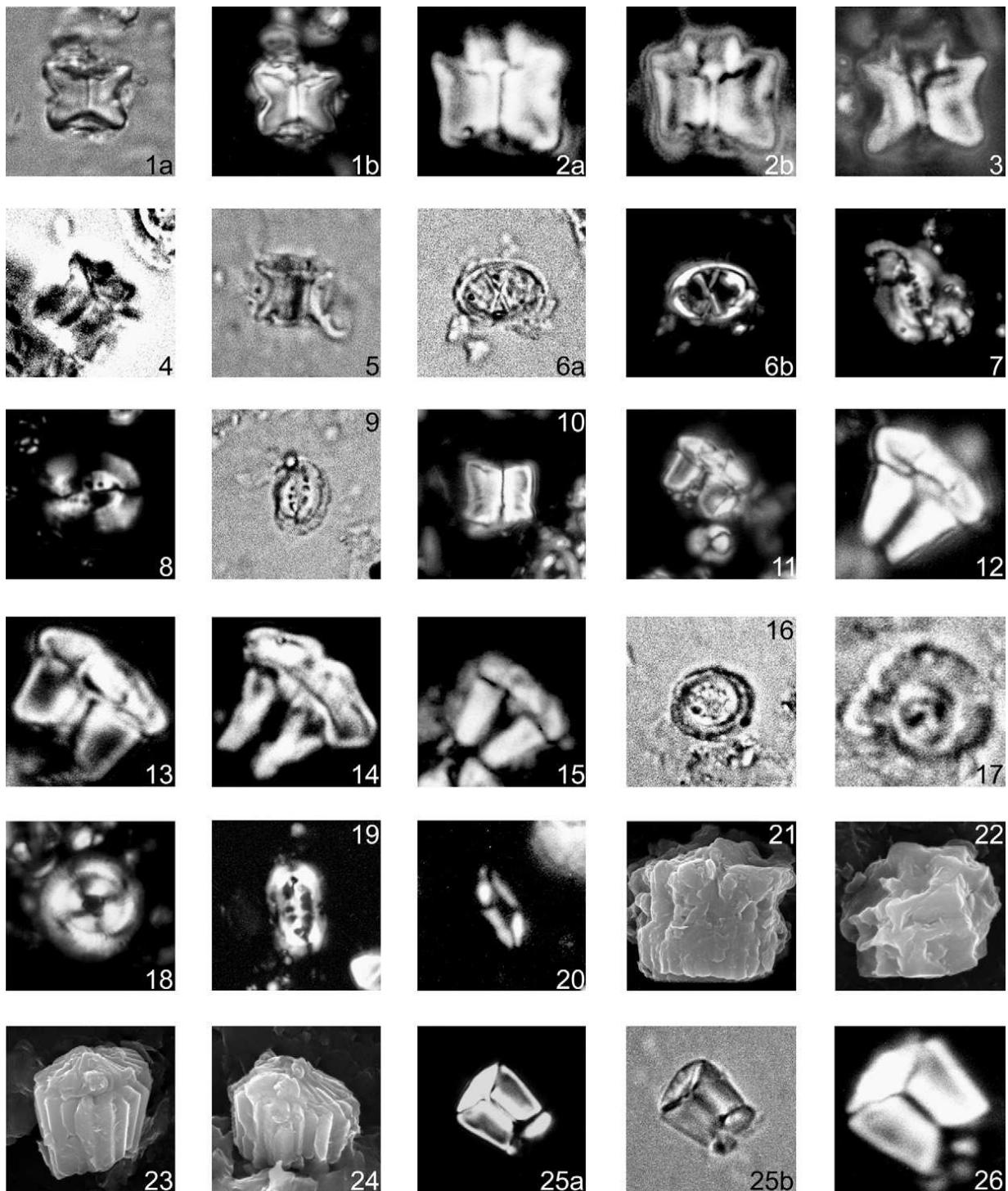
The present study also reveals that the Loubieng and the Zumaia sections are the only currently known D/S boundary sections, of which the microbiota shares elements with that of the North Sea Basin and that of the Tethys area, allowing global correlation. Both sections are marked by a common depositional history, as shown by the almost identical stratal succession and sequence of bio-events. Both sections fulfil all necessary conditions and recommendations for the establishment of a Global Stratotype Section and Point (GSSP) for the Danian/Selandian boundary. The final decision in

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Plate II. The calcareous nannofossil specimens figured on Plates II and III, as well as the negatives of micrographs, are stored at the Royal Belgian Institute of Natural Sciences (Brussels). Numbers (e.g. IRScNB b4975) refer to the collections of this institute. The following abbreviations are used: Bt = Bidart, c.p. = cross-polarised light, D = diameter, H = height, L = Loubieng, Le = length, SEM = Scanning Electron Microscope, t.l. = transmitted light and W = width. 1–3, *Neochiastozygus imbriei* Haq and Lohmann, 1976 — 1: Bt16, t.l., Le=6.4 µm, ×3125 (IRScNB b4967); 2: Bt15, t.l., Le=5.6 µm, ×3125 (b4968); 3: Bt17, t.l., Le=6.0 µm ×3125 (b4969). 4, *Ellipsolithus macellus* (Bramlette and Sullivan, 1961) — Bt18, c.p., Le=9.2 µm, ×2950 (IRScNB b4970). 5–6, *Sphenolithus primus* Perch-Nielsen, 1971 — 5: L1, c.p., W=5.2 µm, ×3650 (IRScNB b4971); 6: L3, c.p., W=4.8 µm, ×3750 (b4972). 7–12, *Fasciculithus magnus* Bukry and Percival, 1971 — 7: L2, t.l., W=12 µm, ×1420 (IRScNB b4973); 8: L3, c.p., W=13.5 µm, ×1700 (b4974); 9: L4, c.p., W=12 µm, ×1750 (b4975); 10: L4, a=c.p., b=t.l., W=12 µm, ×1500 (b4976); 11: L4, t.l., W=12 µm, ×1500 (b4977); 12: L4, c.p., W=12 µm, ×1600 (b4978). 13, *Fasciculithus magnicordis* Romein, 1979 — L4, t.l., W=8 µm, ×3000 (IRScNB b4979). 14–15, *Braarudosphaera bigelowii* (Gran and Braarud, 1935) — 14: L27, a=t.l., b=c.p., D=18.4 µm, ×1630 (IRScNB b4980); 15: L5, t.l., D=17.0 µm, ×1700 (b4981). 16, *Ellipsolithus macellus* (Bramlette and Sullivan, 1961) — L27, c.p., Le=10 µm, ×3300 (IRScNB b4982). 17–18, *Fasciculithus varolii* n. sp. — 17: L10, paratype, c.p., a=low focus, b=high focus, H=6.4 µm, ×1330 (IRScNB b4983); 18: L10, holotype, a=t.l., b=c.p., H=5.6 µm, ×1520 (IRScNB b4984). 19–20, *Fasciculithus ulii* Perch-Nielsen, 1971 — 19: L1bis, t.l., H=5.6 µm, ×1700 (IRScNB b4985); 20: L1bis, a=t.l., b=c.p., H=6.4 µm, ×1400 (IRScNB b4986). 21, *Chiasmolithus edentulus* van Heck and Prins, 1987 — L27, c.p., Le=8.8 µm, ×1700 (IRScNB b4987). 22, *Fasciculithus* sp. — L32, c.p., H=5.6 µm, ×1520 (IRScNB b4988). 23, *Toweius* sp. 1 — L2bis, c.p., Le=8.0 µm, ×1440 (IRScNB b4989). 24, *Toweius* sp. 2 — L8bis, c.p., Le=7.9 µm, ×1580 (IRScNB b4990). 25, *Fasciculithus tympaniformis* Hay and Mohler in Hay et al., 1967 — L32bis, c.p., W=5.6 µm, ×1520 (IRScNB b4991).

favour of Zumaia was made during an International Workshop of the Paleocene Working Group the 20th June 2007. The members of the group unanimously chose the base of the Itzurun Formation in the Zumaia section as GSSP, because of a somewhat better and more

permanent accessibility of the outcrop (coastal section versus quarry) and the wider gamut of scientific information available (magnetostratigraphic and cyclostratigraphic studies only currently present at Zumaia). However, the fossil content is better preserved at



Loubieng, and the quarry section presents no major structural displacements, as some parts of the Zumaia section do (although not in the D/S boundary interval). Exhibiting a permanent outcrop of 0.9 m.y. non-faulted microfossil-rich continuous sedimentation and situated in the same paleogeographic context as Zumaia, the Loubieng section constitutes an excellent auxiliary section for the D/S boundary. The good quality of its microbiota allows definition of correlative D/S boundary criteria for the Tethys area. The LCsO of *F. janii*, the LO of *Bomolithus elegans* and the LO of *Subbotina velascoensis* are coeval with D/S boundary criteria in the type area, permitting identification of the D/S boundary event on a global scale.

## 6. Conclusions

Forty-seven bio-events, of which 16 planktonic foraminiferal and 31 nannofossil events are identified in the Danian/Selandian boundary interval in SW France, in the 1.5 m.y. period spanning the upper Lasseube Formation and the lower Pont-Labau Formation. This sequence of bio-events, ranging from 61.2 Ma to 59.7 Ma, has allowed to clarify the temporal and spatial significance of the different depositional events marking the D/S transition in its type area in the North Sea Basin (the 4 steps or 4 phases of sea-level change of Clemmensen and Thomsen, 2005) and to correlate these throughout the S Tethys. Contrarily to what has been postulated, only the two lowermost steps and not all 4 (Clemmensen and Thomsen, 2005), represent widespread sea-level changes, due to plate tectonic adjustments, whereas the second, corresponding to the D/S boundary as defined in Denmark, is 400 k.y. younger than the supposed D/S boundary in the southern Tethys (Steurbaut et al., 2000; Speijer, 2003).

The first step, corresponding to a sea-level fall of the order of 40 to 50 m and dated as 60.3 Ma, caused

considerably biotic and depositional changes in all areas studied. It corresponds to 1. disappearance of bryozoa in Denmark and installation of a continental depositional regime in Belgium (e.g. the Hainin Formation, bearing the oldest Tertiary mammals from Europe); 2. development of channel systems with glauconite infill and replacement of a *Praemurica*-dominated by a *Morozovella*-dominated planktonic foraminiferal association in Tunisia and 3. onset of a period of non-deposition and the entry of a shallow marine benthic foraminiferal association (the well-known *Neo-duwi* event) in Central Egypt. The second step, dated as 59.9 Ma, corresponds to a major transgressive event, which is associated with the deposition of the Lellinge Greensand in Denmark, and hence, represents the D/S boundary. It corresponds to fundamental changes in the Aquitaine Basin, as shown by the replacement of limestone-dominated (Lasseube Fm) by siliciclastic deposition (Latapy Member of Pont-Labau Fm) and by the disappearance of the hypersaline braarudosphaeraceae, events that are simultaneously recorded in the North Sea Basin. The sudden almost complete disappearance of this nannofossil taxon in different basins throughout Europe at the D/S boundary seems to indicate major climatic changes, most probably a drastic decrease in precipitation. In Central Egypt this step coincides with the boundary between the shaly lower Dakhla Formation and the marly upper Dakhla Formation. The third step, marked by a major influx of Cretaceous nannofossils during the early Selandian, is a regional tectonic North Sea Basin-related event, whereas the fourth step, the abrupt change from marl to clay sedimentation in the later part of the early Selandian appears to be restricted to Denmark, and thus, represents a local tectonic phenomenon.

The Loubieng section supplements the Zumaia section, which, the 20th June 2007, was designated as GSSP for the D/S boundary by unanimous decision of the Paleocene Working Group. Because of its rich and

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Plate III. 1–5, *Fasciculithus vertebratoides* n. sp. — 1: L31, paratype, *a*=t.l., *b*=c.p.,  $W=7.5 \mu\text{m}$ ,  $\times 1670$  (IRScNB b4992); 2: L12, paratype, c.p., *a*=high focus, *b*=low focus,  $W=6.8 \mu\text{m}$ ,  $\times 2800$  (b4993); 3: L27, paratype, c.p.,  $W=6.4 \mu\text{m}$ ,  $\times 2810$  (b4994); 4: L27, paratype, t.l.,  $W=8.4 \mu\text{m}$ ,  $\times 1670$  (b4995); 5: L31, holotype, t.l.,  $W=8.8 \mu\text{m}$ ,  $\times 1360$  (IRScNB b4996). 6, *Neochiastozygus perfectus* Perch-Nielsen, 1971 — L2bis, *a*=t.l., *b*=c.p.,  $Le=8.8 \mu\text{m}$ ,  $\times 1590$  (IRScNB b4997). 7–8, *Ellipsolithus bollii* Perch-Nielsen, 1977 — 7: L29, c.p.,  $Le=10.5 \mu\text{m}$ ,  $\times 1620$  (IRScNB b4998); 8: L31, c.p.,  $Le=11.0 \mu\text{m}$ ,  $\times 1360$  (IRScNB b4999). 9, *Toweius* sp. 2 — L31, t.l.,  $Le=7.2 \mu\text{m}$ ,  $\times 1600$  (IRScNB b5000). 10, *Fasciculithus involutus* Bramlette and Sullivan, 1961 — L31, c.p.,  $W=7.0 \mu\text{m}$ ,  $\times 1570$  (IRScNB b5001). 11–15, *Fasciculithus janii* Perch-Nielsen, 1971 — 11: L28, c.p.,  $W=8.8 \mu\text{m}$ ,  $\times 1930$  (IRScNB b5002); 12: L29, c.p.,  $W=7.2 \mu\text{m}$ ,  $\times 2780$  (b5003); 13: L28, c.p.,  $W=7.2 \mu\text{m}$ ,  $\times 3125$  (b5004); 14: L29, c.p.,  $W=8.4 \mu\text{m}$ ,  $\times 2860$  (b5005); 15: L27, c.p.,  $W=6.0 \mu\text{m}$ ,  $\times 3000$  (b5006). 16, *Toweius tovae* Perch-Nielsen, 1971 — L6bis, t.l.,  $Le=8.4 \mu\text{m}$ ,  $\times 1370$  (IRScNB b5007). 17, *Bomolithus elegans* Roth, 1973 — L31, c.p.,  $W=8.0 \mu\text{m}$ ,  $\times 2750$  (IRScNB b5008). 18, *Coccolithus subpertusus* (Hay and Mohler, 1967) — L28, c.p.,  $D=11.2 \mu\text{m}$ ,  $\times 1420$  (IRScNB b5009). 19, *Ellipsolithus distichus* (Bramlette and Sullivan, 1961) — L32, c.p.,  $Le=9.6 \mu\text{m}$ ,  $\times 1560$  (IRScNB b5010). 20, *Scapholithus apertus* Hay and Mohler, 1967 — L31, c.p.,  $Le=4.0 \mu\text{m}$ ,  $\times 3375$  (IRScNB b5011). 21, *Fasciculithus vertebratoides* n. sp. — L28, paratype, SEM,  $W=8.3 \mu\text{m}$ ,  $\times 2890$  (IRScNB b5012). 22, *Sphenolithus primus* Perch-Nielsen, 1971 — L32, SEM,  $W=5.5 \mu\text{m}$ ,  $\times 4180$  (IRScNB b5013). 23–26, *Fasciculithus pileatus* Bukry, 1973 — 23: L32, SEM,  $W=5.1 \mu\text{m}$ ,  $\times 3430$  (IRScNB b5014); 24: L32, SEM,  $W=5.0 \mu\text{m}$ ,  $\times 4000$  (b5015); 25: L32, *a*=c.p., *b*=t.l.,  $H=7.2 \mu\text{m}$ ,  $\times 1530$  (b5016); 26: L32, c.p.,  $H=6.0 \mu\text{m}$ ,  $\times 3000$  (b5017).

well-preserved fossil content and continuous sedimentation the Loubieng section constitutes an excellent auxiliary section, forming a kind of intermediate station between Zumaia and the rest of the world.

## Acknowledgements

The authors wish to thank H. De Potter and W. Miseur (RBINS) for providing graphical assistance. Thanks are due to E. Molina and an anonymous reviewer for their critical reading of the manuscript and helpful suggestions. This research was financially supported by the Royal Belgian Institute of Natural Sciences — Brussels and by the “Fonds voor Wetenschappelijk Onderzoek (FWO) — Vlaanderen” (grant G.0527.05).

## Appendix A. Taxonomic remarks on the calcareous nannoflora

The taxonomy adopted here is that of Perch-Nielsen (1985), taking into account the modifications of Van Heck and Prins (1987) and Varol (1992). The taxonomic discussions are restricted to key-species with a doubtful taxonomic record and to taxa that are new to science or have been recognized for the first time. Species are discussed in alphabetic order. Synonymy lists, if present, only include the original citation, the citations related to the same geographic area and those that gave rise to subsequent erroneous interpretations. A full taxonomic list of all nannofossil and foraminiferal taxa cited in this paper is given in Appendix B. Abbreviations used: B = breadth, D = diameter, H = height, Le = length, W = width.

**Family Fasciculithaceae Hay and Mohler, 1967**  
**Genus *Fasciculithus* Bramlette and Sullivan, 1961**  
*Fasciculithus involutus* Bramlette and Sullivan, 1961  
 Plate III, Fig. 10

1961 *Fasciculithus involutus* Bramlette and Sullivan, p. 164, Plate 14, Figs. 1–5.

1971 *Fasciculithus involutus* Bramlette and Sullivan, 1961; Perch-Nielsen, p. 351, Plate 4, Figs. 1–10; Plate 7, Fig. 5; Plate 14, Figs. 28–30.

1989 *Fasciculithus involutus*; Varol, Plate 12.5, Fig. 5.

**Remarks:** Medium-sized species of *Fasciculithus* ( $H \sim 8 \mu\text{m}$ ,  $W \sim 8 \mu\text{m}$ ) consisting of a cylindrical proximal column with several (around ten) conspicuous surface ridges and many depressions usually arranged in various cycles and an overlying very low cone.

*Fasciculithus janii* Perch-Nielsen, 1971  
 Plate III, Figs. 11–15

1971 *Fasciculithus janii* Perch-Nielsen, p. 352, Plate 5, Figs. 1–4 (non Plate 14, Figs. 37–39).

1973 *Fasciculithus pileatus* Bukry, p. 307, Plate 2, Fig. 1 (non Plate 1, Figs 7–9; Plate 2, Figs 2–5).

1989 *Fasciculithus janii* Perch-Nielsen, 1971; Varol, Plate 12.5, Figs. 1–2.

1989 *Fasciculithus janii* Perch-Nielsen, 1971; Aubry, p. 132, Figs. 127–131 (non p. 130, Figs. 124–126).

*Fasciculithus bitectus* Romein, 1979; Aubry, p. 130, Figs. 122–123 (non Fig. 121).

1989 *Fasciculithus pileatus* Bukry, 1973; Aubry, p. 130, Fig. 110 (non Figs. 107–109, 111–114).

2002 *Fasciculithus pileatus* Bukry, 1973; Steurbaut and Sztrákos, Plate 4, Fig. 10.

2002 *Fasciculithus janii* Perch-Nielsen, 1971; Steurbaut and Sztrákos, Plate 3, Figs. 10–11 (non Plate 4, Fig. 8).

**Remarks:** Medium-sized species ( $H \sim 7 \mu\text{m}$ ,  $W$  disk  $\sim 8 \mu\text{m}$ ,  $W$  column  $\sim 5 \mu\text{m}$ ) marked by a solid, proximally tapering proximal column and a distal disk, consisting of a series of radial elements, which form a central cone around a small central hole. It shows strong birefringence in cross-polarized light in side view, marked by a bended cap with a central diamond-like structure, clearly overlapping the proximal column. The differences in outline of some specimens (less tapering and more rectangular, see Plate III, Figs. 11 and 13) are considered to represent intraspecific variability. Some of the paratypes, notably those figured with the light microscope Perch-Nielsen, 1971, Plate 14, Figs. 37–39), do not belong to *F. janii*, but to *Fasciculithus vertebroides* n. sp. (see below) on the basis of differences in birefringence (irregular pattern with higher order colors e.g. deep blue), an egg-timer-shaped outline and the absence of a distal disk. Between crossed nicols the distal disk in *F. janii* appears as a single optically uniform cycle of elements, contrarily to *F. bitectus* (see Perch-Nielsen, 1985, p. 482, Fig. 38.24), which shows distally two superimposed, optically differently oriented rings of elements.

*Fasciculithus magnicordis* Romein, 1979

Plate II, Fig. 13

1979 *Fasciculithus magnicordis* Romein, p. 149, Plate 9, Figs. 12–13.

**Remarks:** Medium-sized species ( $H \sim 7 \mu\text{m}$ ,  $W \sim 9 \mu\text{m}$ ) with flat cylindrical outline, consisting of 20 to 30 wedges with a smooth outer surface and a large and deep distal depression (central body).

*Fasciculithus magnus* Bukry and Percival, 1971

Plate II, Figs. 7–12

1971 *Fasciculithus magnus* Bukry and Percival, p. 131, Plate 4, Figs. 9–12.

1979 *Fasciculithus magnus* Bukry and Percival; Romein, p. 148, Plate 9, Fig. 14.

1985 *Fasciculithus magnus* **Bukry and Percival, 1971**; Perch-Nielsen, p. 483, Figs. 38.64, 39.6–7.

1989 *Fasciculithus magnus* **Bukry and Percival, 1971**; Aubry, p. 110, Figs. 1–4; p. 112, Fig. 5–8.

**Remarks:** Easily recognizable large species ( $H \sim 12 \mu\text{m}$ ,  $W_{\text{prox}} \sim 9.5 \mu\text{m}$ ,  $W_{\text{dist}} \sim 12 \mu\text{m}$ ) marked by a solid column, consisting of a short proximal part and a much higher distal part. The latter shows a deep conical depression.

#### *Fasciculithus pileatus* **Bukry, 1973**

**Plate III**, Figs. 23–26

1973 *Fasciculithus pileatus* **Bukry**, p. 307, Plate 1, Figs. 7–9; Plate 2, Figs. 2–5 (non Plate 2, Fig. 1).

1989 *Fasciculithus pileatus* **Bukry, 1973**; Varol, Plate 12.5, Figs. 3–4.

**Remarks:** Medium-sized species ( $H \sim 6$  to  $8 \mu\text{m}$ ,  $W \sim 6$  to  $8 \mu\text{m}$ ) with truncated cone-shaped column, covered by a lens-shaped cap, which does not extend beyond the column. In cross-polarized light, the bisected column and the cap form three distinct bright areas in side view.

*Fasciculithus tympaniformis* Hay and Mohler in **Hay et al., 1967**

**Plate II**, Fig. 25

*Fasciculithus tympaniformis* Hay and Mohler in **Hay et al., 1967**; Hay and Mohler, p. 1537, Plate 204, Figs. 10–15; Plate 205, Figs. 4,5,7,8.

1971 *Fasciculithus tympaniformis* **Hay and Mohler, 1967**; Perch-Nielsen, p. 349, Plate 1, Figs. 1–5, 7.

1985 *Fasciculithus tympaniformis* Hay and Mohler in **Hay et al., 1967**; Perch-Nielsen, p. 483, Fig. 38.37–38, Fig. 39.10.

1989 *Fasciculithus tympaniformis*; Varol, p. 304, Plate 12.5, Figs. 8–9.

2002 *Fasciculithus tympaniformis* Hay and Mohler in **Hay et al., 1967**; Steurbaut and Sztrákos, Plate 4, Fig. 24.

**Remarks:** Species of variable size ( $H \sim 5.5$  to  $8 \mu\text{m}$ ,  $W \sim 5$  to  $7 \mu\text{m}$ ) with a sub-cylindrical distally slightly tapering column, forming a rounded, slightly pointed end. The outline is smooth, without conspicuous ridges and depressions. A few tabular plates are present on the pointed end. In side view, in cross-polarized light, the longitudinal optical extinction line is bifurcated or passes from vertical to oblique at the central body.

#### *Fasciculithus ulii* **Perch-Nielsen, 1971**

**Plate II**, Figs. 19–20

1971 *Fasciculithus ulii* Perch-Nielsen, p. 350, Plate 2, Figs. 1–4; pl. 14, Figs. 17–18.

1979 *Fasciculithus ulii* Perch-Nielsen; Romein, p. 149, Plate 4, Fig. 7.

1989 *Fasciculithus ulii*; Varol, Plate 12.5, Fig. 10.

2002 *Fasciculithus ulii* **Perch-Nielsen, 1971**; Steurbaut and Sztrákos, Plate 4, Fig. 11–13.

**Remarks:** Medium-sized ( $H \sim 7 \mu\text{m}$ ,  $W \sim 7 \mu\text{m}$ ) robust form with an irregularly outlined column, marked by various conspicuous protruding elements. The proximally tapering column is covered by a distal dome-like structure, consisting of one or more flat cycles of elements.

#### *Fasciculithus varolii* n. sp.

**Plate II**, Figs. 17–18

**Derivation of name:** In honour of Dr. Osman Varol (Llandudno, UK), author of a high-resolution low to middle latitude Paleocene calcareous nannofossil zonation.

**Diagnosis:** Small form ( $\sim 5.5 \mu\text{m}$ ), of equal height and width, consisting of three distinct structures, including a proximal column, a middle cycle of lateral elements and a distal superimposed mushroom-shaped cone.

**Description:** The proximal column is only half as high as the fasciculith. It is highly concave at its proximal end and made up of numerous elements with clear edges. It is covered by a distal dome-shaped structure, consisting of a rather small cycle of lateral elements, which slightly overlap the column. A much higher, but slightly less wide mushroom-shaped cone occurs on top of this cycle. Both the lateral cycle and the dome are well distinguishable as two superimposed, optically different structures in cross-polarized light in side view.

**Dimensions:** Height  $5.2$ – $6.4 \mu\text{m}$ , width  $5.3$ – $6.2 \mu\text{m}$ .

**Holotype:** **Plate II**, Fig. 18 (IRScNB b4984).

**Paratype:** **Plate II**, Fig. 17 (IRScNB b4983).

**Type-level:** Upper part of Lasseube Formation, sample L10, Uppermost Danian, upper part of nannozone NP4.

**Type locality:** Loubieng quarry, S Aquitaine, SW France.

**Stratigraphical range:** Lower upper part of Laseube Formation (L10 to L12).

#### *Fasciculithus vertebratoides* n. sp.

**Plate III**, Figs. 1–5, Fig. 21

1971 *Fasciculithus janii* Perch-Nielsen, Plate 14, Figs. 37–39 (non Plate 5, Figs. 1–4).

**Derivation of name:** Vertebratoides = vertebra-like, points to its superficial resemblance to fish vertebrae.

**Diagnosis:** Egg-timer-shaped fasciculith with variable size ( $W \sim 6$  to  $8 \mu\text{m}$ ), consisting of a high proximal column and a low and small distal cone forming a cylindrical ring of elements.

**Description:** Fasciculith with an egg-timer-shaped outline in side view, resembling fish vertebrae. Early forms (L12:  $H \sim 5.6 \mu\text{m}$ ,  $W$  base  $\sim 5.6 \mu\text{m}$ ,  $W$  center  $\sim 4.5 \mu\text{m}$ ) are much smaller than later forms (L27:  $H \sim 7.2 \mu\text{m}$ ,  $W$  base  $\sim 8 \mu\text{m}$ ,  $W$  center  $\sim 5.6 \mu\text{m}$ ). The proximal column is build up of a series of conspicuous surface ridges and deep grooves and is strongly birefringent presenting an irregular color pattern. A low distal cone is present. It consists of a cylindrical ring of elements, the width of which is only 1/3 of the total width of the fasciculith. In single polarized light this ring is seen as two low knobby protrusions.

**Dimensions:** Height  $5.6$ – $7.2 \mu\text{m}$ , width base  $5.6$ – $8.0 \mu\text{m}$ .

**Holotype:** Plate III, Fig. 5 (IRScNB b4996).

**Paratypes:** Plate III, Figs. 1–4, Fig. 21 (IRScNB b4992–b4995).

**Type-level:** Lower part of Pont-Labau Formation, sample L31, Top Danian, top of nannozone NP4.

**Type locality:** Loubieng quarry, S Aquitaine, SW France.

**Stratigraphical range:** Upper part of Lasseube Formation to base Pont-Labau Formation; from L12 to L32.

**Remarks:** Is easily distinguishable from the holotype of *F. janii* (Perch-Nielsen, 1971, Plate 5, Fig. 1) by its egg-timer-shaped form, the absence of a distal cap and differences in birefringence (see above).

#### *Fasciculithus* sp.

Plate II, Fig. 22

**Remarks:** Relatively small forms ( $H \sim 6.4 \mu\text{m}$ ,  $W \sim 5.6 \mu\text{m}$ ) with a proximally tapering column, consisting of a series of rather smooth elements with small depressions, especially in the more distal parts, and a dome-shaped very small cone. In side view, in cross-polarized light, the longitudinal optical extinction line is bifurcated. On the basis of these characters these forms are grouped in a separate taxon, which shares features with *F. involutus* (optical colour pattern between crossed nicols; presence of depressions). However, differences, such as their smaller size, tapering outline and configuration of the cone, exclude inclusion in *F. involutus*, and may point to a species new to science.

#### Family Heliolithaceae Hay and Mohler, 1967

Genus *Bomolithus* Roth, 1973

*Bomolithus elegans* Roth, 1973

Plate III, Fig. 17

1973 *Bomolithus elegans* Roth, p. 734, Plate 15, Figs. 1–6.

2002 *Bomolithus elegans* Roth, 1973; Steurbaut and Sztrákos, Plate 4, Fig. 27.

**Remarks:** Medium-sized form ( $D \sim 8 \mu\text{m}$ ) consisting of a rather high column and two wider cycles of elements of almost equal diameter (median and distal cycle). Only the column is birefringent in cross-polarised light.

Family Prinsiaceae Hay and Mohler, 1967

Genus *Toweius* Hay and Mohler, 1967

*Toweius tovae* Perch-Nielsen, 1971

Plate III, Fig. 16

1971 *Toweius tovae* Perch-Nielsen, p. 359, Plate 13, Figs. 1–3, 5, Plate 14, Figs. 8–9.

1995 *Toweius eminens* (Bramlette and Sullivan, 1961) Gartner, 1971 var. *tovae* Perch-Nielsen, 1971; Bybell and Self-Trail, p. 33, pl. 26, Figs. 2, 5a,b, 7, 9; pl. 27, Figs. 2, 3, 5, 8; pl. 37, Fig. 22.

1998 *Toweius tovae* Perch-Nielsen, 1971; Steurbaut, Plate 2, Figs. 1–2.

**Remarks:** Round elliptical coccolith ( $L \sim 8.0 \mu\text{m}$ ,  $B \sim 7.2 \mu\text{m}$ ) with irregularly distributed perforations in the central area. Number and size of perforations vary greatly, although the small and somewhat larger pores always co-occur.

*Toweius* sp.1

Plate II, Fig. 23

**Remarks:** round rather large elliptical coccolith ( $L \sim 8.8 \mu\text{m}$ ,  $B \sim 7.5 \mu\text{m}$ ) with 10 to 15 very small perforations in the central area of the coccolith.

*Toweius* sp. 2

Plate II, Fig. 24; Plate III, Fig. 9

**Remarks:** large elongated coccolith ( $L \sim 9.6 \mu\text{m}$ ,  $B \sim 7.2 \mu\text{m}$ ) with around 10 medium-sized perforations. Central part is strongly birefringent.

*Toweius* sp. 3

**Remarks:** small, elongated elliptical coccolith ( $L \sim 4.8 \mu\text{m}$ ,  $B \sim 3.9 \mu\text{m}$ ) with 4 to 5 equally sized perforations in the center.

#### Appendix B. Alphabetic list of foraminiferal and nannofossil species mentioned

##### Planktonic foraminifera

*Acarinina strabocella* (Loeblich and Tappan, 1957)  
(Plate I, Figs. 1–2)

*Chiloguembelina midwayensis* (Cushman, 1940)  
*Chiloguembelina* sp.  
*Globanomalina compressa* (Plummer, 1927) (Plate I, Fig. 9)  
*Globanomalina ehrenbergi* (Bolli, 1957) (Plate I, Fig. 10)  
*Igorina albeari* (Cushman and Bermudez, 1949) (Plate I, Figs. 8, 11)  
*Igorina pusilla* (Bolli, 1957) (Plate I, Figs. 13–14)  
*Morozovella angulata* (White, 1928) (Plate I, Fig. 4)  
*Morozovella apanthesma* (Loeblich and Tappan, 1957) (Plate I, Fig. 7)  
*Morozovella conicotruncata* (Subbotina, 1947) (Plate I, Fig. 5)  
*Morozovella praearangulata* (Blow, 1979) (Plate I, Fig. 3)  
*Morozovella velascoensis* (Cushman, 1925) (Plate I, Fig. 6)  
*Parasubbotina pseudobulloides* (Plummer, 1927)  
*Parasubbotina varianta* (Subbotina, 1953) (Plate I, Fig. 12)  
*Praemurica inconstans* (Subbotina, 1953)  
*Praemurica uncinata* (Bolli, 1957)  
*Subbotina triangularis* (White, 1928)  
*Subbotina triloculinoides* (Plummer, 1927)  
*Subbotina velascoensis* (Cushman, 1925) (Plate I, Fig. 15)  
*Subbotina* sp.

Species discussed in text although not recorded:  
*Globanomalina pseudomenardii* (Bolli, 1957)

#### Benthic foraminifera

*Angulogavelinella avnimelechi* (Reiss, 1952)  
*Cibicidoides allenii* (Plummer, 1927)  
*Gavelinella abudurbensis* (Nakkady, 1950)  
*Gyroidinoides globosa* (von Hagenow, 1842)  
*Gyroidinoides subangulata* (Plummer, 1927)  
*Neoeponides duwi* (Nakkady, 1950)  
*Nuttallides truempyi* (Nuttall, 1930)  
*Osangularia velascoensis* (Cushman, 1925)  
*Svenia bulbosa* (Halkyard, 1919)  
*Stensioeina beccariiformis* (White, 1928)  
*Textularia plummerae* Lalicker, 1935  
*Thalmannita madrugaensis* (Cushman and Bermudez, 1947)  
*Tritaxilina cubensis* (Cushman and Bermudez, 1937)

#### Calcareous nannofossils

*Bomolithus elegans* Roth, 1973 (Plate III, Fig. 17)  
*Braarudosphaera alta* Romein, 1979

*Braarudosphaera bigelowii* (Gran and Braarud, 1935) Deflandre, 1947; (Plate II, Figs. 14–15)  
*Braarudosphaera discula* Bramlette and Riedel, 1954  
*Chiasmolithus edentulus* van Heck and Prins, 1987 (Plate II, Fig. 21)  
*Coccolithus pelagicus* (Wallich, 1877) Schiller, 1930  
*Coccolithus subpertusus* (Hay and Mohler, 1967) van Heck and Prins, 1987 (Plate III, Fig. 18)  
*Cruciplacolithus* spp.  
*Ellipsolithus bollii* Perch-Nielsen, 1977 (Plate III, Figs. 7–8)  
*Ellipsolithus distichus* (Bramlette and Sullivan, 1961) Sullivan, 1964 (Plate III, Fig. 19)  
*Ellipsolithus macellus* (Bramlette and Sullivan, 1961) Sullivan, 1964 (Plate II, Figs. 4, 16)  
*Fasciculithus billii* Perch-Nielsen, 1971  
*Fasciculithus chowii* Varol, 1989  
*Fasciculithus involutus* Bramlette and Sullivan, 1961 (Plate III, Fig. 10)  
*Fasciculithus janii* Perch-Nielsen, 1971 (Plate III, Figs. 11–15)  
*Fasciculithus magnicordis* Romein, 1979 (Plate II, Fig. 13)  
*Fasciculithus magnus* Bukry and Percival, 1971 (Plate II, Figs. 7–12)  
*Fasciculithus pileatus* Bukry, 1973 (Plate III, Figs. 23–26)  
*Fasciculithus tympaniformis* Hay and Mohler in Hay et al., 1967 (Plate II, Fig. 25)  
*Fasciculithus ulii* Perch-Nielsen, 1971 (Plate II, Figs. 19–20)  
*Fasciculithus varolii* n. sp. (Plate II, Figs. 17–18)  
*Fasciculithus vertebratoides* n. sp. (Plate III, Figs. 1–5, Fig. 21)  
*Fasciculithus* sp. (Pl. 2, Fig. 22)  
*Micrantholithus* spp.  
*Neochiastozygus eosaeipes* Perch-Nielsen, 1981  
*Neochiastozygus imbriei* Haq and Lohmann, 1976 (Plate II, Figs. 1–3)  
*Neochiastozygus perfectus* Perch-Nielsen, 1971 (Plate III, Fig. 6)  
*Placozygus* sp.  
*Scapholithus apertus* Hay and Mohler, 1967 (Plate III, Fig. 20)  
*Sphenolithus primus* Perch-Nielsen, 1971 (Plate II, Figs. 5–6; Plate III, Fig. 22)  
*Sullivania* aff. *consueta* (Bramlette and Sullivan, 1961) Varol, 1992  
*Sullivania* spp.  
*Toweius pertusus* (Sullivan, 1965) Romein, 1979  
*Toweius tovae* Perch-Nielsen, 1971 (Plate III, Fig. 16)

- Toweius* sp. 1 (Plate II, Fig. 23)  
*Toweius* sp. 2 (Plate II, Fig. 24; Plate III, Fig. 9)  
*Toweius* sp. 3
- Species discussed in text although not recorded:  
*Toweius eminens* (Bramlette and Sullivan, 1961)  
Perch-Nielsen, 1971

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