Biostratigraphy of the Danian/Selandian transition in the southern Tethys. Special reference to the Lowest Occurrence of planktic foraminifera *Igorina albeari*

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┤ A B S T R A C T ├

The P3a/P3b subzonal boundary is delineated by the lowest occurrence of *Igorina albeari*. Using literature, identification of the first representatives of *I. albeari* appeared to be very confusing. In this study descriptions of *I. albeari* are compared and a consistent definition is proposed. Igorinid specimens with an incipient keel are considered to be *I. albeari*. Flattening of the last chambers and the fusion of muricae on the peripheral margin may indicate such a slight keel. This keel enables an unambiguous distinction between *I. pusilla* and the first form of *I. albeari* and is in keeping with the original descriptions without introducing an intermediate species. In the southern Tethys, the lowest occurrence of *I. albeari* occurs just prior to the pinkish-brown marl bed in Egypt and immediately overlies the glauconitic bed in Tunisia. Furthermore, the NTp7A/NTp7B subzonal boundary, delineated by the lowest occurrence of *Chiasmolithus edentulus*, is in close correlation with these marker beds. In Egypt *C. edentulus* appears 1 m below the entry of *I. albeari*, whereas in Tunisia they co-appear. This implies significant erosion at the glauconitic bed in the studied parts of the Tunisian Trough and a more complete succession at the dark-brown marl bed in the Nile Valley. These marker beds can also be correlated to a level of minor lithologic change in the upper part of the Danian Limestone Formation in the Zumaia section through the lowest occurrence of *Chiasmolithus edentulus*. The distinct lithologic change in Zumaia, from the Danian Limestone to the Itzurun Formation, however, appears to be ~600 kyr younger than what we now call upper Danian event beds, in Tunisia and Egypt.

KEYWORDS │ Planktic foraminifera. Calcareous nannofossils. Egypt. Tunisia. Paleocene.

INTRODUCTION

The Danian, the lowermost stage of the Paleocene, was introduced by Desor (1847), who named it after its type area in Denmark. It consists of chalks and limestones overlying the Maastrichtian chalks. The Selandian, the second Paleocene stage, was also defined in Denmark, named after the island of Sjælland. In the type region, this

stage is composed of greensands, marls and clays unconformably overlying the Danian limestones (Rosenkrantz, 1924; Thomsen and Heilmann-Clausen, 1985). The transition to more terrestrially influenced deposition during the Selandian terminated a ~35 m.y. period of hemipelagic carbonate deposition in the Danish basin (Håkansson et al., 1974; Schmitz et al., 1998). This change in depositional regime, which occurred around 60 Ma, has been related to the opening of the northeast Atlantic and the uplift of west European landmasses (Berggren, 1994; Nielsen et al. 2005).

Like most Paleogene stages defined in northwest European basins, the Danian and Selandian Stages and their unconformable contacts have proven difficult to correlate globally. Age and duration of the unconformity between these stages vary geographically, but there is general consensus that the top of the Danian correlates with a level within the upper part of calcareous nannofossil Zone NP4, close to the NP4/NP5 boundary (Thomsen and Heilmann-Clausen, 1985) and within planktic foraminiferal Zone P3 (Clemmensen and Thomsen, 2005). The base of the Selandian correlates with a level in the upper half of Zone NP4 or the lower part of Zone NP5 (Thomsen and Heilmann-Clausen, 1985; Thomsen, 1994; Stouge et al., 2000) and Zone P3 (Stouge et al., 2000; Clemmensen and Thomsen, 2005). The unconformity at the Danian/Selandian (D/S) boundary in the type region would thus span an interval within upper Zone NP4/lower Zone NP5, correlative with a level within Zone P3.

Because correlation of the D/S boundary with standard biostratigraphic schemes has remained ambiguous, there has been no agreement on a stratigraphic marker for this boundary. Berggren (1994) and Berggren et al. (1995, 2000) proposed to correlate the D/S boundary with the P2/P3 zonal boundary (~60.9 Ma), whereas Hardenbol et al. (1998) positioned the sequence boundary Sel 1 (the unconformity between the Danian and Selandian Stages) in western Europe within the lower part of Subzone P3a (~60.7 Ma) and Clemmensen and Thomsen (2005) placed it at the top of Zone NP4 within Zone P3 (~60 Ma). In search of the D/S boundary in middle to low latitude outcrops, studies were carried out in Egypt (Speijer, 2003a; Guasti et al., 2005) and Tunisia (Steurbaut et al., 2000; Guasti et al., 2006; Van Itterbeeck et al., 2007). In all sections, the D/S boundary was suggested to coincide with a distinct lithologic change or marker bed, but it remained uncertain whether these levels accurately correlate. Both in Egypt and Tunisia, the lithologic and associated biotic changes suggest sea-level fall and rise, tentatively correlated with Sel 1 of Hardenbol et al. (1998). Biostratigraphically this interval is situated in the middle part of Zone P3 and within the upper part of calcareous nannofossil Zone NP4 (Guasti et al., 2005; Van Itterbeeck et al.,

2007). In this report we further explore the biostratigraphic position (planktic foraminifera and calcareous nannofossils) of these changes by comparing successions from eight sections in six localities from Egypt and Tunisia. We particularly focus on delineating the P3a/P3b subzonal boundary on the basis of the lowest occurrence of *Igorina albeari* (Berggren et al., 1995; Berggren and Pearson, 2005) relative to the lithologic and biotic changes observed.

GEOLOGY AND LITHOSTRATIGRAPHY

Egypt

The studied sections are located along the Nile Valley (Gebel Aweina, Gebel Qreiya) and the Red Sea coast (Gebel Duwi) (Fig. 1). The sediments studied were deposited in an epicontinental basin on the northwestern margin of the Arabian-Nubian shield. All localities studied are situated on the tectonically inactive part of the basin, the so-called stable shelf (Said, 1962). During the early to early late Paleocene, the Egyptian successions were deposited at middle to outer neritic depths (Speijer, 2003a). In the study area, the Danian and Selandian Stages are represented by the upper part of the Maastrichtian-Paleocene Dakhla Formation (Fm) (Said, 1962, 1990; Hendriks et al., 1987). This formation consists of rather monotonous brownish to grey marls and shales with occasional intercalated thin marly limestone beds (Fig. 2).

Within the D/S transition, the monotonous sequence of the Dakhla Fm is interrupted by a pinkish-brown marl bed (up to 30 cm thick), which is laminated in the lower part, heavily bioturbated, rich in fish remains and has abundant numbers of planktic foraminifera (>99%) and no in situ benthic foraminifera. The upper part has ~85% planktic foraminifera and contains abundant specimens of the benthic foraminiferal species *Neoeponides duwi*.

Tunisia

The studied successions in NW Tunisia, Sidi Nasseur (subsections NSF and NSC'05), Garn Halfaya and Elles, were also located at the southern margin of the Tethys (Fig. 1) and were part of a basin known as the Tunisian Trough (Burollet, 1956, 1991; Salaj, 1980; Bobier et al., 1991). During the early to early late Paleocene, the Tunisian successions were deposited at middle to outer neritic depths (e.g., Guasti et al., 2006). The three studied localities expose the El Haria Formation (Fm), spanning the Maastrichtian to lower Ypresian, and mainly consist of brown-grey homogeneous marls and shales (Burollet, 1956). Within the D/S transition a distinct glauconite-rich
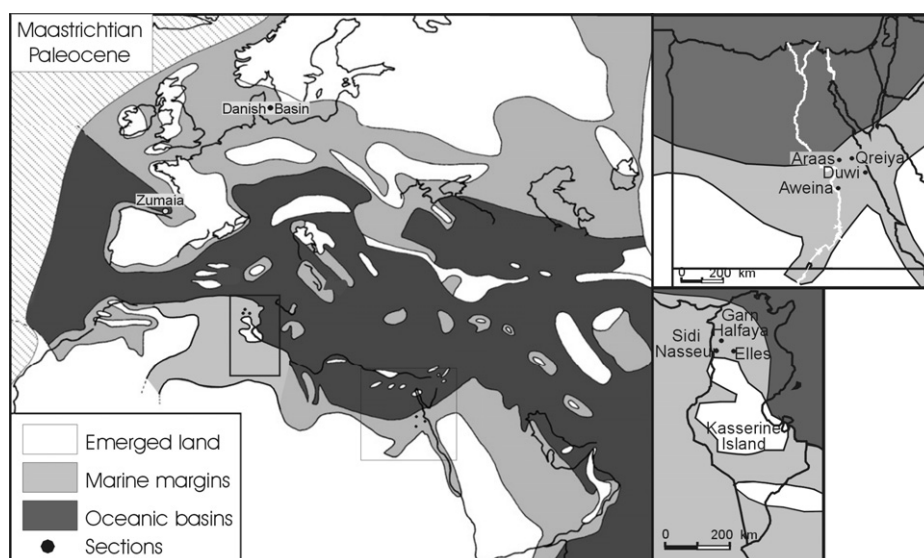
FIGURE 1 | **Location of sections within Europe and northern Africa superimposed on the paleogeographic situation around the Maastrichtian-Paleocene transition (modified after Gheerbrandt and Rage, 2006). Egypt and Tunisia are shown in more detail.**

marl bed (50-80 cm thick at Sidi Nasseur, about 30 cm at Garn Halfaya and about 20 cm at Elles) interrupts the homogeneous sequence of the El Haria Fm. At Elles this glauconitic bed separates underlying grey marls from overlying dark brown shaley marls (Fig. 2).

MATERIAL AND METHODS

The Paleocene *Igorina* lineage is studied on the basis of samples from the six localities from Egypt and Tunisia. These samples were collected during fieldtrips in 2005 and 2006, except for some samples of Sidi Nasseur, which were kindly provided by C. Dupuis of the Faculté Polytechnique de Mons. Sample density is high (cm to dm scale) around the interval across the marker beds, decreasing (every ~50 cm one sample) in the upper and lower parts of the sections.

For Sidi Nasseur in Tunisia two subsections have been sampled around the glauconitic bed. The NSF section comprises a 17-m-thick interval. The NSC'05 section is a partial lateral equivalent (only 50 m to the south) of 8 m thickness. At Sidi Nasseur the thick glauconitic bed tops a complex channel system that complicates the correlation between the two subsections (Van Itterbeeck et al., 2007). Garn Halfaya (GHB'05) and Elles (Els'05) are the two other sections sampled in Tunisia. GHB'05 spans 30 m, while Els'05 is 3 m thick. Garn Halfaya is located about 50 km NW of Elles and 25 km NNE of Sidi Nasseur. In Egypt, five sections have been sampled. We studied two sections at Gebel Qreiya. In Q3'06 a 24 m thick interval around the pinkish-brown marl bed has been sampled.

Q1'06 is situated 15 km to the NNW of Q3'06. The studied interval at Q1'06 1 is 11 m thick. The Araas section (Ar'06) is situated in the Wadi Qena area, 20 km WSW of Q1'06 and 30 km N of the town of Qena. The studied part of the Araas section spans 5 m and the exposure starts only 35 cm below the pinkish-brown marl bed. Fifteen samples were collected from a 60 cm thick interval in the Aweina section (Aw'06). In the Duwi section (Du'06) a 5 m interval has been sampled. The Aweina, Duwi and Elles sections were only investigated over a short interval, because earlier lower resolution studies (Speijer, 2003a; Guasti et al., 2006) pointed out that these short intervals comprised the D/S interval of interest.

Standard micropaleontologic procedures have been used to process the samples for calcareous-nannofossil studies. Smear-slides were made and examined with a light microscope at 1000× or 1250× magnification. For foraminiferal studies the rock samples were dried in a stove at 60°C for at least 24 hours. About fifty grams of dry rock were soaked in a soda solution (50g Na_2SO_4/l H_2O). Whenever repeated soda processing was not sufficient to break down the samples, the tenside Rewoquat (CH_3OSO_3) was used. After disintegration, each sample was washed over a sieve of 63 μm mesh size and dry-sieved over sieves of 630 μm and 125 μm mesh size, respectively. The fractions 63-125 μm and 125-630 μm were used for the present biostratigraphic study.

Calcareous nannofossil biostratigraphy has been determined from smear-slides of the sections of Sidi Nasseur and Qreiya-3. Lower resolution calcareous nannofossil data on Elles were documented by Guasti et al.
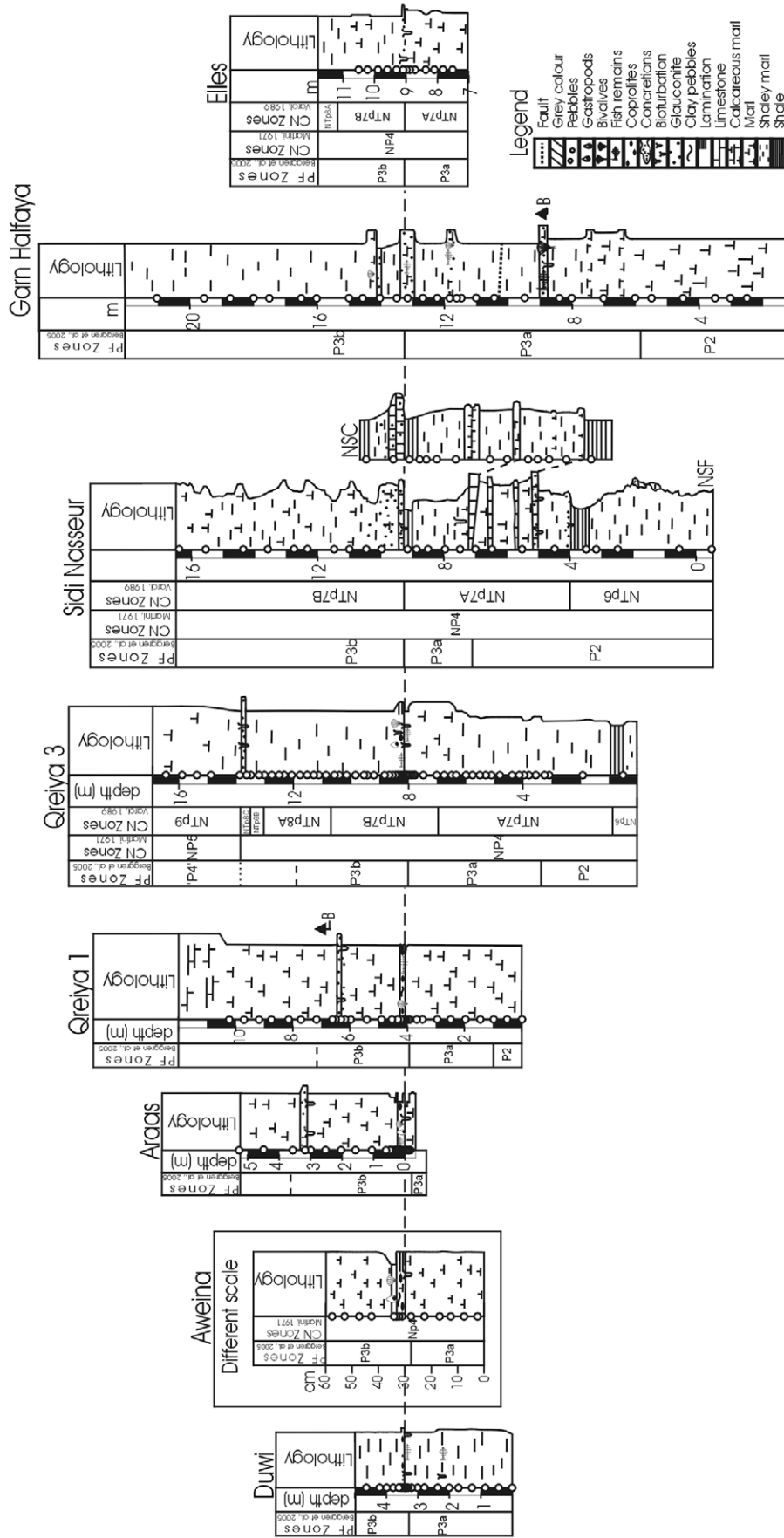
FIGURE 2 | Detailed litho- and biostratigraphy of the Danian/Selandian boundary interval of the sections from Egypt (Qreiya, Aweina, Duwi) and Tunisia (Sidi Nasseur, Garn Halfaya, Elles). In Garn Halfaya and Qreiya 1 the sampled succession was interrupted at point B and moved laterally for a few meters to obtain the best succession. The Aweina-log is in a centimetre scale. 'P4' indicates the LO of *M. velascoensis* and the dashed line indicates the LO of small *G. cf. pseudomenardii*.

(2006). The biozonation follows the schemes and criteria of Martini (1971) and Varol (1989). The planktic foraminiferal biozonation follows Berggren and Pearson (2005). Washed residues of 20 samples of the Q3'06 section, 30 samples from Q1'06, 15 samples from Aweina, 15 samples from Duwi and 19 samples from Araas have been analyzed. For Sidi Nasseur 20 samples have been analyzed (NSF and NSC'06) as well as 20 samples for Garn Halfaya and 15 samples for Elles.

TAXONOMY

GENUS *Igorina* DAVIDZON, 1976

The genus *Igorina* represents small-sized, praemuricate and trochospirally-coiling taxa of Paleocene planktic foraminifera. Igorinids are believed to have evolved from *Praemurica* almost simultaneously with the first morozovellids (*M. praeangulata*, *M. angulata*). The igorinids show a trend toward chamber compression and development of a peripheral keel (Olsson et al., 1999).

Igorina pusilla BOLLI, 1957

1957   *Globorotalia pusilla* subsp. *pusilla* Bolli: pl. 20, figs. 8-10.

Original description: "Shape of test is low trochospiral, biconvex, compressed; periphery nearly circular, slightly lobate; axial periphery acute to subacute. Wall calcareous, perforate, surface smooth. Chambers compressed, 12-16, arranged in 2.5-3 whorls, the 5-6 chambers of the last whorl increasing moderately in size. Sutures on spiral side strongly curved, slightly depressed; on umbilical side radial, depressed. Umbilicus narrow, open. Aperture a low arch, with narrow lip; interiomarginal, extraumbilical-umbilical. Coiling random. Largest diameter of holotype 0.24 mm" (Bolli, 1957).

Remarks

Originally the wall of *I. pusilla* was described as finely perforate and smooth. However, the poor preservation of the holotype makes a proper description impossible. Stainforth et al. (1975) mention well preserved specimens with a very coarsely perforate wall. Therefore, *I. pusilla* is considered the earliest representative of the biconvex, praemuricate igorinids (Olsson et al., 1999).

In the literature various secondary descriptions of *I. pusilla* (BOLLI) are available, but they all seem to vary somewhat from the original. *Planorotalites pusilla pusilla* of TOUMARKINE and LUTERBACHER (1985) is small, biconvex, tightly coiled with 5-6 crescentic chambers in the last whorl, increasing gradually in size. Spiral sutures are strongly curved backwards. The umbilicus is narrow. The surface of the test is coarsely perforate and pitted. This description is in accordance with Bolli (1957). In the Atlas of Paleocene planktic foraminifera (Olsson et al., 1999) the well-preserved specimens of *I. pusilla* depicted on pl. 57 appear to differ significantly from the holotype (pl. 16, figs. 7-9). The differences are that the holotype has an acute axial periphery, while the specimens on plate 57 have a subacute to rounded axial periphery. The chambers of the holotype are compressed on the spiral side and slightly inflated on the umbilical side. The chambers of the specimens on plate 57 are inflated on the spiral side and strongly inflated on the umbilical side. Olsson et al. (1999) describe *I. pusilla* as an essentially circular, biconvex, pustulous species with 5-6 chambers in last whorl; axial periphery subacute and non-carinate, while Bolli (1957) describes a nearly circular, compressed, perforate test with an acute to subacute axial periphery.

Several authors (e.g., Stainforth et al., 1975) followed the description of *Igorina* Davidzon (1976) and described *I. pusilla* as a circular, slightly lobate outline, biconvex trochospiral form, muricate test (idem ditto) with 5-6 chambers in the last whorl; acute to subacute axial periphery. This description, together with the description in Olsson et al. (1999) is followed. *Igorina pusilla* in this report is considered a praemuricate, essentially circular, biconvex, pustulous species with 5-6 chambers in last whorl; intercameral sutures on umbilical side are radial, depressed, on spiral side sutures are moderately to strongly curved, depressed/weakly incised; axial periphery subacute and non-carinate (Plate 3.I, figs. 1-3 and 7-9).

Igorina albeari, CUSHMAN and BERMUDEZ, 1949

1949   *Globorotalia albeari* Cushman and Bermudez: pl. 6, figs. 13-15.

Original description: "Test very small, strongly biconvex, dorsal side showing all the coils and ventral side only the last-formed whorl, periphery somewhat rounded; chambers not very distinct, 9 or 10 in the last-formed whorl, only slightly inflated ventrally, increasing very gradually in size as added; sutures fairly distinct but only slightly depressed, except in the last whorl on the ventral side, rather strongly curved on the dorsal side; wall slightly spinose, coarsely perforate; aperture an elongate opening on the ventral side of the last-formed chamber extending from nearly the inner end to the periphery and with a distinct lip. diameter 0.30-0.32 mm; thickness 0.20 mm" (Cushman and Bermudez, 1949).

1957 *Globorotalia pusilla laevigata* Bolli: pl. 20, figs. 5-7.

Original description: "Shape of test low trochospiral, biconvex, compressed; equatorial periphery circular, slightly lobate; axial periphery acute, last chambers often with a faint keel. Wall calcareous, perforate, surface smooth. Chambers strongly compressed, 12-16, arranged in about 3 whorls; the 5-6 chambers of the last whorl increasing moderately in size. Sutures on spiral side strongly curved; on umbilical side radial. Umbilicus narrow, open. Aperture a low arch; interiomarginal, extraumbilical-umbilical" (Bolli, 1957).

Remarks

Originally, the wall of *I. pusilla laevigata* was described as finely perforate and smooth. As for *I. pusilla*, the poor preservation of the holotype makes a proper description impossible. Olsson et al. (1999) mention well preserved specimens with a very coarsely perforate wall. According to the original descriptions, *Globorotalia pusilla laevigata* differs from *Globorotalia pusilla pusilla* by its more circular outline and acute axial periphery and by its spiral sutures not being depressed (Bolli, 1957). Olsson et al. (1999) considered *Globorotalia pusilla laevigata* BOLLI (1957) as a junior synonym of *Igorina albeari* CUSHMAN and BERMUDEZ (1949), because of the presence of a distinct peripheral carina in both taxa (Olsson et al., 1999). The main difference between *I. albeari* and *G. pusilla laevigata* (BOLLI, 1957) is the 6-8 chambers in the final whorl instead of 5-6 chambers (Olsson et al., 1999).

In the literature various descriptions of *I. albeari* are available. In the Atlas of Paleocene planktic foraminifera (Olsson et al., 1999) *I. albeari* has a moderately to strongly biconvex, essentially circular, pustulous test with 6-8 chambers in final whorl. The peripheral margin is distinctly carinate, particularly on last chambers of final whorl. Cushman and Bermudez (1949) described a somewhat rounded periphery, 9 or 10 chambers in the last-formed whorl and a slightly spinose and coarsely perforate wall.

Finally, based on Blow (1979), Arenillas and Molina (1997) and Orue-Etxebarria et al. (2006) only include forms within the concept of *Igorina albeari* that have a biconvex, trochospiral, almost circular, muricate test, more than 7 chambers in the last whorl with a peripheral margin with muricocarina (on the last chambers) and a high spiral side. The form of Bolli (1957) has a low trochospiral, biconvex, compressed test with 5-6 chambers in the last whorl.

Arenillas and Molina (1997) added the *M. crosswicksensis* zone between the *M. angulata* and *I. albeari* zones. The base of this zone is defined by the lowest occurrence

(LO) of *M. crosswicksensis*. *M. crosswicksensis* is considered an early representative form and junior synonym of *M. occlusa* (Olsson et al., 1999), and it resembles *I. albeari* in being biconvex and having a slight keel. However, it is clearly a morozovellid, with umbilical shoulders. In the *Igorina* lineage an evolutionary trend is recorded from *I. pusilla* to *I. albeari* (Berggren et al., 1995). A description to consistently identify the earliest representatives of *I. albeari* is offered here.

Guasti (2005) reported findings from Tunisian and Egyptian successions of P3b indicators (e.g., *I. tadjikistanensis*) together with specimens of *Igorina* that start to develop a keel, like in *I. albeari*. Even though the typical *I. albeari* as observed in Zone P4 does not occur, Guasti (2005) suggested that this assemblage with the primitive *I. albeari* is indicative of planktic foraminifera subzone P3b in Egypt and Tunisia. In this report this suggestion is embraced and the *Igorina* specimens that start to develop a keel are placed within the concept of *I. albeari*. In our view, this feature enables an unambiguous distinction between *I. pusilla* and *I. albeari* and is in keeping with the original descriptions without introducing an intermediate species. In addition, it is conformable with the concept of *I. albeari* as employed by Quillévéré et al. (2002) and in the time scale by Berggren et al. (1995) and its more recent updates, Berggren et al. (2000) and Berggren and Pearson (2005) (Berggren pers. comm. 2007). This correspondence of concepts allows an accurate correlation with the current zonal schemes in the magneto-biochronologic timescale (Berggren and Pearson, 2005).

Plate 3.I shows specimens of *I. pusilla* and *I. albeari* from Egypt and Tunisia. The test of the primitive *I. albeari* (Plate 3.I, figs. 4-6 and 10-12) is biconvex and circular, slightly lobate and with 5 chambers in the last whorl. The umbilical side is usually less convex than the spiral side, but there is a range of variation in the degree of convexity of the spiral side in *I. albeari* (e.g., compare Plate 3.I, figs. 10b and 11b). The test is praemuricate and the final chamber is often flattened and less pustulous than the remainder of the test (Fig. 4, 10A). Preservation of the tests from the interval with the marker beds varies. Especially growth of secondary calcite crystals poses a problem to the identification (e.g., Fig. 4, 7-8). The intercameral sutures on the umbilical side are radial to weakly recurved, which results in triangular-shaped chambers (Fig. 4, 5C). On the spiral side, the intercameral sutures are strongly recurved and exhibit a stacking-pattern of the chambers, particularly between the last 3-4 chambers, which leads to crescentic-shaped chambers (Fig. 4, 4A). The flattening of the last chamber and sometimes the fusion of muricae on the peripheral margin of the last chambers gives the impression of the development of a slight keel (e.g., Fig. 4, 4-6 and 10-12; detail 10B). This

P2	P3		P4	PF Zones	PF zonation evolution
	P3a	P3b			
P. uncinata	M. angulata		Gl. pseudomenardii	PF Zonation species	
NP4			NP5	CN Zone (Martini, 1971)	
M. uncinata	M. angulata	P. pusilla pusilla	P. pseudomenardii	Bolli (1957), Premoli Silva and Bolli (1973), Toumarkine and Luterbacher (1985)	
M. uncinata	M. angulata	P. pusilla	P. pseudomenardii	Berggren et al. (1985)	
M. uncinata	M. angulata	I. pusilla	Gl. pseudomenardii	Berggren and Miller (1988)	
P. uncinata	M. angulata	I. albeari	Gl. pseudomenardii	Berggren et al. (1995)	
P. uncinata	I. pusilla	I. albeari	Gl. pseudomenardii	Berggren and Pearson (2005)	
A. uncinata	M. angulata	M. cross wick sensis	I. albeari	Gl. pseudomenardii	Arenillas and Molina (1997)

FIGURE 3 | **Evolution of Danian-Selandian planktic foraminifera zonations. *Praemurica uncinata* was previously included in *Morozovella*. *Igorina pusilla*, *I. albeari* and *Globanomalina pseudomenardii* were previously included in *Planorotalites*.**

incipient keel on the last chambers of the earliest representatives of *I. albeari* specimens is very important for its identification.

BIOSTRATIGRAPHY

Planktic foraminifera

Zones P2, P3 and P4 are identified by the LO of their respective zonal markers, i.e. *Praemurica uncinata*, *Morozovella angulata* and *Globanomalina pseudomenardii* (Berggren and Pearson, 2005). Since the major revision of the integrated magnetobiochronologic time scale for the Paleocene (Berggren et al., 1995) the LO of *I. albeari* is used to delineate the base of Subzone P3b. What is now accepted as typical *I. albeari* are the specimens described by Olsson et al. (1999), that essentially occur in planktic foraminiferal Zone P4 (59.4-55.9 Ma). However, *I. albeari* developed earlier (at 60.0 Ma) from *I. pusilla*. This concept of the base of Zone P3b was retained in the recent update by Berggren and Pearson (2005). In earlier zonal schemes from the last 50 years (Fig. 3; e.g., Bolli, 1957; Premoli-Silva and Bolli, 1973), nevertheless, *I. albeari* was not considered as a zonal marker. Instead, the LO of its precursor, *I. pusilla*, delineated the position of the P3a/P3b boundary in the schemes of e.g., Berggren et al. (1985) and Toumarkine and Luterbacher (1985). It was thought that *I. pusilla* appeared considerably later than *Morozovella angulata*, a view now abandoned through studies on well-preserved deep-sea material (Berggren et al., 1995; Olsson et al., 1999).

The zonal marker for Planktic Foraminiferal Zone P4, *G. pseudomenardii*, was not encountered in the sections. In line with the suggestion of Speijer (2003a) the LO of *Morozovella velascoensis* is used to approximate the base of Zone P4, referred to as 'P4'. This species is traditionally thought to appear approximately simultaneously with *G. pseudomenardii* (e.g., Blow, 1979; Toumarkine and Luterbacher, 1985), although more recent studies suggest that *M. velascoensis* appears somewhat below the base of Zone P4 (Arenillas and Molina, 1997; Premoli Silva et al., 2003; Steurbaut and Sztrákos, 2008) or even simultaneously with *I. albeari* (Olsson et al., 1999). Furthermore, small specimens (<125 *μ*m) of *G. pseudomenardii*, referred to here as *G.* cf. *pseudomenardii*, have been found. The LO of these specimens was in the top of calcareous nannofossil zone NP4.

Continuously exposed successions from Zone P1 to P4 in Tunisian (Sidi Nasseur, Elles) and Egyptian (Duwi, Aweina, Qreiya) sections have been described before (Burollet, 1956; Said, 1962, 1990; El Naggar, 1966; Speijer and Schmitz, 1998; Steurbaut et al., 2000; Guasti, 2005; Guasti et al., 2006). Garn Halfaya and Araas are sections newly described in this report. Zone P2 is studied in Q1'06, Q3'06, Sidi Nasseur and Garn Halfaya. It is known to be present in all other sections as well (except Araas), but was not investigated here (Fig. 2).

To delineate the P3a/P3b subzonal boundary the LO of *I. albeari* is found in all Tunisian sections at the base of the glauconitic bed; in Sidi Nasseur from sample NSC +9.5 m, in Garn Halfaya from 13.5 m and in Elles from sample 1.6 m (Fig. 5). The P3a/P3b subzonal boundary in
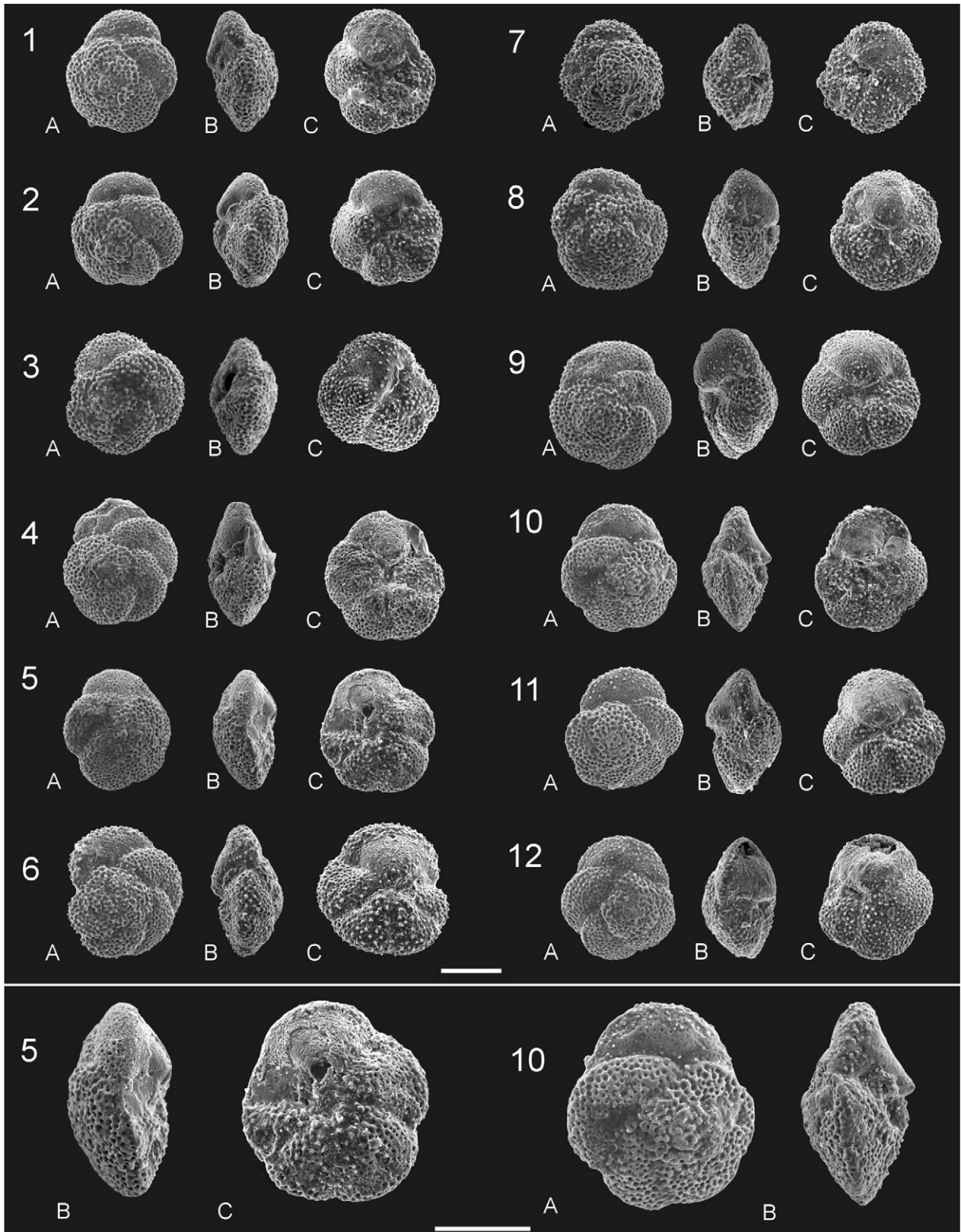
FIGURE 4 | **Egypt 1)** *Igorina pusilla*: Duwi, sample 3.35-3.4 m. **2)** *Igorina pusilla*: Aweina, sample 20-25 cm. **3)** *Igorina pusilla*: Qreiya3, sample 8.35-8.4 m. **4)** *Igorina albeari*: Duwi, sample 3.45-3.5 m. **5)** *Igorina albeari*: Qreiya1, sample 4.35 m. **6)** *Igorina albeari*: Duwi, sample 3.8 m. **Tunisia 7)** *Igorina pusilla*: Sidi Nasseur NSC, sample 9.2 m. **8)** *Igorina pusilla*: Garn Halfaya, sample 13.1 m. **9)** *Igorina pusilla*: Garn Halfaya, sample 14.6 m. **10)** *Igorina albeari*: Elles, sample 1.6 m. **11)** *Igorina albeari*: Elles, sample 1.8 m. **12)** *Igorina albeari*: Sidi Nasseur NSF, sample 16.5 m. A) spiral view; B) apertural view; C) umbilical view of same specimen scale bar: 50 μm. Photo 5) A,C and 10) A,B are enlarged for a more detailed view.

Egypt closely correlates with an pinkish-brown marl bed, but in some sections the LO of *I. albeari* is slightly below this bed. The lowest single occurrence (LSO) of *I. albeari* is found in Duwi at 15 cm below the pinkish-brown marl bed (sample Du'06 3.25 m) and in Aweina 25 cm below this bed (sample Aw'06 5 cm). Also at Q1'06 and Q3'06 the LSO of *I. albeari* is situated at approximately 15 cm below the pinkish-brown marl bed (Q1'06 3.90 m and Q3'06 8.04 m, respectively). From the base of the pinkish-brown marl bed upwards *I. albeari* occurs continuously in these sections. The Araas section is exposed from 35 cm below the pinkish-brown marl bed and from this level onwards *I. albeari* is continuously present.

Different researchers have used different taxonomic concepts of *I. albeari*. Therefore, the planktic foraminiferal biostratigraphy proposed in this study can differ from that proposed in earlier studies for the same or complementary sections. For instance, Molina in Steurbaut et al. (2000) placed the LO of *I. albeari* much higher up section (80 m) at Sidi Nasseur. However, our results are in agreement with those of Guasti et al. (2006) on the Aïn Settara ASP section, 1 km south of the Sidi Nasseur section, where the LO of *I albeari* is also situated at the glauconitic bed. Similarly, El Naggar (1966) observed *G. pusilla laevigata* in the Aweina section at the same position were we place the LO of *I. albeari*, i.e., ~10 m below the base of the Tarawan Formation.

In order to obtain some insight into the duration of the hiatus at the marker beds, the thickness of the sections was compared. There is a high variation in the relative thicknesses of Zone P2 and Subzones P3a and P3b between the sections. Table 1 shows that Subzone P3a varies from 2.0 m in the NSF part of Sidi Nasseur to 10 m in Aweina. In Tunisia, Garn Halfaya has an expanded P3a in comparison with Sidi Nasseur and Elles (2.0 m and 3.5 m in Sidi Nasseur; 7.0 m in Garn Halfaya; 2.5 m in Elles). In Egypt the thickness more than triples from 3.0 m in Duwi and Qreiya-1 to 10.0 m in Aweina. Even locally the thickness can vary greatly. In Sidi Nasseur subzone P3a almost doubles its thickness, from 2.0 m in NSF to 3.5 m in NSC'05, with only 50 m in between the subsections. The reason for this local variation is the sedimentary channel structures with beds pinching out laterally observed in the Sidi Nasseur area. From literature the thickness of Subzone P3b was determined (Table 1). It varies from 2.0 m in Duwi to 14 m in Elles.

In the Egyptian sections subzone P3a is slightly more expanded (1-2 m) than Subzone P3b, which is in agreement with the relative durations of the P3a and P3b Subbiochrons (1 ka vs. 0.6 ka). The Tunisian sections show the opposite. There Subzone P3b is consistently much thicker than P3a. Elles is most extreme, with only 2.5 m

thickness of Subzone P3a and 11.0 m for P3b. This can be interpreted in two ways: either Subzone P3b is more expanded because sediment accumulation increased within this time interval, or Subzone P3a is less expanded because a part is missing in Tunisia. Also noteworthy is the comparison of Subzones P3a and P3b with the thickness of Zone P2. Zone P2 is consistently thicker than P3a and in Egypt also thicker than P3b. However, Biochron P2 represents only ~0.4 ka, while Subbiochrons P3a and P3b represent 1.0 ka and 0.6 ka, respectively. Again, this either suggests increased sediment accumulation during Biochron P2, or parts of P3a and P3b are missing, both in Egypt and Tunisia. Another indication of decreased sediment accumulation or non-deposition/erosion during the early late Paleocene comes from comparing subzones P3a and P3b with the total thickness of the Paleocene in the sections. Zone P3 represents only 2-14% of the total successions, while Biochron P3 represents ~1.6 ka, which is almost 17% of the total duration of the Paleocene (65.0-55.5 Ma). All in all, these observations suggest that the P3a/P3b boundary was at least a period of non-deposition, and that in Tunisia an even larger part is missing than in Egypt.

Calcareous nannoplankton

The calcareous nannofossil zonation of Varol (1989) has proved to be an excellent tool for subdividing Martini's (1971) standard nannofossil zone NP4 at low latitudes. Zones NTp6, NTp7A, NTp7B and NTp8A, encompassing the main part of NP4, have been accurately identified in the southern Tethys by one of us (ES) (Steurbaut et al., 2000; Guasti et al., 2006; Van Itterbeeck et al., 2007). The boundaries of these zones are marked by the highest occurrence (HO) of *Neochiastozygus eosaepes* (NTp6/NTp7A), and the LOs of *Chiasmolithus edentulus* (NTp7A/NTp7B) and *Sphenolithus primus* (NTp7B/NTp8A), respectively.

The HO of *N. eosaepes* has been recorded in the Sidi Nasseur sections NSF and NSC-05 at the top of a 1 m thick clay-unit. The top of this clay is marked by rare occurrences of the short-ranging *Fasciculithus magnus*, the earliest representative of the genus *Fasciculithus*. The NTp7A/NTp7B boundary is characterized by a series of coinciding events, among which are the LOs of *C. edentulus*, small *Fasciculithus* taxa (*F. chowii* and others), a medium-sized *Toweius* sp. and the start of the consistent occurrence of *Pontosphaera* sp. These events were recorded at the base of a prominent glauconitic bed, believed to represent a sequence boundary. Between this level and the top of the clay bed, about 5.50 m lower, occur rich and well-diversified associations without *Fasciculithus*. The LO of *S. primus* was encountered some 20 m above the glauconitic bed (Steurbaut, pers. obs.). At

FIGURE 5 | **Schematic figure of the lithostratigraphy and biostratigraphy of the Danian/Selandian transition in the type region (Denmark), Zumaia (Spain), Tunisia and Egypt, completed in accordance with recent papers and discussions and outcomes at the Workshop of the Paleocene Working Group, June 21-22, Zumaya, Spain (Clemmensen and Thomsen, 2005; Orue-Etxebarria et al., 2006, 2007; Bernaola, 2007; Arenillas et al., 2007; Steurbaut and Sztrákos, 2008) and this study.**

Elles sediment thickness is much more condensed. Zone NTp7B, which is up to 20 m thick in the Sidi Nasseur area, is reduced to about 2 m at Elles.

From the Egyptian sections sampled during the field campaign of 2006 only Qreiya-3 has been fully investigated for nannofossils. The changes in nannofossil associations are similar to those recognized in the Tunisian sections, allowing accurate correlation. The HO of *N. eosaepes*, defining the NTp6/NTp7A boundary, is recorded near the base of the section at 0.72 m. It coincides, just as in the Tunisian sections, with the HO of *F. magnus*. The base of subzone NTp7B, defined by the same series of coinciding nannofossil-events as in Tunisia, is positioned at 7.0 m, at the transition from marly shales to chalky marls. The underlying subzone NTp7A again contains rich and highly diverse assemblages without *Fasciculithus*.

The preservation of the nannofossils rapidly deteriorates from 7.9 m upward. Partly dissolved, poorly interpretable associations are recorded up to about 9.45 m. The quality of the associations improves again from 9.9 m upward. The first specimens of *Sphenolithus primus*,

defining the NTp7B/NTp8A boundary, are recorded at 10.63 m. *Fasciculithus ulii* and *F. janii*, marking the subzonal boundaries NTp8A/NTp8B and NTp8B/NTp8C, first appear at 12.99 m and 13.46 m, respectively. Above a calcareous bed (~13,75 m.), separating marly shales from overlying marls, nannofossils become abundant, showing a much higher species diversity and better preservation. *Fasciculithus tympaniformis*, the marker of the base of Zone NP5 (and NTp9), occurs from 13.9 m onward.

DISCUSSION

Southern Tethys

The D/S transition interval in the Sidi Nasseur section is characterized by at least two unconformities (Steurbaut et al., 2000; Van Itterbeeck et al., 2007). The lower one coincides with the P2/P3 Zonal boundary, the second one, at the base of the main glauconitic bed, coincides with the P3a/P3b and NTp7A/NTp7B subzonal boundaries. The main biotic changes, both in ostracoda and foraminifera, occur at this level. Only the upper unconformity, marked

TABLE 1 | **The thickness of subzone P3a and P3b for all sections investigated in this report. Some information is derived from literature. The base of Zone P4 is sometimes approximated by the LO of *M. velascoensis* (Duwi and Qreiya-3). At Elles and Aweina the LO of *Gl. pseudomenardii* and at Araas and Qreiya-1 the LO of the small *Gl.* cf. *pseudomenardii* is used. In Sidi Nasseur and Garn Halfaya *M. velascoensis* or *Gl. pseudomenardii* are not encountered. In the second part of this table the thickness of the total Paleocene succession is indicated for all sections. For Garn Halfaya literature data is not available.**

Comparison of thickness of the different Planktic Foraminiferal Zones and the total Paleocene							
Duwi Guasti (2005) (LO *M. velascoensis*)	**Aweina** Speijer & Schmitz (1998) (LO *Gl. pseudomenardii*)	**Araas** This report (LO *Gl.* cf. *pseudomenardii*)	**Qreiya 1** This report (LO *Gl.* cf. *pseudomenardii*)	**Qreiya 3** This report (LO *M. velascoensis*)	**Sidi Nasseur** Van Itterbeeck et al. (2007)	**Garn Halfaya** This report	**Elles** Guasti et al. (2006) (LO *Gl. pseudomenardii*)
P3b (m)	2.0	9.0	2.5	2.0	7.0	>7.0	>9.0	14.0
P3a (m)	3.0	10.0	unknown	3.0	4.5	NSF 2.0 / NSC 3.5	7.0	2.5
P2 (m)	6.0	11.0	unknown	>1.0	>3.5	>4.0	>5.0	6.0
	Faris (1982)	Speijer & Schmitz (1998)		Luger (1985)		C. Dupuis (pers. comm., 2007)		Said (1978)
Paleocene (m)	120	>70	unknown	60		500	unknown	130

by the glauconitic bed, is also observed at Elles (Guasti et al. 2006) and Garn Halfaya, pointing to a regional unconformity. Together with the relatively condensed nature of Subzone P3a below the unconformity (Table 1), this points to significant erosion of the top of Subzone NTp7A in the studied parts of the Tunisian Trough.

In the Egyptian sections Duwi, Aweina, Qreiya and Araas, the D/S boundary is marked by transient biotic change (Speijer, 2003a; Guasti et al., 2005). The D/S boundary is distinguished by the deposition of the pinkish-brown marl bed, with abundant fish remains and planktic foraminifera. There are very few benthic foraminifera observed in this bed leading to planktic/benthic ratios up to 99.5% (Speijer 2003a, b). Directly above pinkish-brown marl bed the shallow water species *Neoeponides duwi* dominates the benthic foraminiferal assemblages, temporarily replacing the normal bathymetrically arranged assemblages (Speijer 2003a; Guasti et al., 2005). Up to 1-cm-thick bioturbations penetrate the underlying pinkish-brown marl bed. Close inspection of the microlayering and the bioturbations reveals that the extremely rare occurrences of *N. duwi* and other benthic taxa in the pinkish-brown marl bed (Speijer 2003 a, b) must be a consequence of this bioturbation. In situ benthic taxa are absent in this bed. These sedimentologic and faunal changes coincide with the LCO of *I. albeari*. The lowest single occurence of *I. albeari* is recurrently found 15-25 cm below the pinkish-brown marl bed. In Araas *I. albeari* continuously occurs from the lowermost sample, already 35 cm below

the pinkish-brown marl bed. The sediments bracketing the marker bed are almost always affected by dissolution, proven by low numbers of planktic foraminifers and dominance by non-calcareous agglutinated benthic foraminifers. The absence of *I. albeari* in some of the samples below the pinkish-brown marl bed could be due to dissolution or the presence of the single occurrences of *I. albeari* might be a matter of down-working through bioturbations. Yet, up to 35 cm of consolidated and compressed clayey sediment certainly seems too deep for the size of the bioturbations penetrating through the pinkish-brown marl bed. Consequently, we consider the single occurrences to be in situ. Thus, the Subzonal boundary P3a/P3b in Egypt occurs slightly below but in close proximity to the pinkish-brown marl bed.

Another biostratigraphic event in close range to the pinkish-brown marl bed is the subzonal boundary NTp7A/NTp7B 1.2 m down-section in Qreiya-3. In Tunisia this subzonal boundary coincides with the glauconitic bed. A part of the succession with the LO of *Chiasmolithus edentulus* and coinciding events is missing in the Tunisian sections, confirming the presence of the regional unconformity. Both the succession in LOs of *C. edentulus* and *I. albeari* and the more expanded Subzone P3a (Table 1) in Egypt are an indication that the sequences are more complete than in Tunisia. Yet, we cannot exclude omission surfaces at the base and/or top of the pinkish-brown marl bed in Egypt, as suggested by the relative condensed nature of Subzones P3a and P3b.

Recapitulating, the base of the glauconitic bed in Tunisia and the base of the dark pinkish-brown marl bed in Egypt are closely associated with the LOs of *Igorina albeari* and *Chiasmolithus edentulous*. This allows accurate correlation of the discontinuities in both regions, even if they are differently expressed: an erosional surface overlain by a glauconitic bed in the Tunisian sections and a laminated pinkish-brown marl bed with abundant planktic foraminifera, fish remains and coprolites, possibly bounded by omission surfaces in the Egyptian sections.

Correlation between Tethys, Zumaia (northern Spain) and Denmark

Recent studies, especially calcareous nannofossil studies (Bernaola, 2007; Steurbaut and Sztrákos, 2008), have made high-resolution correlation between Spanish, Danish and southern Tethyan sections possible (Fig. 5). The NTp7A/B subzonal marker, *Chiasmolithus edentulus*, associated with the marker bed in the southern Tethys, is perhaps the only marker enabling correlation directly between Denmark, northern Spain and the southern Tethys. Recent work in Denmark (Clemmensen and Thomsen, 2005) demonstrated that the NTp7A/B subzonal boundary is found within the Bryozoan limestone, well below the unconformity at the base of the Selandian. In Zumaia the NTp7A/B subzonal boundary is associated with a minor change in lithology. Within the upper part of the Aitzgorri Fm. the lithology changes from the limestone dominated crowded member to the stratified member consisting of limestones and interbedded marls (Apellaniz et al., 1983; Bernaola, 2007). Orue-Etxebarria et al. (2007) reports the LO of *Igorina pusilla laevigata* in association with the change from crowded member to stratified member. We consider these specimens as the first representatives if *I. albeari* at the base of Subzone P3b. Its LO confirms the correlation between the lithological change (crowded to stratified) in Zumaia and the marker bed in Tunisia and Egypt. Note that *Igorina albeari* as defined by Orue-Etxebarria et al. (2006) occurs some 20 m higher up the section at Zumaia within the Itzurun Fm. (Fig. 5).

An acme in *Braarudosphaera* is recorded in the top of the calcisiltite in Denmark and the top of the Aitzgorri Fm. in Zumaia and together with an abrupt decrease in relative and absolute abundance in connection with the lithologic changes in both areas (Bernaola, 2007; Steurbaut and Sztrákos, 2008). The unconformity at the D/S boundary in the type region and the change from Aitzgorri Fm to Itzurun Fm in Zumaia most likely correlate. *Braarudosphaera* did not occur in the southern Tethys, and direct correlation of the D/S boundary is thus not possible. According to recent cyclostratigraphic studies carried out at Zumaia (Dinarès-Turrell et al., 2003) the LO of *C. edentulus* (NTp7A/NTp7B) and the LCO of *S. primus*

(NTp7/NTp8) are respectively 32 and 22 bedding couplets below the top of the Aitzgorri Fm (Bernaola, 2007). Since these couplets most likely represent precession cycles with a mean period of 21 ka, the LO of *C. edentulus* and LCO *S. primus* would respectively be ~672 ka and ~462 ka older than the D/S boundary. The subzonal boundaries NTp7A/NTp7B and NTp7/NTp8 occur respectively 1.2 m below and 2.4 m above the pinkish-brown marl bed of Qreiya-3. Schmitz et al. (1998) suggested that the base of the Itzurun Fm at Zumaia and the pinkish-brown marl bed in Egypt were correlative. It can now be ascertained that this is not the case. Assuming a similar sedimentation rate below and above the omission surface, this Southern Tethyan marker bed would be ~600 ka older than the base of the Itzurun Fm at Zumaia and the D/S boundary in the type region.

The biostratigraphy has revealed that the marker beds of Egypt and Tunisia are correlatable and that this level is older than the D/S boundary. In Egyptian sections the marker bed has been referred to as Danian/Selandian transition (Speijer, 2003), "*N. duwi*"-event (Guasti, 2005) and has been described as pinkish-brown marl bed in this report. In Tunisian sections the marker bed has always been described as glauconitic marker bed (Steurbaut et al., 2000; Guasti, 2005; Van Itterbeeck et al., 2007; this report). Now we propose to use one name for this southern Tethyan upper Danian level, which is upper Danian event beds.

Direct correlation of the D/S boundary in the type region and the southern Tethys is not possible, but the calcareous nannofossil zonation of Varol (1989) might make correlation of the D/S boundary between Zumaia and the southern Tethys possible. In Bernaola (2007) and Steurbaut and Sztrákos (2008) the D/S boundary in Zumaia is placed between the second radiation of *Fasciculithus* and the LO of *F. tympaniformis* (Fig. 5). In the Q3 section in Egypt the first specimens of *F. ulii* and *F. janii*, marking the boundary of Subzones NTp8A/NTp8B NTp8B/NTp8C, first appears at 13.0 and 13.45 m, respectively. *F. tympaniformis*, the marker of the base of Zone NTp9 (NP5), occurs from 13.9 m onwards. At 13.8 m, between these two biostratigraphic events, a 50-meter wide and up to 0.2 m thick channel structure incised the Q3 succession. This event might be correlatable to the D/S-boundary, as suggested in Steurbaut and Sztrákos (2008), but detailed studies are required to confirm this suggestion.

CONCLUSIONS

Igorinid species that start to develop a keel are considered the earliest representatives of *Igorina albeari*, marking the base of Subzone P3b in agreement with taxonomic criteria and zonal schemes of Berggren et al. (1995),

Olsson et al. (1999) and Berggren and Pearson (2005). Other workers have placed the base of P3b generally higher up, particularly in Spanish sequences, because of a more narrowly defined taxonomic concept of *I. albeari*. The base of Subzone P3b closely correlates with the upper Danian event beds in otherwise monotonous marl sequences both in Egypt and Tunisia. The upper Danian event beds can also be correlated to a level of minor lithologic change in the upper part of the Aitzgorri Formation in the Zumaia section through the LO of *Chiasmolithus edentulus*. The distinct lithologic change in Zumaia, from the Aitzgorri Fm. to the Itzurun Fm., however, appears to be ~600 ka younger than the upper Danian event beds in Tunisia and Egypt. The same probably holds true for the age of the base of the Selandian in Denmark, based on the last common occurrence of *Braarudosphaera*.

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