# Planktonic foraminiferal biostratigraphy and paleoenvironment of the Danian/Selandian in west-central Sinai (Egypt), implications from the Nukhul section

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**Abstract** The foraminiferal analysis at the Danian/Selandian boundary of the Nukhul section (Egypt) enabled us to determine the biozones of *Praemurica uncinata* (P2); *Morozovella angulata* (P3a); *Igorina albeari* (P3b), and *Acarinina soldadoensis/Globanomalina pseudomenardii* (P4c). Thus, the base of Selandian is defined by the first occurrence of *I. albeari* and the P4c subzone covers unconformably the P3b subzone. The quantitative and qualitative analysis of the planktonic and benthic foraminifera assemblages and the isotopic analysis permitted characterization of the paleoclimate and paleoenvironment. Thus, at the middle to upper Danian, the environment was marine intertidal under a relatively cold climate. At the lower Selandian base of the Thanetian, a rise in the sea level was recorded and the warmer climatic conditions seem to be settling. In the upper Thanetian, we note the installation of colder weather conditions and a further sudden drop in sea level.

**Keywords** Foraminifera · Biostratigraphy · Danian/Selandian boundary · Paleoenvironment

## Introduction

The Global Stratotype Section and Point (GSSP) of the Danian/Selandian (D/S) boundary has been defined in the Zumaia section (northern Spain), based on the radiation of the nannofossil (*Fasciculithus*) considered as a global event (Schmitz et al. 2011; Monechi et al. 2013). However the determination of the D/S boundary, based on planktonic foraminifera, is not further clarified because of the taxonomic problems and the uncertainty in the correlation of Paleocene biozones (Arenillas 2008, 2012; Orue-Etxebarria et al. 2007; Farouk and Faris 2013). The D/S boundary is marked by the presence of a level benchmark rich in phosphate and glauconite grains associated with a drop in sea level. This level coincides with the first appearance of the species *Igorina albeari* marker of the base of the P3b subzone of the Selandian. This level has been considered by some authors as the precursor event of Paleocene-Eocene Thermal Maximum (PETM) (Speijer 2003; Guasti et al. 2005; Obaidalla et al. 2009; Bornemann et al. 2009; Youssef 2009; Soliman and Obaidalla 2010; Sprong et al. 2009, 2011, 2013; Farouk and El-Sorogy 2015). Several studies have been performed on the Danian/Selandian transition of the Nile Basin in Egypt but the limit had not been well identified despite the definition of the global stratotype (Luger 1985; Bassiouni et al. 1991; Tantawy et al. 2001; Hewaidy et al. 2006; El-Azabi and Farouk 2011; Boukhary et al. 2013).

The main objectives in this work are to identify the D/S boundary and to reconstruct the paleoenvironmental and eustatic changes in the Nukhul section, using the planktonic and benthic foraminifera study and isotopic analysis.

## Geographical and geological setting of the Nukhul section

The Nukhul section is located in the eastern part of the Gulf of Suez (Fig. 1), about 6 km to the south of Abu Zenima, in the southwest of Sinai. The NE Egypt and Sinai are limited in the

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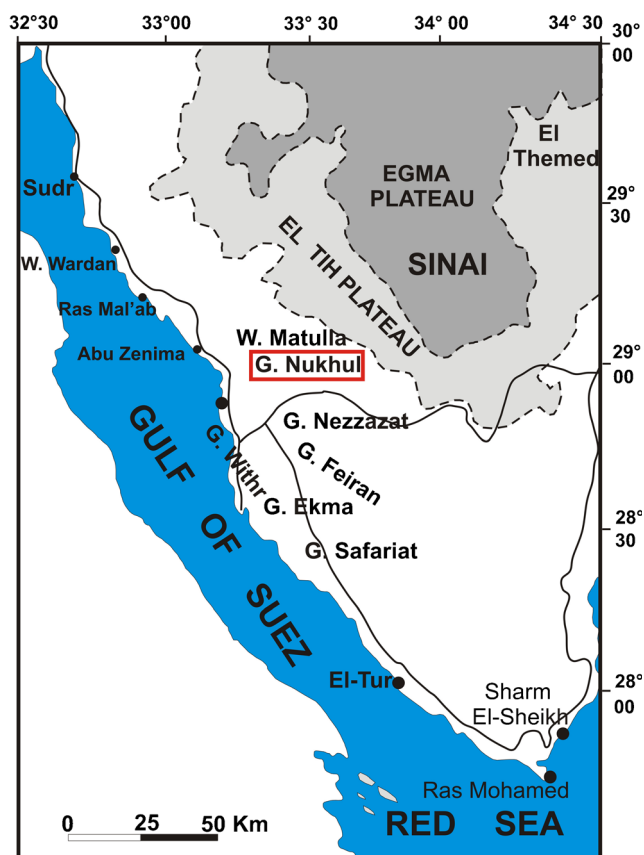
**Fig. 1** Geographical location of the Nukhul section (Egypt) (after Faris et al. (2007), modified)

south by the stable Arabo-Nubian Shield and in the north by the Alpine mobile orogenic belt, which are considered as two major regional tectonic units. In this area, there are two zones: the stable and the unstable shelves (Said 1962; Faris et al. 2007; Khozyem et al. 2013). This region presents well-developed outcrops and the sediment series appears to be continuous from the Danian to Thanetian. The D/S transition is located in the Dakhla Formation, mainly composed of marl and gray clays to brownish and yellowish with greenish hues.

## Material and methods

Material and methods of samples covering the D/S interval were examined for planktonic and benthic foraminifera, total phosphorus (Ptot), and stable isotopes (δ13Ccar). In the field, the sampling of the Nukhul section was done according to the high-resolution biostratigraphy; 30 samples of the D/S interval were collected at 1 to 10-cm intervals. The washing of marl was performed through a single sieve of 63 um. For the statistical analysis of planktonic and benthic foraminifera, residues are divided using a standard microsplitter type "OTTO" for a non-selective separation of grains. The number of "splits" is determined according to the abundance of

planktonic and benthic foraminifera enumerated. The data obtained are thereafter processed by a computer to determine the frequencies (relative abundances) of the recognized species and track the vertical evolution along the interval studied.

Carbon isotope analyses of aliquots of all samples were performed using a Thermo Fisher Scientific (Bremen, Germany) Gas Bench II preparation device interfaced to a Thermo Fisher Scientific Delta Plus XL continuous flow isotope ratio mass spectrometer. Analytical uncertainty (2σ) monitored by replicate analyses of the international calcite standard NBS-19 and the laboratory standards Carrara Marble and Binn Dolomite is no greater than ±0.05 ‰ for δ13Ccarb. Total phosphorus (Ptot) analyses were performed for Nukhul samples using the ascorbic acid method (Mort et al. 2007; Khozyem et al. 2013).

## Results

### Biostratigraphic results

The outcrop series of D/S interval, about 8 m thick, are divided into three lithostratigraphic units, which are distinguished from base to top.

### The Dakhla Formation (Unit 1) (45 Nu-Nu 58)

The Dakhla Formation, with thickness of about 3.7 m, contains gray marls and is intercalated with yellowish clay beds rich in calcite. In this interval, planktonic foraminifera are abundant but very little diversified compared to the benthic. The association is composed of species belonging to the genera *Woodringina*, *Globanomalina*, *Eoglobigerina*, *Parasubbotina*, *Subbotina*, *Praemurica*, *Igorina*, *Acarinina*, and *Zeauvigerina* (Fig. 2).

The benthic microfauna are scarce but highly diversified (Fig. 3). The association is composed of species belonging to the genera *Karreriella*, *Lagena*, *Pleurostomella*, *Spiroplectammina*, *Lenticulina*, *Anomalinoides*, *Rhabdammina*, *Gyroidinoides*, *Angulogavelinella*, *Gavellinella*, *Pullenia*, *Clavulinoides*, *Tritaxia*, *Ellipsonodosaria*, *Dorothia*, *Sigmoilina*, *Ramulina*, *Coryphostoma*, *Bathysiphon*, *Tappanina*, *Loxostomoides*, *Siphogenerinoides*, *Nuttallides*, *Marssonella*, *Caudammina*, *Oridorsalis*, *Neoflabellina*, *Gaudryina*, *Alabamina*, *Dentalina*, *Laevidentalina*, *Bulimina*, *Stilostomella*, *Quadrimorphina*, and *Cibicidoides.*

### The Tarawan Formation (Unit 2) (Nu 58 + 10 X-60)

The Tarawan Formation is composed of thick (about 80 cm) gray silty marls that are brownish to yellowish, are framed at the base and located at the top by a condensed level of clays
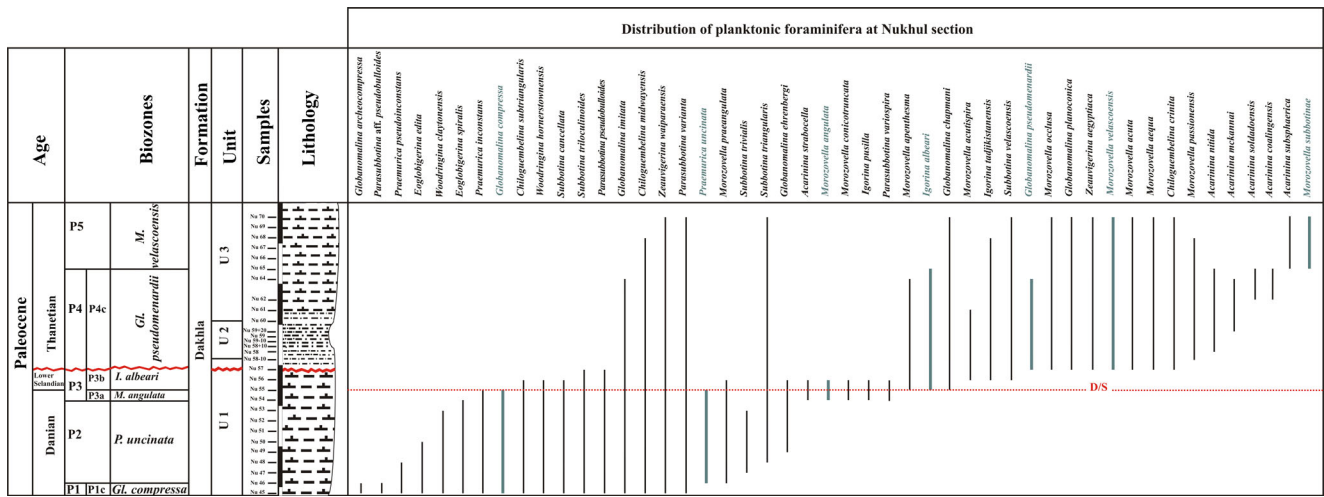
**Fig. 2** Vertical distribution of planktonic foraminifera at the Nukhul section

(about 10 cm thick); it is markedly lity, black to brownish, and rich in glauconite grains, phosphates, and shark teeth. In this unit, planktonic foraminifera are the most numerous, more diversified, and present a good state of preservation (Fig. 2). The species occurring belong to the genera *Woodringina*, *Chiloguembelina*, *Globanomalina*, *Parasubbotina*, *Subbotina*, *Acarinina*, *Igorina*, *Morozovella*, and *Zeauvigerina*.

The benthic foraminifera are scarce, poorly diversified, fragmented, and represented by species belonging to the genera *Astacolus*, *Lagena*, *Stilostomella*, *Coryphostoma*, *Pullenia*, *Spiroplectammina*, *Lenticulina*, *Caudammina*, *Anomalinoides*, *Rhabdammina*, *Marssonella*, *Neoflabellina*, *Gyroidinoides*, *Angulogavelinella*, *Gavellinella*, *Ellipsonodosaria*, *Clavulinoides*, *Tritaxia*, *Dorothia*, *Pyrulina*, *Marginulina*, *Cibicidoides*, *Pleurostomella*, *Tappanina*, *Loxostomoides*, *Siphogenerinoides*, *Nuttallides*, *Bathysiphon*, *Dentalina*, *Sigmoilina*, *Ramulina*, *Marssonella*, *Oridorsalis*, *Quadrimorphina*, *Alabamina*, *Bulimina*, *Gaudryina* (Fig. 3).

**The Esna Formation (Unit3) (Nu 61-Nu70)**

The measured part of the Esna Formation is about 3.2 m. It is composed by gray-greenish marls intercalated with gray to brown marls and is rich in iron concretions and crystals of pyrite. Planktonic foraminifera become fewer and less diversified (Fig. 2). The association is composed of species belonging to the genera *Woodringina*, *Chiloguembelina*, *Globanomalina*, *Parasubbotina*, *Subbotina*, *Igorina*, and *Morozovella*, *Zeauvigerina*, *Acarinina*.

Benthic foraminifera are much diversified but remain less numerous compared to planktonic (Fig. 3). The identified species belong to the genera *Gaudryina*, *Lagena*, *Stilostomella*, *Coryphostoma*, *Bolivina*, *Pullenia*, *Spiroplectammina*, *Lenticulina*, *Caudammina*, *Anomalinoides*, *Rhabdammina*, *Neoflabellina*, *Gyroidinoides*, *Gyroidina*, *Ellipsonodosaria*, *Dorothia*, *Karreriella*, *Marssonella*, *Pyrulina*, *Marginulina*, *Tritaxia*, *Clavulinoides*, *Pleurostomella*, *Tappanina*, *Loxostomoides*, *Gavellinella*, *Angulogavelinella*, *Siphogenerinoides*, *Bathysiphon*, *Dentalina*, *Ramulina*,
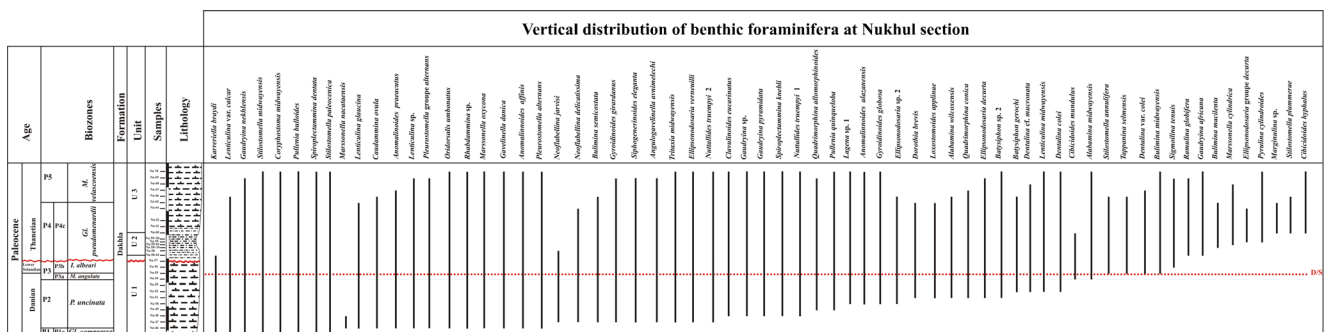


**Fig. 3** Vertical distribution of benthic foraminifera at the Nukhul section

*Cibicidoides*, *Bulimina*, *Planulina*, *Oridorsalis*, *Nuttallides*, *Quadrimorphina*, *Alabamina*, and *Valvalabamina*.

## Biochronology of the Nukhul section

Based on the first (FAD) and the last appearances (LAD) of the species markers of planktonic foraminifera, we had determined the different biozones and were able to establish the relative age of lithological units and accurately identify the location of the D/S boundary in the Nukhul section (Fig. 4). The recognized biozones were correlated with those established by Berggren et al. (1995), Olsson et al. (1999), Berggren and Pearson (2005), Vandernberghe et al. (2012); Mtimet et al. (2013), and Farouk and El-Sorogy (2015), and thus we distinguish the following biozones below.

### Biozone of *Praemurica uncinata* (P2)

We adopt this biozone as an interval zone as has been defined by Bolli (1957); Berggren et al. (1995), and Olsson et al. (1999). Its lower limit is defined by the first appearance of the fossil marker *P. uncinata*. Its upper limit coincides with the first appearance of the two species *Morozovella angulata* and *I. pusilla*. This zone is marked by the first appearance of low-keeled species (*M. praeangulata*).

### Biozone of *M. angulata* (P3a)

It corresponds to an interval range zone, and its base is defined by the appearance of the fossil marker *M. angulata* in association with *I. pusilla* (as noted by, Olsson et al. (1999); Berggren et al. (1995); Farouk and El-Sorogy 2015). Its summit is defined by the first appearance of the marker *I. albeari*.

This latter boundary is placed over the top. Mtimet et al. (2013) defined this zone (P3a) as a zone of *I. pusilla* (Fig. 4).

### Biozone of *I. albeari* (P3b)

According to Berggren et al. (1995), Berggren and Pearson (2005), Vandernberghe et al. (2012), Arenillas (2012), and Farouk and El-Sorogy (2015), it corresponds to an interval of subzone. Its lower limit is defined by the appearance of *I. albeari* while its upper limit coincides with the appearance of *Gl. pseudomenardii*, marker of the biozone P4. At the base of this biozone, we notice the sudden disappearance of several species of the genus *Praemurica* such as *Pr. pseudoinconstans*, *Pr. inconstans*, *Pr. uncinata*, and the species *Gl. compressa* and *I. pusilla*. The genus *Morozovella* in the two biozones P3a and P3b underwent a great proliferation (Figs. 4 and 5).

### Precisions of the Danian/Selandian boundary

We place the D/S boundary in the Nukhul section in the level of the first occurrence of the fossil marker *I. albeari* that occurs in the sample Nu55.

From the sample Nu 57, somewhere within the P3b subzone, we noted the simultaneous occurrence of the *M. occlusa*, *M. acuta*, *M. aequa*, and *S. velascoensis* species with the first occurrence of *Gl. pseudomenardii*, the marker of the P4 zone. Thus, it is obvious that there is an absence of the upper part of the subzone P3b as noted by Arenillas and Molina (1997), Premoli Silva et al. (2003), Steurbaut and Sztrakos (2008), Obaidalla et al. 2009, Faris and Farouk (2012), Farouk and Faris (2013), and recently by Farouk and El-Sorogy (2015). At the same time, there is a sudden extinction of *M. angulata*, *M. conicotruncata*, and *S. triloculinoides*.



**Fig. 4** Biozonation of the Danian/Selandian boundary at the Nukhul section
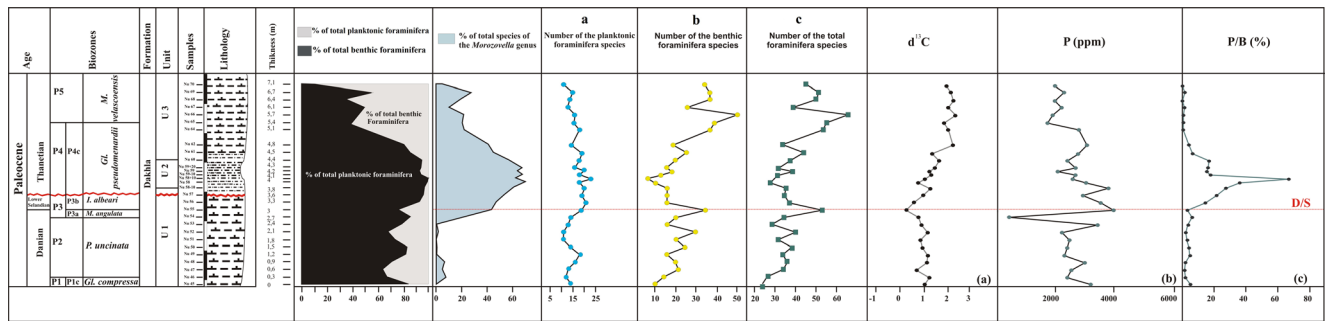
**Fig. 5** Curves of the percentage of planktonic foraminifera and percentage of benthic foraminifera. Curve of the variation in total percentage of the species belonging to *Morozovella* genus. **a** Curve of the number of planktonic foraminifera species. **b** Curve of the number of benthic foraminifera species. **c** Curve of the total number of planktonic and benthic foraminifera species. Curves of isotopic variation ($\delta^{13}$C) (**a**), of the phosphate content (P) (**b**) and the percentage change of the P/B ratio (**c**) at the Danian/Selandian boundary in the Nukhul section

## Paleoenvironment reconstruction

### Quantitative study

The quantitative study of planktonic and benthic foraminifera showed remarkable pertinent events throughout the Nukhul section including the D/S boundary. The curve of the species richness in planktonic foraminifera indicates the following variations (Figs. 5 and 6.)

Below the D/S boundary (Nu 46-Nu 54), the number of planktonic species is between 10 and 19 which is reached in the middle of the P2 zone (Nu 49). At the same time, the number of benthic foraminifer's species varies between 10 and 29 reached in the Nu 52 sample. The total number of planktonic and benthic species varies between 22 and 36. Simultaneously, the number of planktonic foraminifera

individuals varies between 280 and 380, the number of benthic foraminifera individuals varies between 50 and 100, and the total number of individuals varies between 200 and 400 (Figs. 5 a, b, c; 6 a′, b′ and c′).

It should be noted that in this interval, some planktonic species essentially globular such as *Parasubbotina varianta*, *P. pseudobulloides*, *Subbotina cancellata*, and *S. triloculinoides* show a considerable number of individuals that gradually increases toward the D/S boundary (Fig. 7).

Therefore at the D/S boundary and the base of Selandian, benthic foraminifera are more diversified but less numerous than the planktonic foraminifera. At the base of Selandian and far from the base of the P4c zone, planktonic foraminifera exist with a high increase in numbers, although they remain less diversified. On the top of the P4c zone, there is a decrease in the individual number of planktonic foraminifera and low
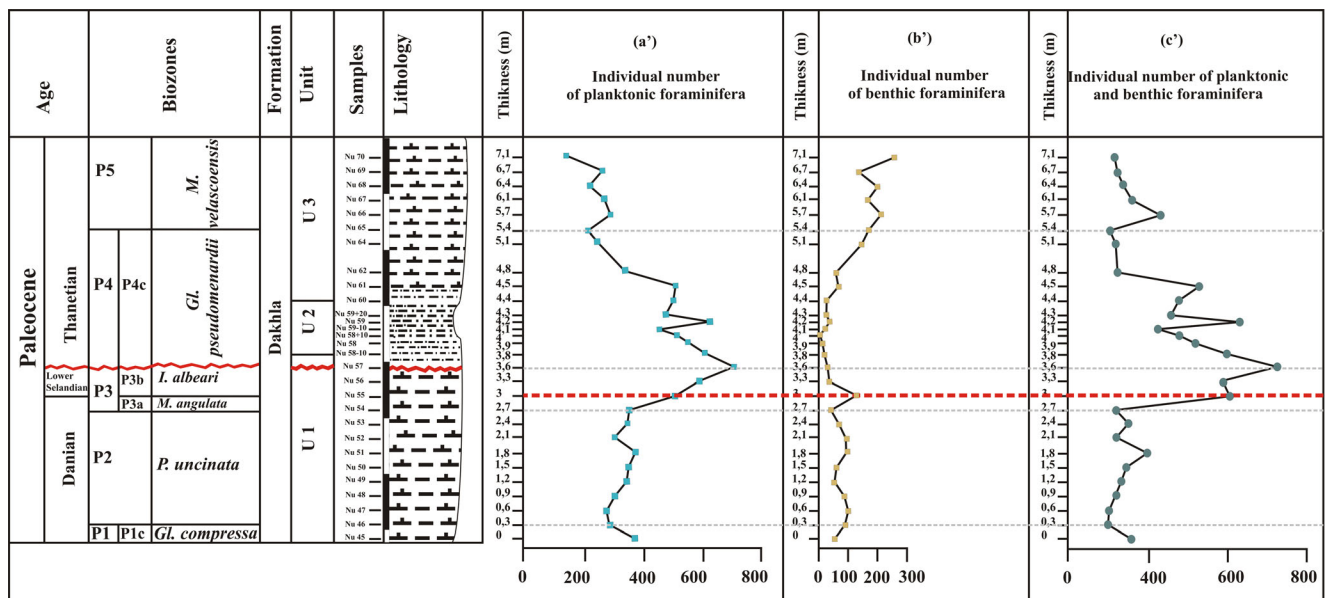


**Fig. 6** Curve of the number of planktonic foraminifera individuals (*a′*). Curve of the number of benthic foraminifera individuals (*b′*). Curve of the number of individuals of planktonic and benthic foraminifera (*c′*)
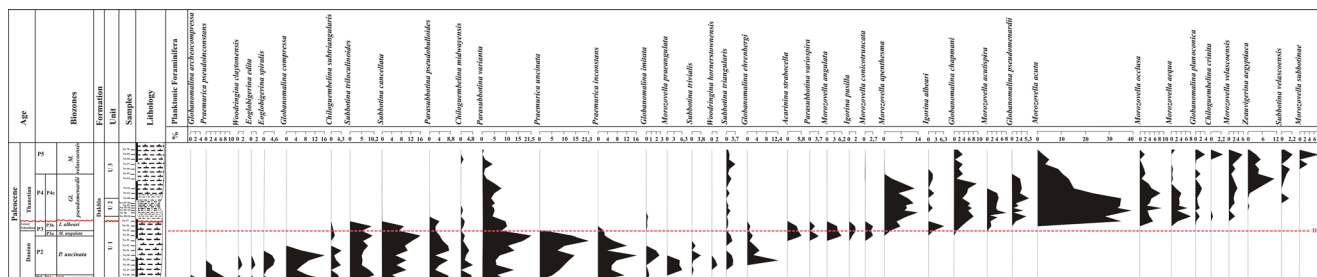
**Fig. 7** Specific frequency curves of planktonic foraminifera of the Danian/Selandian boundary at the Nukhul section

species diversity. In contrast, benthic foraminifera live very important increases in the diversity and in the number of individuals.

Only in the D/S boundary, the number of planktonic foraminifera species increase (20 species) and the number of individuals indicates a considerable increase (570 individuals). The number of benthic foraminifera species and the number of individuals decreased although they showed a small peak just at the limit. The total number of species and the total number of individuals are globally increasing.

In the Selandian far from the base of the P4c zone, the number of species and the number of individuals of planktonic foraminifera remains high (with a maximum of 23 species and 687 individuals). This proliferation is well recorded by a peak in the curve of the P/B (Fig. 13). On the other hand, benthic foraminifera mark a major drop far from the base of the P4c zone. The fall is also registered in the curve of the total number of species.

From the top of the P4c zone and particularly from the sample Nu 61, the number of species and the number of individuals of planktonic foraminifera decreases while benthic foraminifera become more important in the number of species and individuals. The total number of species and individuals follow the same evolution.

*Diversity index and living strategies*

To distinguish between the different environments under continental influence, only the benthic foraminifera are considered. Therefore, we made use directly of the abacus from Murray (1991) in Bellier et al. (2010) (Fig. 8). The statistical analysis of benthic foraminifera enabled us to determine the diversity index and hence the salinity of the environment. The diversity index is calculated by the following formula:

$$(\text{Number of individuals}/\text{Number of species}) \times 100$$

The statistical results show that most samples are concentrated below the diversity index V. However, it is necessary to mention the presence of a few points above the index diverse

line V (Table 1, Fig. 8). They essentially correspond to the intervals of samples located on either side of the D/S boundary.

• The interval of samples (Nu 52-Nu 55) of the upper part of the P2 zone corresponding to the upper Danian
• The interval of samples (Nu 64-Nu 70) corresponding to the interval of the limits of the P4c-P5 biozones of the upper Thanetian

These two intervals are already well marked on the curves of species richness and the curves of the number of individuals of all microfauna (Figs. 5 and 6).

**The planktonic and benthic foraminifera behavior on the D/S boundary**

*The frequency curves of planktonic foraminifera*

According to the specific frequency curves of planktonic foraminifera during the D/S interval, we note that the species belonging to the genera *Morozovella*, *Subbotina*, and *Parasubbotina* are more or less abundant throughout the series (Fig. 7).

Some species of the D/S boundary show fairly high percentages such as *S. cancellata* with a percentage equal to 9.16 %, *S. triloculinoides* with 9.16 %, *P. varianta* with 10.69 %, *M. apenthesma* with 6.28 %, and *M. angulata* with 4.44 % (Table 1). Be noted that the genus *Morozovella* is the most common as noted in Farouk and El-Sorogy (2015) (Figs. 5 and 7). According to Arenillas (2008) and Boudagher-Fadhel (2013), the genus *Morozovella* is the first to characterize the warm seas, tropical to subtropical type.

**The frequency curves of benthic foraminifera**

The curves of quantitative analysis based on the nature of the test of foraminifera (Fig. 9) allowed us to conclude that at the base of the Selandian, there has been an increase in the abundance of the foraminifera with porcelaneous tests (limited in the sample Nu 56) and agglutinated tests besides a decrease in

**Fig. 8** Diversity index (Murray, in 1991 Bellier et al. 2010; modified.): hyposaline <33 ‰, normal = 33–37 ‰, hypersaline >37 ‰
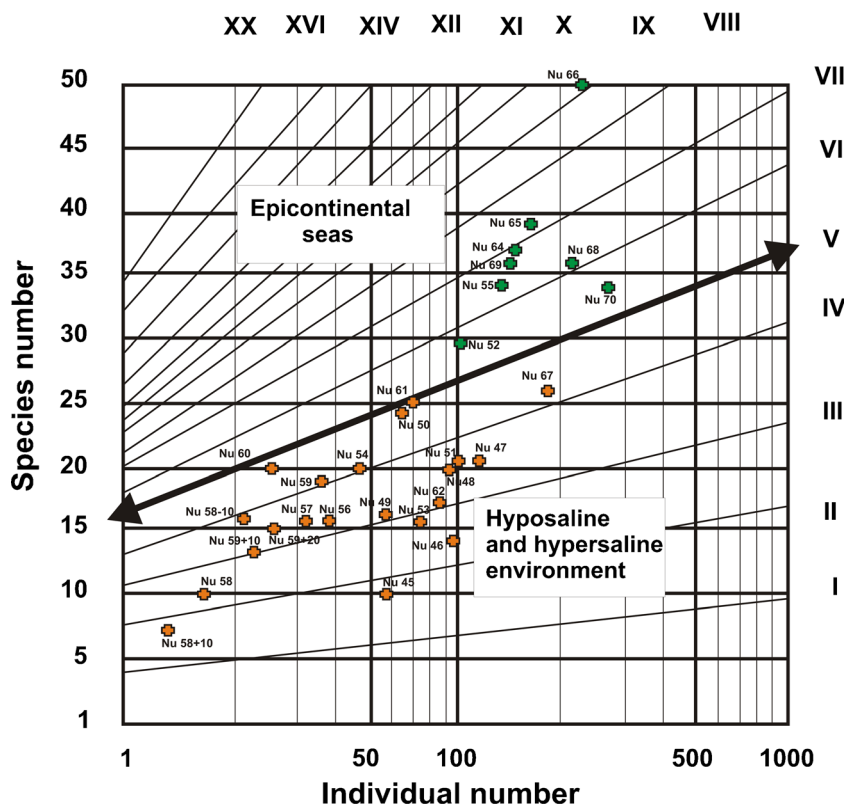


the percentages of the hyaline foraminifera tests. Above the Thanetian (P4c zone), we note the presence of two phases, at the beginning a decrease in the rates of porcelaneous and agglutinated tests and an increase of hyaline test. On the contrary, at the interval samples Nu 59 + 20–Nu 62 (still on the top of the P4c zone), there is a simultaneous increase in the abundance of foraminifera with porcelaneous and agglutinated tests with a decrease in percentages in hyaline tests.

It should be noted that throughout the D/S interval, the hyaline test species are frequently the most dominant and their frequency varied from 61.29 to 96.87 % (Table 2, Fig. 9). The species with the agglutinated test are often less abundant having values ranging from 3.12 to 28.57 %, but they can reach higher values, such as 38.7 % in the sample Nu 48. Porcelaneous test species are very rare, except for few samples, in which the values have reached 2.56 % just below the D/S boundary. At the top of Thanetian (zone P4c), a value of 7.4 % of porcelaneous species has been registered in two samples, Nu 59 and Nu 60 + 20.

At either side of the D/S boundary, some species belonging to the families Buliminidae, Cibicidoidae, and Gyroididae, typical of the bathyal area, are abundant in the sample intervals, respectively, Nu 45-Nu 56 and Nu 61-Nu70, corresponding to the upper Danian and the Thanetian. In the Thanetian, these forms show considerable percentages that may reach 6 %. These include among them, *Coryphostoma midwayensis*

with 6 %, *Bulimina semicostata* with 2.9 %, *Gyroidinoides girardanus* with 4.1 %, and *Gyroidinoides globosa* with 3.1 % (Table 2, Fig. 9). It should be noted that in the lower Selandian and according to the benthic foraminifera frequency curves, all the species have been affected by a crisis, with the exception of few species that have been adapted (Fig. 10). Among the species which seem to be not affected by the crisis, we note the following: *Stilostomella paleocenica*, *Lenticulina* sp., *Marssonella oxycona*, *Pleurostomella alternans*, *Gyroidinoides girardanus*, *Siphogenerinoides eleganta*, *Nuttallides truempyi*, *Gaudryina pyramidata*, and *Pullenia quinqueloba*. At the upper Thanetian, the percentage of these species is increasing gradually.

*Paleobathymetric indications and environment deposition by planktonic and benthic foraminifera*

As the optimal productivity of planktonic foraminifera is in non-coastal marine waters, the Oceanity Index provides an estimate bathymetry (Gibson 1989). The analysis values of the curve of the Oceanity Index shows the existence of three marine domains on either side of the D/S boundary (Fig. 11a).

Below the D/S boundary, the values of the Oceanity Index show slight fluctuations in the upper Danian (Zone P2 and P3a) from 65 to 86 %. The lowest values are intimately linked to the falls in the number of planktonic foraminifera

**Table 1** Different types of the environments in the Nukhul section

| Samples | Number of benthic species | Number of individuals | Environment |
|---|---|---|---|
| Type | | | |
| Nu 70 | 34 | 279 | Epicontinental seas with normal salinity |
| Nu 69 | 36 | 151 | Epicontinental seas with normal salinity |
| Nu 68 | 36 | 213 | Epicontinental seas with normal salinity |
| Nu 67 | 26 | 184 | Hypersaline and hyposaline environments |
| Nu 66 | 50 | 227 | Epicontinental seas with normal salinity |
| Nu 65 | 39 | 183 | Epicontinental seas with normal salinity |
| Nu 64 | 37 | 158 | Epicontinental seas with normal salinity |
| Nu 62 | 19 | 61 | Hypersaline and hyposaline environments |
| Nu 61 | 25 | 70 | Hypersaline and hyposaline environments |
| Nu 60 | 20 | 27 | Hypersaline and hyposaline environments |
| Nu 59 + 20 | 16 | 27 | Hypersaline and hyposaline environments |
| Nu 59 | 18 | 37 | Hypersaline and hyposaline environments |
| Nu 59 – 10 | 13 | 23 | Hypersaline and hyposaline environments |
| Nu 58 + 10 | 7 | 7 | Hypersaline and hyposaline environments |
| Nu 58 | 10 | 14 | Hypersaline and hyposaline environments |
| Nu 58 – 10 | 16 | 21 | Hypersaline and hyposaline environments |
| Nu 57 | 16 | 31 | Hypersaline and hyposaline environments |
| Nu 56 | 16 | 39 | Hypersaline and hyposaline environments |
| Nu 55 | 34 | 138 | Epicontinental seas with normal salinity |
| Nu 54 | 20 | 47 | Hypersaline and hyposaline environments |
| Nu 53 | 16 | 73 | Hypersaline and hyposaline environments |
| Nu 52 | 29 | 100 | Epicontinental seas with normal salinity |
| Nu 51 | 21 | 99 | Epicontinental seas with normal salinity |
| Nu 50 | 24 | 64 | Hypersaline and hyposaline environments |
| Nu 49 | 16 | 58 | Hypersaline and hyposaline environments |
| Nu 48 | 20 | 93 | Hypersaline and hyposaline environments |
| Nu 47 | 21 | 108 | Hypersaline and hyposaline environments |
| Nu 46 | 14 | 96 | Hypersaline and hyposaline environments |
| Nu 45 | 10 | 58 | Hypersaline and hyposaline environments |

(Fig. 11b). The ratio P/B% indicates low values not exceeding 6 % (Fig. 13). From the base of Selandian, the Oceanity Index rises until the value of 98 % and the P/B ratio shows very high values, which can reach 67 %. At the top of the P4c and P5 zones of the upper Thanetian, the index of oceanity, decreases suddenly to 11 % and becomes lower toward the top of the section (Fig. 11a, b, c). The P/B ratio also marks a drop (Fig. 13).

*Paleoclimatic and paleobathymetric indications*
*by the morphology of the test*

The analysis of the morphology of the tests as the keeled and globulous forms of planktonic foraminifera could inform us about the change in the climatic conditions that prevailed during that time. Thus, there are three intervals.

Below the D/S boundary or at the upper Danian (interval samples Nu 45-Nu 53), the keeled forms, represented by *Morozovella* and *Acarinina* genera, are very scarce and represented by a small number of individuals not exceeding 55 (Fig. 12). In contrast, in that same interval, the globulous forms are abundant and show a number of individuals that constantly increases. For example, in the sample Nu 52, the number of keeled individual forms is five compared to the globulous forms which are very numerous (220 individuals).

Amidst the P3a zone (Nu 55), there is an abrupt increase in the number of keeled forms (288 individuals). Starting from the D/S boundary, the number of keeled forms shows a

**Table 2** Variation in the percentages (%) of benthic foraminifera according to the nature of the test

| Age | Biozones | Samples | % of Hyaline tests | % Agglutinated tests | % of Porcelaneous Tests |
|---|---|---|---|---|---|
| Thanetian | P5 | Nu70 | 75.62 | 22.93 | 1.43 |
| | | Nu69 | 77.48 | 21.19 | 1.32 |
| | | Nu68 | 85.91 | 14.08 | 0 |
| | | Nu67 | 90.21 | 9.78 | 0 |
| | | Nu66 | 77.97 | 21.14 | 0.88 |
| | | Nu65 | 86.33 | 12.02 | 1.63 |
| | P4c | Nu64 | 78.48 | 20.25 | 1.26 |
| | | Nu62 | 88.52 | 11.47 | 0 |
| | | Nu61 | 84.28 | 12.85 | 2.85 |
| | | Nu60 | 74.07 | 18.51 | 7.4 |
| | | Nu59 + 20 | 66.66 | 25.92 | 7.4 |
| | | Nu59 | 83.78 | 16.21 | 0 |
| | | Nu59–10 | 82.6 | 17.39 | 0 |
| | | Nu58 + 10 | 85.71 | 14.28 | 0 |
| | | Nu58 | 85.71 | 14.28 | 0 |
| | | Nu58−10 | 71.42 | 28.57 | 0 |
| | | Nu57 | 90.32 | 9.67 | 0 |
| Lower Selandian | P3b | Nu56 | 79.48 | 17.94 | 2.56 |
| | | Nu55 | 78.26 | 21.73 | 0 |
| Danian | P3a | Nu54 | 89.36 | 10.63 | 0 |
| | P2 | Nu53 | 84.93 | 15.06 | 0 |
| | | Nu52 | 81 | 19 | 0 |
| | | Nu51 | 90.9 | 9.09 | 0 |
| | | Nu50 | 96.87 | 3.12 | 0 |
| | | Nu49 | 74.13 | 25.86 | 0 |
| | | Nu48 | 61.29 | 38.7 | 0 |
| | | Nu47 | 90.74 | 9.25 | 0 |
| | P1C | Nu46 | 78.13 | 21.87 | 0 |
| | | Nu45 | 75.86 | 24.13 | 0 |

number of individuals equal to 446. The number of globulous forms gradually decreases and remains lower than the number of keeled forms (Fig. 12).

At the top of the upper Thanetian, there is a gradual decrease in the number of keeled forms. From the top of the upper P4c biozone, the number of the keeled forms becomes almost equal to that of globulous forms (Fig. 12).

*Paleobathymetric indications by benthic foraminifera*

Due to their behavior vis-à-vis of the environmental conditions, their diversity and their richness in different marine domains, benthic foraminifera are good indicators of palaeodepths (El-Dawy 2001; Bellier et al. 2010; Speijer 2003; Sprong et al. 2009, 2011, 2013; Storme et al. 2014).

According to Fig. 13 and Table 3, there are three intervals corresponding to three types of benthic foraminifera associations. Below the D/S boundary, there is a dominance of epibenthic species (about 24.05 %). In contrast, endobenthic forms show a smaller percentage of about 11 %.

From the base of the lower Selandian to the base of the upper Thanetian, there was a sudden drop in the total number of benthic foraminifera (6.62 %) compared to planktonic foraminifera which show a very high value reaching 93.37 %. Epibenthic and endobenthic forms show low values but have approximately the same proportions.

Higher up the series, at the top of the upper Thanetian (P5), the two forms become abundant again. However, epibenthic forms dominate with a percentage equal to 46.59 %, and in contrast, endobenthic forms have low values but increase
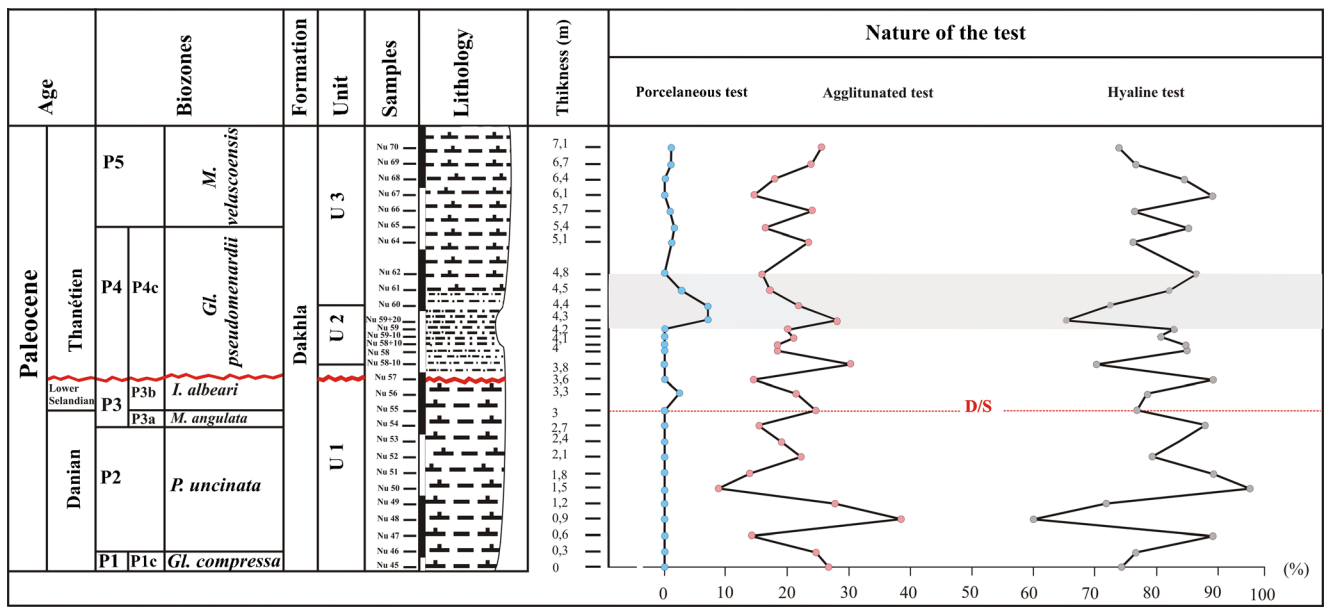
**Fig. 9** Variation in the percentage of benthic foraminifera according to the nature of the test

steadily to a maximum estimated 42.26 % toward the top (Fig. 13 and Table 3).

*Isotopic analysis*

In most of southeast Tethyan regions, the D/S boundary coincides with the identification of several events, specially the downfall of the value of $\delta^{13}C$, synchronous to the period of the decrease in sea level (Arenillas et al. 2008; Schmitz et al. 2011; Vandernberghe et al. 2012; Storme et al. 2014).

The analysis of the $\delta^{13}C$ isotopic curve of the Nukhul section shows a value of 1 ‰ at the upper Danian (Fig. 5). On the contrary, in the interval Nu52-Nu 58-10, its value abruptly annuls which coincides with the downfall of the total number of benthic foraminifera (from 100 to 21 individuals) in the D/S transition (Fig. 6 b′).

The zero value of $\delta^{13}C$ at the D/S boundary of the Nukhul section is higher than that estimated in the Nile Basin (Egypt) which is of the order of −2 ‰ registered in the test of benthic foraminifera in the late Danian or that of Zumaia (Schmitz
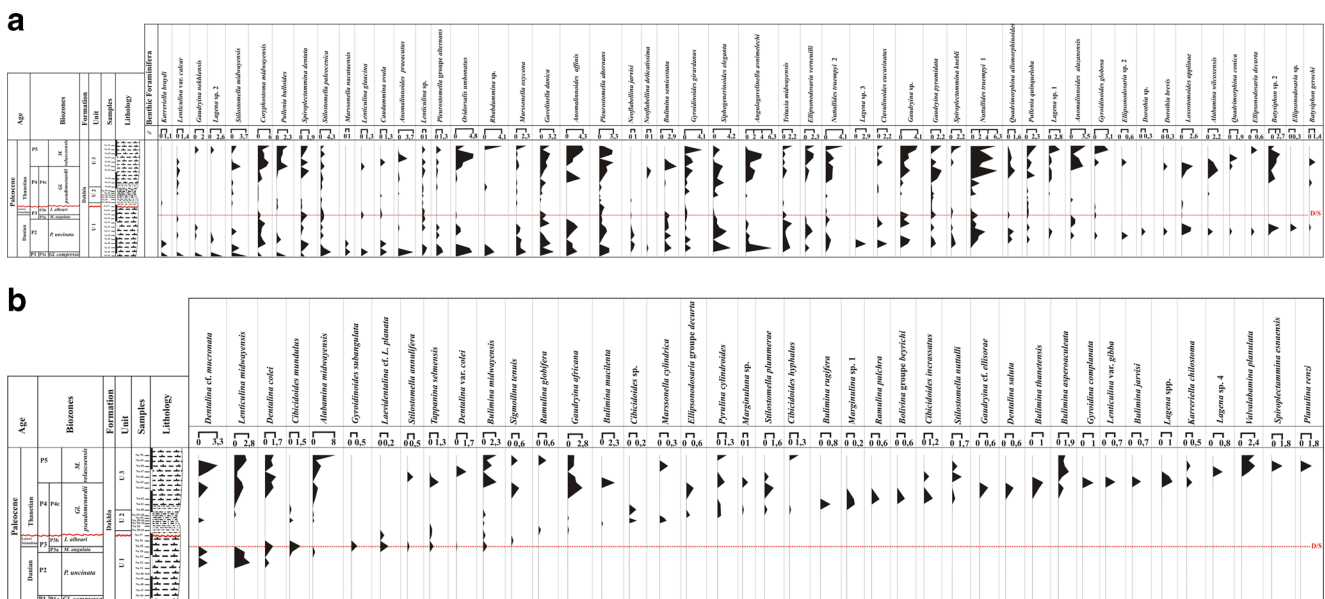


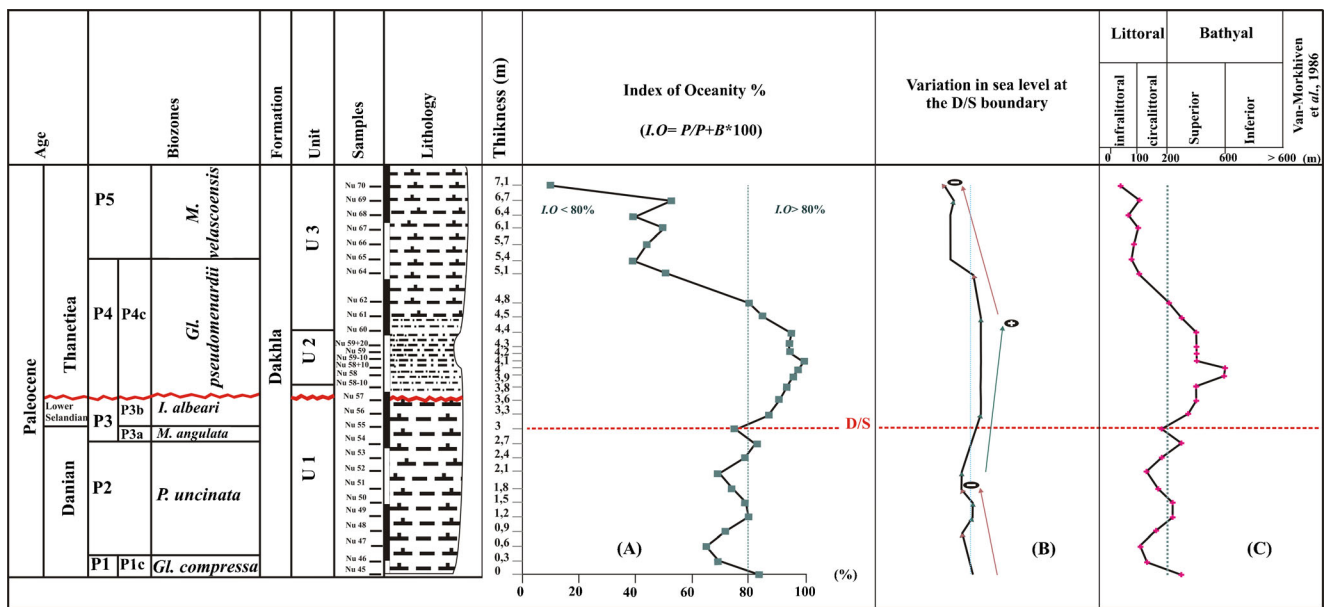**Fig. 10 a**, **b** Specific frequency curves of benthic foraminifera of the Danian/Selandian boundary at the Nukhul section

**Fig. 11** Curves of the variation of the oceanity index (**a**), the variation in sea level (**b**), and bathymetry (**c**) of the Nukhul section

et al. 2011; Speijer 2003; Bornemann et al. 2009). Indeed, Fig. 5b shows an increase in the phosphate content at the same time with negative incursion ($\delta^{13}$C) and coinciding with a low P/B ratio. These events are recorded in the lithological landmark level which is rich in phosphate and is recognized worldwide (Obaidalla et al. 2009; Mtimet et al. 2013; Sprong et al. 2009). The phosphate content has undergone a considerable drop in the top of the upper Danian. On the contrary, from the

lower Selandian, the content increased and lasted until the base of the upper Thanetian (P4c).

*Discussion and interpretation*

In the upper Danian, the decrease in the diversity of planktonic foraminifera as well as the drop in the number of individuals would indicate a marine regression probably due to the
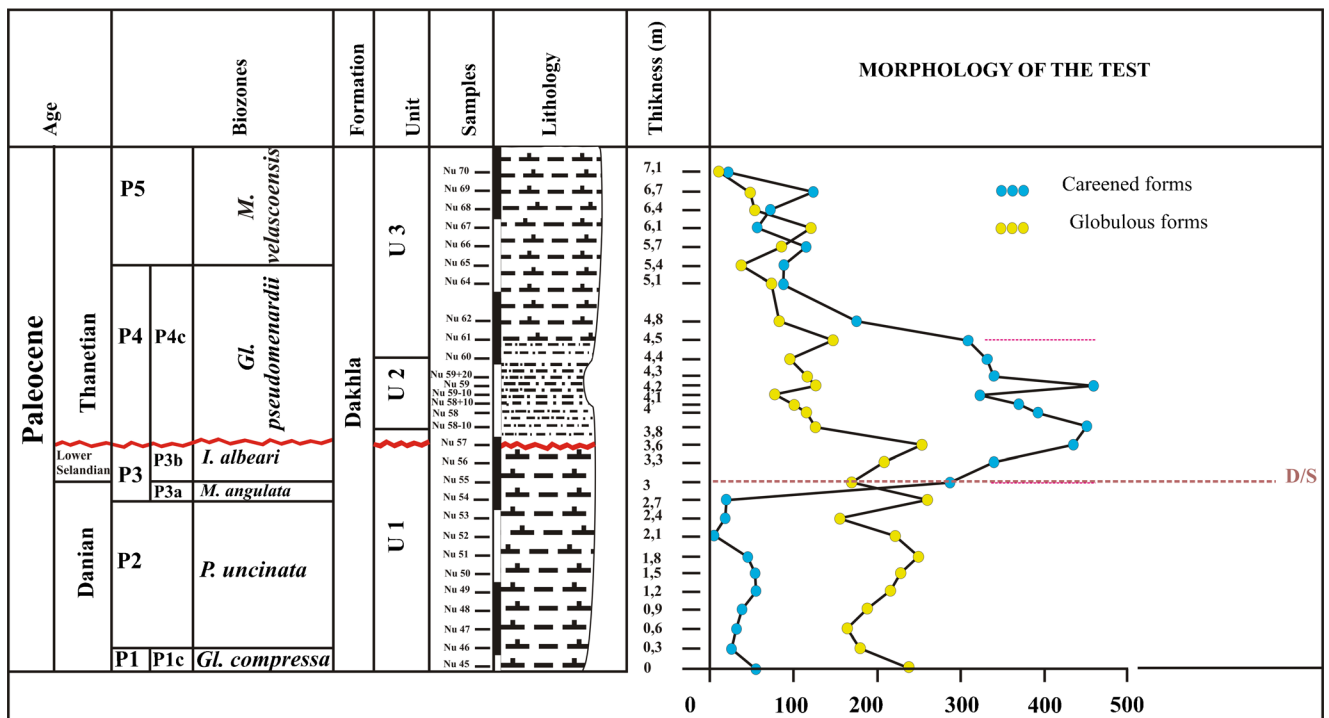


**Fig. 12** Variation in the number of globulous and keeled forms in the Nukhul section in the Danian/Selandian interval
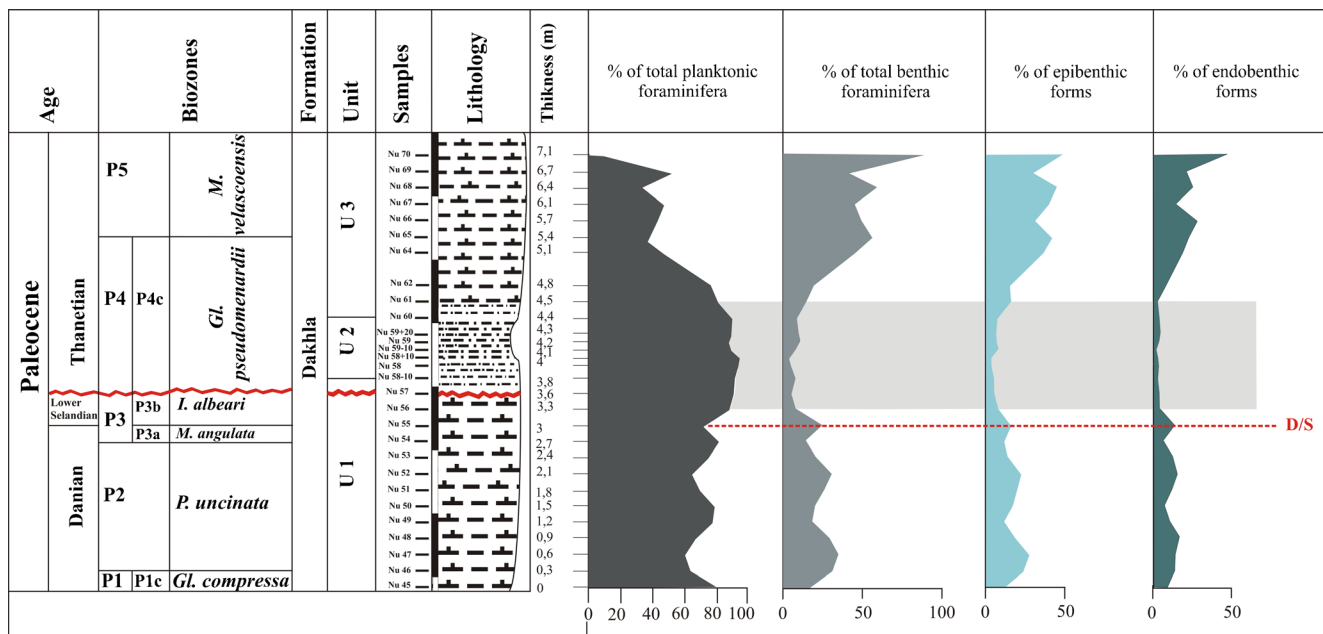
**Fig. 13** Relative abundance of individuals of endobenthic and epibenthic forms

tectonic activity. In the Selandian until the base of the P4c zone, a considerable increase in the number of individuals and species of planktonic foraminifera would certainly witness the transgression in the Selandian (Farouk 2016; and Farouk and El-Sorogy 2015; Haq 2014). Simultaneously, during the D/S, we noticed the sudden disappearance of several species of the genus *Praemurica*, such as *Pr. pseudoinconstans*, *Pr. inconstans*, and *Pr. uncinata*, and the species *I. pusilla*. This is a global biological event; these extinctions would probably be linked to global warming.

The statistical results show that the majority of the samples are concentrated below the diversity index V, indicating hyposaline environments (Table 1). These results confirm the works of Farouk and El-Sorogy (2015) and Farouk (2016) on the Dakhla Formation. These authors have demonstrated that at the D/S boundary, benthic foraminifera assemblages are typical of restricted hyposaline facies, near the shoreline associated with a wide marginal carbonate shelf. According to Berggren (1974), similar faunal associations characterized the intertidal marine environments.

Benthic foraminifer's assemblages are much diversified and bear witness to sedimentation mainly above the compensation level of calcite (CCD). In the upper Danian, biocenosis corresponds to temperate seas to slightly cold. Just at the limit D/S, the new association indicates that the seas become warmer. In the upper Thanetian, the absence of porcelaneous tests would indicate the installation of new environmental conditions less favorable to their survival.

Below the D/S boundary, the values of IO and the P/B ratio indicate depths not exceeding 200 m, which is possibly related

to the gradual decline of the sea level due to the global regressive phase (Speijer 2003; Haq 2014; Farouk and El-Sorogy 2015; Farouk 2016) (Fig. 11a). The sedimentation reflects a shallow infralittoral zone domain more often to circalittoral. From the base of the Selandian, the oceanity index and the P/B ratio reflect the Selandian transgression that continues until the base of the upper Thanetian and the installation of environment sedimentation type superior bathyal to inferior (Fig. 11b). The considerable number and the state of the planktonic foraminifera clearly confirm that the living conditions during this interval become more favorable for their development. This is certainly due to the global warming that has generated a rising sea level (Fig. 11c). This marine transgression of Selandian is registered in several world sections (Speijer 2003; Vandernberghe et al. 2012; Farouk and El-Sorogy 2015). At the top of the P4c and P5 zones of the upper Thanetian, the P/B ratio decreases and the oceanity index falls suddenly and reaches the value 11 % toward the top of the section. This is evidence of a sudden drop of the sea level which is probably due to a second phase of a marine regressive and the paleoenvironmental became intertidal rather than infralittoral (depth <−40 m) (Fig. 11b, c).

The increased number of the keeled forms characterizes the warm waters and their decrease reflects the installation of a cooling phase. Since they are indicative of paleotemperatures, their almost total absence in parallel with the remarkable abundance of the globulous species typical of deeper waters is an index of the temperature drop (Frakes 1999). This proliferation of keeled forms concerns the lower Selandian and the base of the upper Thanetian.

**Table 3** Variation in relative abundance of individuals (%) of endobenthic and epibenthic forms in the Nukhul section at the Danian/Selandian boundary

| Samples | Thikness (m) | % of planktonic foraminifera | % of benthic Foraminifera | % of endobenthic forms | % of epibenthic forms |
|---------|--------------|------------------------------|---------------------------|------------------------|-----------------------|
| Nu 70 | 7.1 | 11.14 | 88.85 | 42.26 | 46.59 |
| Nu 69 | 6.7 | 53.25 | 46.74 | 18.78 | 27.96 |
| Nu 68 | 6.4 | 36.79 | 63.2 | 21.3 | 41.9 |
| Nu 67 | 6.1 | 49.31 | 50.68 | 12.63 | 38.05 |
| Nu 66 | 5.7 | 46.58 | 53.41 | 23.69 | 29.72 |
| Nu 65 | 5.4 | 40.77 | 59.22 | 20.98 | 38.24 |
| Nu 64 | 5.1 | 50.15 | 49.84 | 16.04 | 33.8 |
| Nu 62 | 4.8 | 80.99 | 19 | 6.21 | 12.79 |
| Nu 61 | 4.5 | 86.39 | 13.6 | 1.71 | 11.89 |
| Nu 60 | 4.4 | 94.31 | 5.68 | 2.1 | 3.58 |
| Nu 59 +-20 | 4.3 | 94.11 | 5.88 | 2.35 | 3.53 |
| Nu 59 | 4.2 | 94.05 | 5.94 | 1.76 | 4.18 |
| Nu 59 −10 | 4.1 | 94.54 | 5.45 | 0.7 | 4.75 |
| Nu 58 +-10 | 4 | 98.52 | 1.47 | 1.05 | 0.42 |
| Nu 58 | 3.9 | 97.29 | 2.7 | 1.52 | 1.18 |
| Nu 58 −10 | 3.8 | 96.45 | 3.54 | 1.45 | 2.09 |
| Nu 57 | 3.6 | 95.54 | 4.45 | 2.19 | 2.26 |
| Nu 56 | 3.3 | 93.37 | 6.62 | 2.33 | 4.29 |
| Nu 55 | 3 | 76.84 | 23.15 | 10.53 | 12.62 |
| Nu 54 | 2.7 | 85.58 | 14.41 | 4.87 | 9.54 |
| Nu 53 | 2.4 | 78.71 | 21.28 | 9.9 | 11.38 |
| Nu 52 | 2.1 | 69.23 | 30.76 | 12.26 | 18.5 |
| Nu 51 | 1.8 | 74.61 | 25.38 | 9.6 | 15.78 |
| Nu 50 | 1.5 | 82.4 | 18.76 | 5.54 | 13.22 |
| Nu 49 | 1.2 | 82.26 | 17.73 | 8.54 | 9.19 |
| Nu 48 | 0.9 | 70.47 | 29.52 | 13.93 | 15.59 |
| Nu 47 | 0.6 | 64.47 | 35.52 | 11.47 | 24.05 |
| Nu 46 | 0.3 | 68.21 | 31.78 | 11.23 | 20.55 |
| Nu 45 | 0 | 83.52 | 16.47 | 7.08 | 9.39 |

According to the statistical studies on the different types of benthic foraminifera, we note that below the D/S boundary, neritic conditions seem to settle. From the base of the lower Selandian to the base of the upper Thanetian, a decrease in the total number of benthic foraminifera and the equal proportions of both forms probably indicate that the bathymetries become more important. From the top of the upper Thanetian (P4c), the neritic conditions seem to be installed again.

The negative $\delta^{13}C$ incursion is closely linked to global warming and the rising in the sea level according to some authors (Steurbaut et al. 2000; Speijer 2003; Arenillas et al. 2008; Vandernberghe et al. 2012; Storme et al. 2014; Farouk and El-Sorogy 2015; Molina 2015). The significant increase in the percentages of planktonic foraminifera and particularly in the genus *Morozovella* at the boundary between the biozones of *M. angulata* and *I. albeari* (P3a /P3b) has been identified in the Tethyan sections and often used in the interpretations of the isotopic variation of $\delta^{13}C$ (Arenillas 1996; Arenillas and Molina 1997; Guasti et al. 2006).

Indeed, the increase in the phosphate content at the same time with the negative incursion of $\delta^{13}C$ and with a low P/B ratio are the events registered in the lithological landmark level which is rich in phosphate and recognized worldwide (Obaidalla et al. 2009; Mtimet et al. 2013; Sprong et al. 2009). The drop in phosphate content in the top of the upper Danian was linked to regression. On the contrary, from the

lower Selandian, the content increases would be linked to the Selandian transgression that spawned the proliferation of planktonic foraminifera and lasted until the base of the upper Thanetian (P4c). The peak of the P/B ratio reflects the maximum of the transgressive phase.

In the Nukhul section, during the D/S boundary, there is an increase in percentages of the genus *Morozovella* (*M. acuta* 29 %; *M. apenthesma* 6.28 %; *M. aequa* 2.54 %; *M. occlusa* 2.37 %; *M. acutispira* 3.56 %) (Figs. 5 and 7). This increase in the rate of *Morozovella* genus coinciding perfectly with the null value of $\delta^{13}C$ that occurred at the base of Selandian (Fig. 5) demonstrates that the *Morozovella* genus would probably be a witness to a global hyperthermic event affecting mainly the ocean surface (Speijer 2003; Farouk and El-Sorogy 2015).

Small decreases in the percentages of *Morozovella* and increase in the percentages of Trochaminids and *Spiroplectammina* reflect an apparent decrease in the temperature of ocean surfaces and a possible increase in oxygenation of sea water toward the bottom (Arenillas 1996; Schmitz et al. 1997, 1998).

## Conclusions

The micropaleontology, paleoecology, and isotopic analysis of the Nukhul section (Egypt) had allowed us to determine the biozonation, to specify the D/S boundary and to determine the paleoenvironments and the events at that time. Thus, we could recognize the biozones of *P. uncinata* (P2) of the middle Danian; *M. angulata* (P3a) of the upper Danian; *I. albeari* (P3b) of the lower Selandian; *Acarinina soldadoensis/ Globanomalina pseudomenardii* (P4c) of the upper Thanetian; and *M. velascoensis* (P5) of the upper Thanetian. The D/S boundary is defined by the first appearance of the marker *I. albeari* and we concluded that the series is discontinuous and the presence of a sedimentary hiatus covering the whole interval of sub-biozones; the upper part of P3b, P4a, P4b; and probably the base of P4c. Therefore, we have an unconformity of the upper Thanetian on the lower Selandian.

A relatively cold climate with minimum oxygen content was registered during the middle to upper Danian. A global warming climatic conditions seem to be installed from the lower Selandian to the base of upper Thanetian simultaneously with a rise period of the sea level certainly bearing witness to the Selandian transgression. The drop in the value of $\delta^{13}C$, the quantitative analysis of the foraminifera, and the increase of the content in phosphate indicate that the Danian/Selandian event is considered hyperthermic. The similarities between the DSE and PETM events and the similar duration suggest an identical trigger mechanisms.

Therefore, the three phases of sea level registered are regression and cooling in the upper Danian; transgression and warming in the Selandian base of the Thanetian; and cooling and regression in the upper Thanetian.

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