

Thanetian transgressive-regressive sequences based on foraminiferal paleobathymetry at Gebel Matulla, west-central Sinai, Egypt



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ABSTRACT

Qualitative and quantitative analysis of Thanetian foraminiferal assemblages at Gebel Matulla in west-central Sinai has been carried out. Three benthic foraminiferal assemblages are recorded from shallowest to deepest as *Cibicidoides pseudoacutus*, *Angulogavelinella avnimelechi*, *Gavelinella danica* with evidences of fluctuations from middle neritic to upper bathyal environments. Changes in the foraminiferal population enabled us to classify the Thanetian succession into two fourth order transgressive-regressive (T–R) sequences. Three sequence boundaries are identified, at the Selandian/Thanetian (S/T) boundary, within the Thanetian succession, and the Paleocene/Eocene (P/E) boundary. It occurs at the top part of the maximum regression associated with major discontinuities and changes in depositional regimes as well as vertical facies changes. Broad correlation with eustatic records based upon integrated microplanktonic biostratigraphy suggests that the fluctuations of foraminiferal population were controlled by global sea-level changes.

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1. Introduction

The Thanetian Stage is the uppermost stratigraphic stage of the Paleocene Epoch and spans the time from 59.2 to 56 Ma. According to Global Stratotype Section and Point (GSSP), the base of the Thanetian occurs in the Zumaya section of northern Spain, occurs within the upper part of nannofossil Zone NP6 and equivalent planktic foraminifera P4a Subzone corresponds to the base of magnetochron C26n (Schmitz et al., 2011). The Thanetian Stage is not associated with any significant change in marine micro-fauna or flora, so that it is difficult to use faunal content to correlate it globally and identify its base (Schmitz et al., 2011). In Egypt, the Selandian/Thanetian boundary is extremely difficult to delineate, and it lies within the middle of the Tarawan Chalk Formation, in southern Egypt (Berggren et al., 2012).

The Paleocene microplanktonic biostratigraphy in Sinai was subjected to a detail investigation during the last years (e.g. Lüning et al., 1998; Samir, 2002; Ayyad et al., 2003; Speijer, 2003; Farouk and Faris, 2008; Faris and Farouk, 2012; Khozyem et al., 2013).

Furthermore, the Thanetian Stage and its relative sea-level fluctuations are stratigraphically controversial in Egypt and remains a particular subject of debate.

In order to understand the controls on sequence development, it is first necessary to determine the paleoenvironments and relative sea level. Foraminifera are diverse, abundant and widely distributed in Egyptian Paleocene deposits, and they are excellent indicators of paleodepth and oceanic productivity (e.g., Van der Zwaan et al., 1999; Alegret and Ortiz, 2012). It is therefore reasonable to expect that the foraminiferal facies of a particular sedimentary package will contain important information reflecting transgressive-regressive (T–R) developments.

A T–R sequence was originally defined as a sedimentary unit comprised of a transgressive phase, which shows an upward deepening event, and a regressive phase, which shows an upward shallowing event; the two phases are separated by a maximum flooding surface (Johnson and Murphy, 1984; Johnson et al., 1985; Embry, 1993, 1995, 2002). This definition is useful in hemipelagic facies that lack a physical boundary (Lüning et al., 1998; King, 2013). T–R sequences may enable workers to objectively determine correlative conformity across different areas by using the maximum regressive surface (Embry, 1995). The

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present study aims to 1) to establish a high resolution biostratigraphic scheme based on the integration of planktonic foraminiferal and calcareous nannofossil datums; 2) detect paleoenvironmental changes and faunal turnover during the Thanetian succession at Gebel Matulla using qualitative and quantitative analyses of foraminiferal assemblages; 3) classify this succession into T-R cycles; and 4) correlate the Gebel Matulla sequence with other localities inside and outside Egypt to detect episodes of eustatic sea level change.

2. Material and methods

A total of 22 samples covering the Thanetian interval were collected from Gebel Matulla section (29°01'02"N, 33°12'45"E; Fig. 1), sampled at intervals from 0.2 to 0.5 m. T-R sequences and their boundaries are recognized on the basis of foraminiferal paleobathymetry and major lithofacies shifts. Age control for the study interval relies primarily on planktic foraminifera and calcareous nannofossil biostratigraphy. About 20 g of dry rock sample were soaked in 10% hydrogen peroxide, disaggregated in water, washed through a 63 µm sieve, and then dried for foraminiferal analyses. All residues were investigated under an Olympus SZX7 binocular microscope. Nannofossils were identified by preparing smear-slides, and examined under a light microscope at 1250× magnification by both cross-polarized and phase-contrast methods.

3. Results

3.1. Lithofacies

The Paleocene succession consists of, in stratigraphic order from older to younger, the Dakhla Shale (Danian–Selandian), Tarawan Chalk (Thanetian), and Esna Shale (Thanetian–Ypresian). The lithofacies in this study includes the calcareous mudstones of the Dakhla Shale Formation followed upwards by pale yellow gray to medium gray, variably argillaceous chalky limestone with few chert nodules in the Tarawan Chalk and finally the Esna Shale, with calcareous shales and mudstones with a few calcareous sandstone ledges towards the top (Fig. 2). The Tarawan Chalk is marked by a sharp contact and vertical facies change near the Dakhla Shale/Tarawan Chalk and the Tarawan Chalk/Esna Shale formational boundaries (Fig. 2).

3.2. Planktic foraminiferal biostratigraphy

Planktic foraminifera are extremely varied in their abundance, diversity, and preservation. In this study, the planktic biostratigraphy has been identified in the studied interval according to zonal scheme of Berggren and Pearson (2005) and Wade et al. (2011). Zonation is based on the highest and lowest occurrence (HO and LO, respectively) of the marker species. The *Globanomalina pseudomenardii* (P4) Zone is classified into three subzones P4a, P4b and P4c. Zonation relies on the following markers: the LO of *Globanomalina pseudomenardii* identifies the base of Subzone P4a, the HO of *Parasubbotina variospira* identifies the base of Subzone P4b, and the LO of *Acarinina soldadoensis* identifies the base of Subzone P4c. The dominant species in the P4 Zone include angular morozovellids such as *Morozovella acuta*, *Morozovella aequa*, *Morozovella velascoensis*, *Morozovella oclusa*, in addition to *Acarinina mckannai*, *A. strabocella* and *Subbotina velascoensis*.

Some bioevents (e.g., the LO's of *Morozovella aequa*, *M. acuta*, Fig. 3) show variations in the stratigraphic ranges in the basal part of the studied section, within the P4a Subzone, while in other zonal schemes these bioevents are found relatively high within Subzone P4b (Olsson et al., 1999). Similarly early occurrences have also been reported by Arenillas (2011) in the Caravaca section in Spain as well as in Egypt (Faris and Farouk, 2012; Farouk and Faris, 2013).

The *M. velascoensis* (P5) Zone is defined as the interval between the HO of *G. pseudomenardii* and the LO of *A. sibaiyaensis* (Berggren and Pearson 2005; Wade et al., 2011). In this biozone, the morozovellids decrease in abundance and diversity, associated by increase of acarininids (*A. soldadoensis*) and subbotinids (*S. velascoensis* and *S. triangularis*). A planktic foraminiferal faunal turnover is obvious with the incursion and dominance of warm-water acarininids such as *Acarinina africana*, *A. sibaiyaensis* and *Morozovella allisonensis* (Fig. 3).

3.3. Calcareous nannofossil biostratigraphy

Nannofossils are frequent to common with moderate to good preservation in the studied section. Four nannofossil zones (NP5, NP6, NP7/8 and NP9) have been identified in the studied interval according to zonal scheme of Martini (1970, 1971). The basal part of the studied interval (samples 107–109) belongs to the *Fasciculithus*

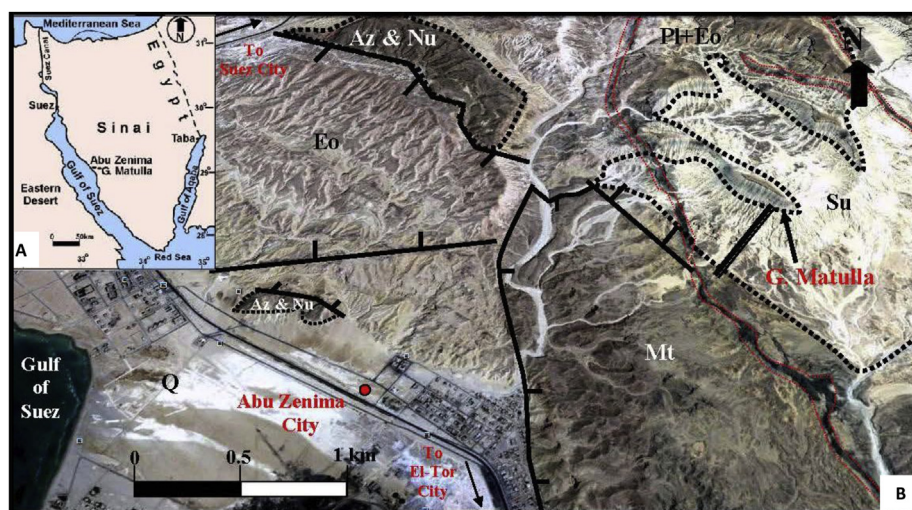


Fig. 1. (A) Schematic map showing the location of the Matulla section in west-central Sinai, Egypt. (B) Interpreted satellite image with faults and the distribution of Cretaceous and Cenozoic lithostratigraphic units. Abbreviations: Mt – Matulla Formation, Su – Sudr Formation, Pl + Eo – Paleocene and Eocene deposits (Dakhla, Tarawan, Esna and Thebes formations), Az – Oligocene Abu Zenima Formation, Nu – Chattian – Aquitanian Nukhul Formation, Q – Quaternary deposits (Farouk, 2014).

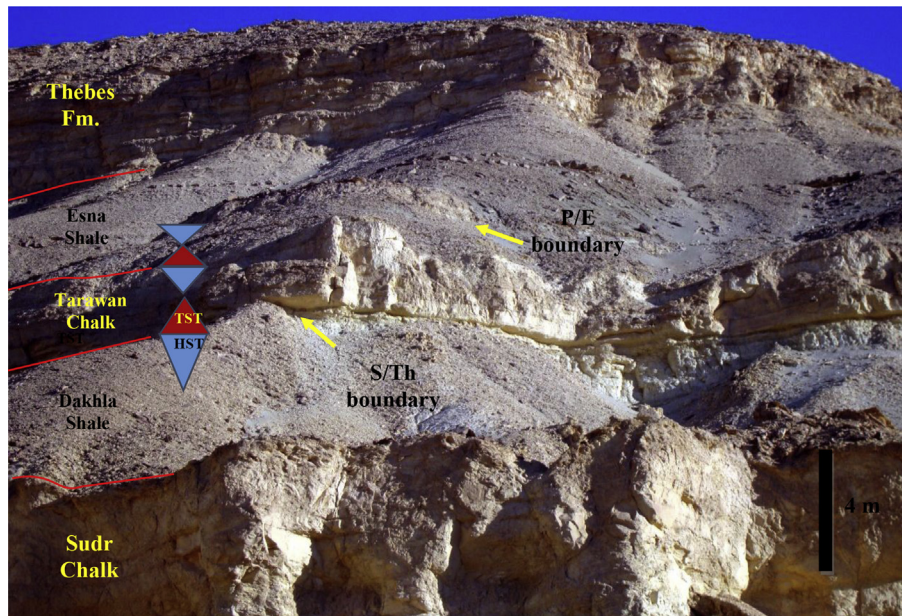


Fig. 2. Outcrop image of the Thanetian succession in Gebel Matulla with a) position of the S/Th and P/E boundaries b) T-R cycle of the Thanetian succession with the Dakhla Shale/Tarwan Chalk and Tarawan Chalk/Esna Shale boundaries.

tympaniformis Zone (NP5), which spans the Selandian Stage. It is defined from the LO of *F. tympaniformis* to the LO of *Heliolithus kleinpellii* (Mohler and Hay, in Hay et al., 1967). This zone is characterized by the presence of *F. tympaniformis*, *Fasciculithus bitectus*, *Fasciculithus involutus*, *Fasciculithus pileatus*, *Coccolithus pelagicus*, *Ericsonia subpertusa*, *Sphenolithus primus*, *Chiasmolithus edentulus*, *Neochiastozygus perfectus*, *N. modestus*, *Lithoptychius stegastus*, *L. callari*, *Ellipsolithus macellus*, *Toweius eminens*, and *Diantholita mariposa*. Species such as *E. subpertusa*, *Fasciculithus* spp. and *Sphenolithus* spp. have been observed in this zone in greater abundances than *E. pelagica/cava* and *Chiasmolithus* spp. The second reported calcareous nannofossils zone is the *Heliolithus kleinpellii* Zone (NP6), which is defined as the interval from the FO of *H. kleinpellii* to the FO of *Discoaster mohleri*. Zone NP6 occupies the lower part of the Tarawan Chalk and is represented by samples 110–111 with a thickness 0.5 m. The characteristic floral assemblage is similar to Zone NP5, with some additional species: *H. kleinpellii*, *Fasciculithus alanii*, *Discoaster bramlettei*, and *Bomolithus conicus*. The Selandian/Thanetian boundary occurs in the lower part of foraminiferal Zone P4, which corresponds to the upper part of NP6 (Schmitz et al., 2011; Gradstein et al., 2012). In the present study, the Selandian/Thanetian stage boundary is associated with the P4a/P4b subzonal boundary between the Dakhla Shale and Tarawan Chalk formational boundary. The reduced thickness suggests a biostratigraphic break, which is supported by the fact that the *Heliolithus kleinpellii* Zone (NP6) is not seen at several localities in Egypt (Faris and Farouk, 2012).

The third reported zone is defined as the interval from the LO of *D. mohleri* to the LO of *Discoaster multiradiatus*, yielding the combined *D. mohleri* Zone (NP7/8). These zones are combined because of the absence of marker species at the top of Zone NP7 (*Heliolithus riedelii*) throughout most of Egypt (Faris and Abu Shama, 2007; Faris and Farouk, 2012). The most important taxa in this zone are the same as recorded in the underlying Zone NP6. In addition, several new species first appear in this zone: *Fasciculithus aubertae*, *Fasciculithus bobii*, *F. involutus*, *D. falcatus*, *D. mohleri* and *Neochiastozygus distentus*. The final zone is the *Discoaster multiradiatus* Zone (NP9) which is defined from the LO of *D. multiradiatus* to the

LO of *Tribrachiatulus bramlettei*. Aubry et al. (1999) subdivided the *D. multiradiatus* Zone (NP9) into two subzones (NP9a and NP9b) based on the LOs of *Rhomboaster* and/or *Discoaster araneus*. The contact between NP9a/NP9b represents the Paleocene/Eocene boundary, which occurs between samples 123/124 in the present study. Several species become extinct below this boundary, such as *Fasciculithus clinatus*, *Fasciculithus alanii*, *T. pertusus*, and others first appear in the basal Eocene interval, such as *Rhomboaster intermedia*, *Rhomboaster bitrifida*, *Rhomboaster spineus*, *Coccolithus bownii* and *D. mahmoudii* (Fig. 3).

3.4. Paleobathymetry

Interpretation of paleobathymetry depends on the estimation of foraminiferal parameters such as the planktic ratio, agglutinated/calcareous benthic ratio, total foraminiferal abundance, and the benthic foraminiferal biofacies and their diversification:

3.4.1. Benthic foraminiferal biofacies

Cluster analysis (using Minitab version 17) showed three stratigraphically significant assemblages interpreted as biofacies 1–3 (Figs. 4 and 5). These are dominated by taxa typical of the Midway-type fauna (*Cibicidoides pseudoacutus* and *Angulogavelinella avnimelechii* biofacies) of middle to outer shelf environments and the Velsco-type fauna (*Gavelinella danica* biofacies) of upper bathyal environments. Each biofacies is interpreted to have inhabited a specific depositional environment and thus provides a paleowater depth estimate. Benthic foraminiferal assemblages from the study interval are diverse and dominated by calcareous taxa, which make up to 98–85% of the assemblages. Here, the biofacies are discussed from shallowest to deepest paleowater depth.

Cibicidoides pseudoacutus biofacies: This biofacies occurs in the uppermost Dakhla Shale and lowermost Esna Shale formations. It is illustrated in cluster 2 (Fig. 4). This benthic biofacies contains diverse and heterogeneous assemblages with mixed infaunal and epifaunal morphogroups of the Midway-type fauna (Berggren and Aubert, 1975), such as *Pseudoclavulina*, *Pullenia coryelli*,

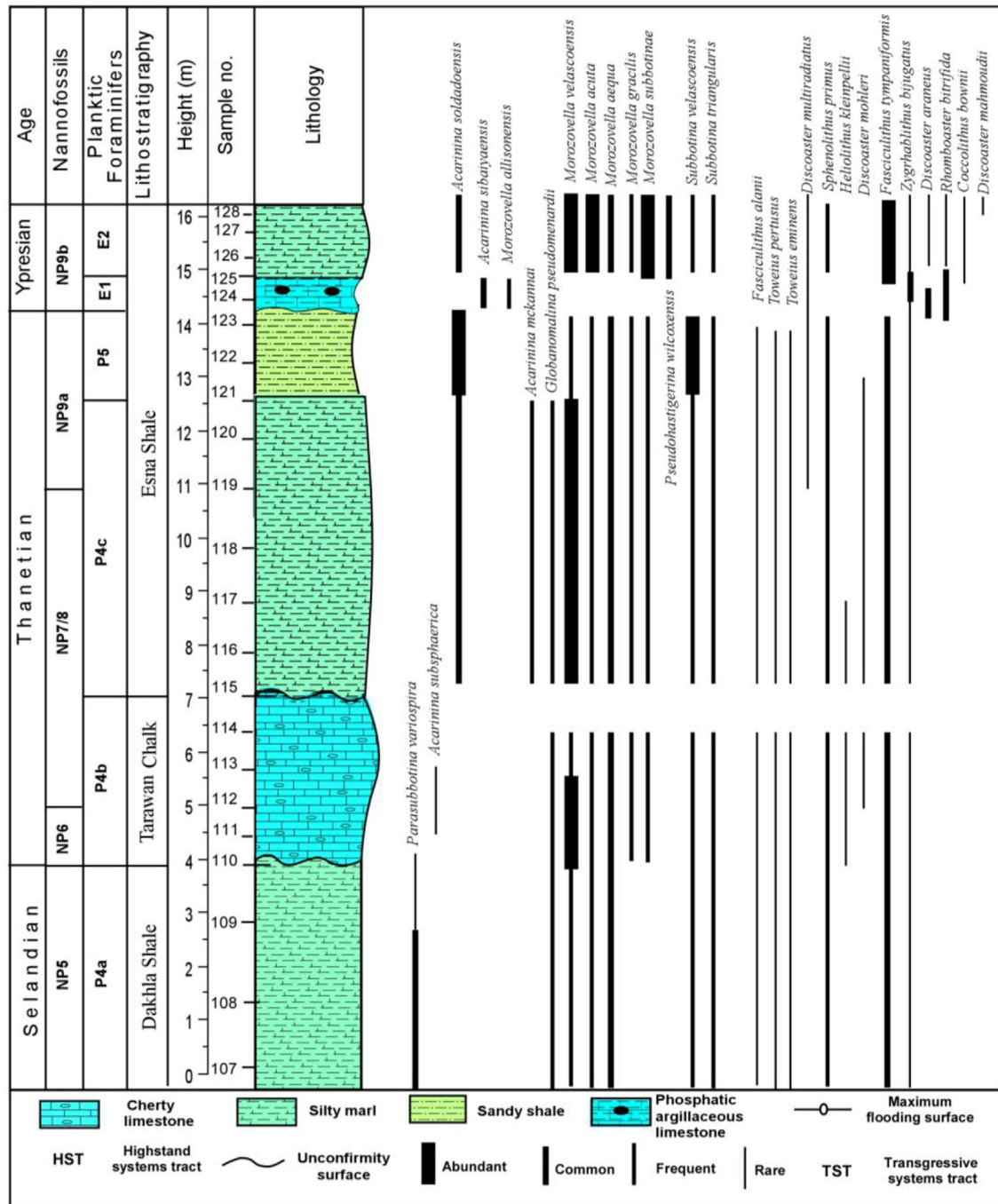


Fig. 3. Distribution of the most important planktic foraminifera and calcareous nannofossil species against the lithology and microplanktic biostratigraphy of the Thanetian succession at Gebel Matulla.

Paralabamina lunata, *Bulimina*, *Spiroplectinella esnaensis*, *Pleurostomella acuta*, *Cibicidoides pseudoacutus*, *Valvulineria scrobiculata*, and *Zeauvigerina aegyptica* (Fig. 4). The absence of deeper water benthic foraminifera species, as well as lowest planktic/benthic ratios (less than to 70‰) with a high species benthic foraminifera richness reflects a middle to outer shelf settings.

Angulogavelinella avnimelechi biofacies: This biofacies comprises the deepest environment with Midway-type fauna and it is commonly found in the P4b Subzone represents in cluster 3 (Fig. 6). The nominative species is the most common in almost all samples studied, in addition to *Dentalina colei*, *Cibicidoides libycus*, *C. pharaonis*, *Bulimina quadrata*, *Gyroidinoides globosus*, *Alabamina*

wilcoxensis and *Osangularia plummerae*. A small percentage of bathyal marker species such as *G. beccariiformis* also appear in this biofacies (Fig. 4), indicating deep outer neritic to upper bathyal environments (at a water depth of approximately 150–250 m; Berggren and Aubert, 1975; Speijer and Schmitz, 1998; Speijer, 2003).

Gavelinella danica biofacies: This biofacies is commonly found in two intervals, the P4c Subzone and E2 Zone (Fig. 6). It represents the deepest Paleocene biofacies and includes Velsco-type fauna representative of continental slope to abyssal environments (Berggren and Aubert, 1975). The absence of shallower water benthic foraminifera species, as well as high planktic ratio (up to

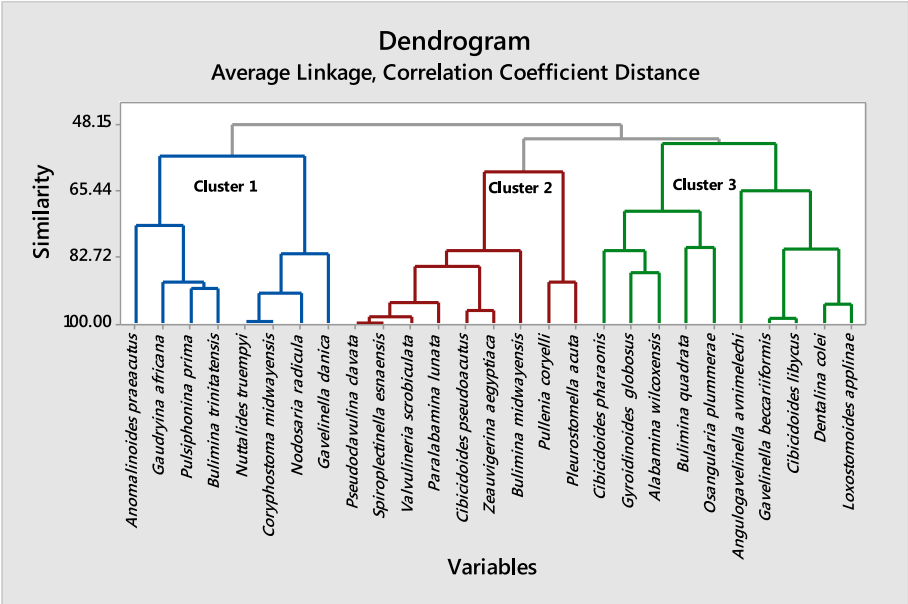


Fig. 4. Cluster analysis of the most common benthic foraminiferal taxa characterized the Thanetian succession at Gebel Matulla database (species with >5% frequency only).

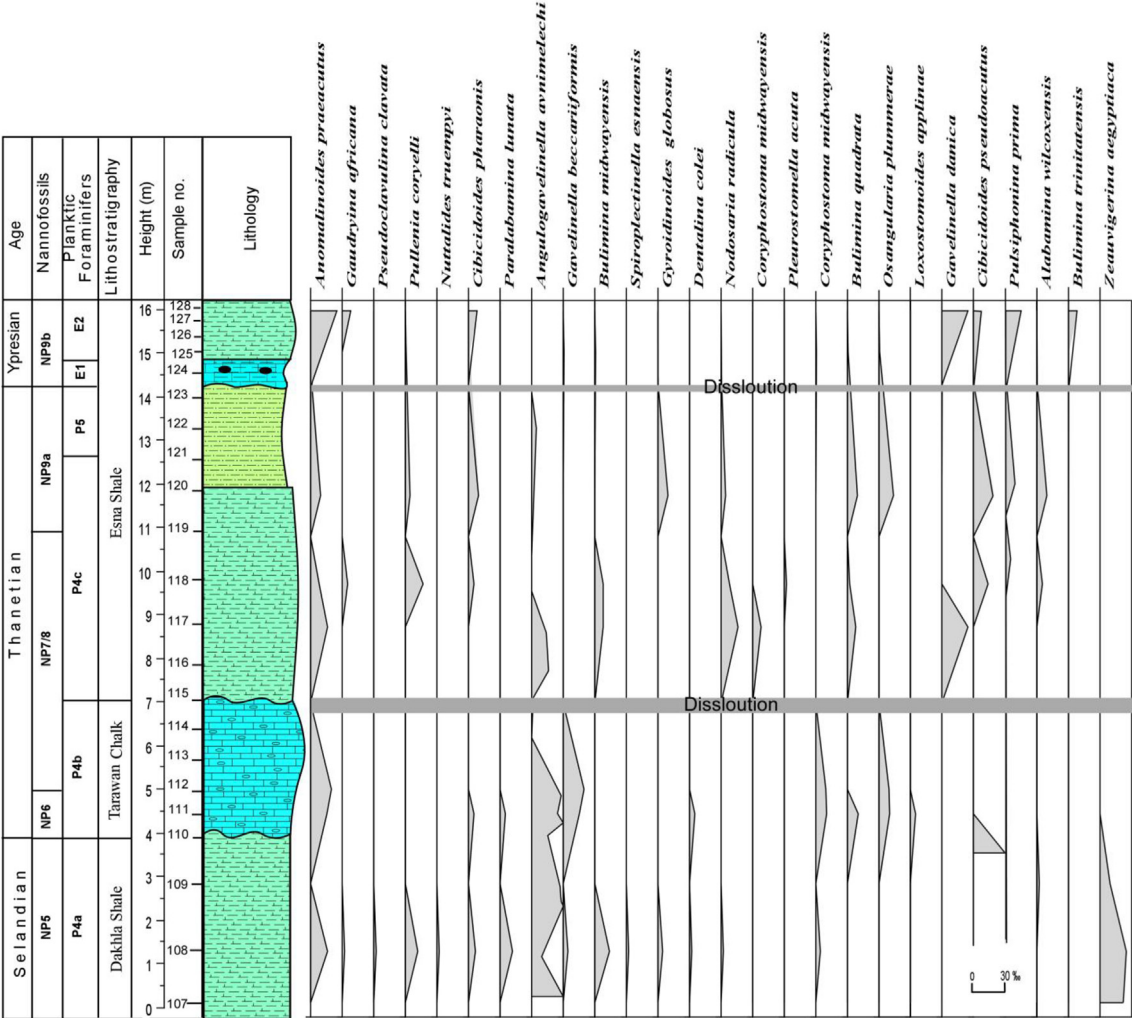


Fig. 5. Vertical distribution of the most common benthic foraminiferal taxa from the Thanetian succession at Gebel Matulla.

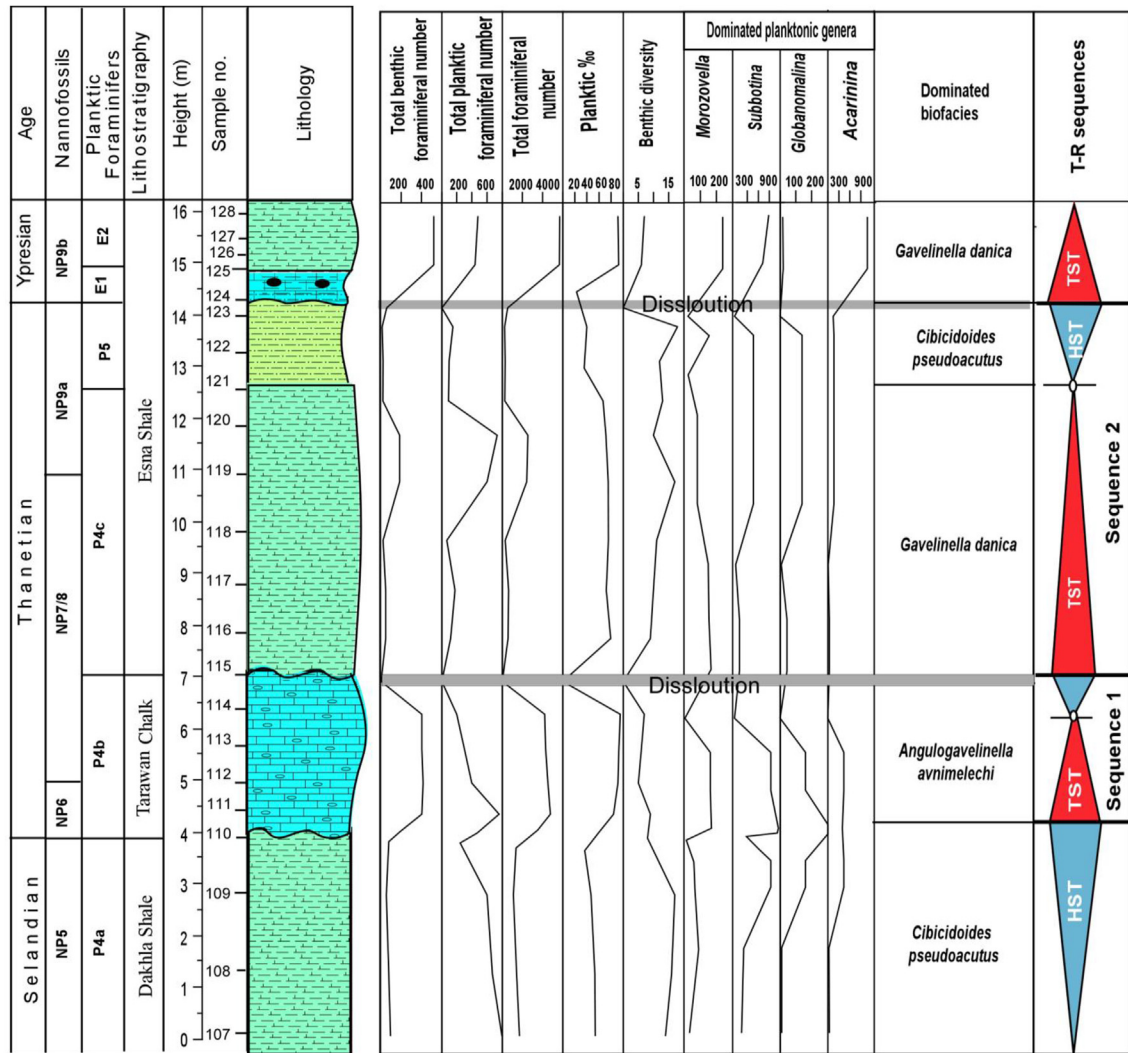


Fig. 6. Thanetian succession in Gebel Matulla showing the percent of planktic and benthic foraminifera; foraminiferal number (number of foraminifera specimens per gram), benthic diversity; planktic percentage; dominated genera of planktic foraminifera; benthic foraminiferal biofacies; transgressive-regressive (T-R) cycle, while the bold black lines are the sequence boundaries.

90‰) with a low benthic foraminifera species richness and high diversity planktic foraminifera suggests water depths >200 m. This assemblage comprises in cluster 1 which includes *Anomalinoidea praeacutus*, *Gaudryina africana*, *Nuttallides truempyi*, *Nodosaria*, *Coryphostoma midwayensis*, *Pulsiphonina prima*, *Siphogenerinoides eleganta*, and numerous other infrequent species (Fig. 4).

3.4.2. Total foraminiferal number (TFN)

The TFN is the total number of foraminiferal (planktic and benthic) in one gram of dry sediment. Actually, the nature of hardness and diagenesis processes of the rocks plays an important role in the TFN parameter. In the present study, the deep marine Paleocene deposits are softer and less affected by diagenesis processes. In general, favorable conditions for the foraminiferal community cause TFN to increase as water depth increases across the shelf. Normal TFN values vary from 150 to 5000 specimens per gram (s/g).

The low total foraminiferal number is recorded in hardly dissolute intervals near the upper part of Tarawan Chalk and the basal Eocene. TFN displays rapid paleoenvironmental fluctuations in the Thanetian succession at Gebel Matulla (Fig. 6). We also note that the total benthic foraminiferal number increased simultaneously

with decreased benthic diversity during the transgressive phase (Fig. 6).

3.4.3. Planktic/benthic (P/B) foraminifera ratio

The foraminiferal assemblage P/B ratios were determined using random square counts in the picking tray and are expressed as $P/(P + B) \times 100$. Based on the numbers of planktic (PFN) and benthic foraminifera (BFN) per gram of sediment, the P/B ratio can be used to determine the paleobathymetric evolution of the site (Berger and Diester-Hass, 1988; Van der Zwaan et al., 1990). In the Gebel Matulla section (Fig. 6), P/B ratios vary considerably, ranging from 20 to 99‰. The lowest P‰ ratio is associated with an abrupt drop in planktic foraminiferal abundance and occurs in the upper part of the P4a and P4c subzones (where P‰ reaches 50–60‰) as well as in the P5 Zone (where it reaches 30‰). The increase in P‰ is consistent with the increase in TFN throughout the transgressive phase in the lower part of the P4b and P4c Subzones and the E2 Zone. These characteristics reflect an outer neritic to upper bathyal open marine environment during these intervals.

3.4.4. Benthic foraminiferal species richness (S)

It can be expressed as the number of different benthic species in a sample (Murray, 1991). The benthic foraminiferal species richness increases in the regressive phase with decreased of P‰ and diversity (in the P4a Subzone and P5 Zone) but it decreases in the transgressive phase associated with increase of P‰ and diversity, especially the benthic species (in the P4b and P4c subzones and the E2 Zone) (Fig. 6).

3.4.5. Epifaunal/infaunal ratio

The relationship between the epifaunal/infaunal ratio could indicate changes in the ecological environment and can easily determined the past oxygen content and organic matter flux (Kaiho and Hasegawa, 1994; Jorissen et al., 1995; Van der Zwaan et al., 1999). In the present study, epifaunal‰ reaches to more 90‰ supports the interpretation of eutrophic and well-oxygenated bottom waters. The slightly increase of infaunal‰ ranging between 80 and 90‰ are observed only in regressive phase (upper Dakhla Shale and lower Esna Shale Formation) reflects mesotrophic and moderate oxygen conditions.

3.5. Depositional sequences

Field observation, vertical facies changes and foraminiferal paleobathymetry data from the Thanetian succession at Gebel Matulla define a series of T-R sequences each bounded by a maximum regressive surface. Three sequence boundaries are identified, at the Selandian/Thanetian boundary, within the Thanetian succession, and at the Paleocene/Eocene (P/E) boundary. Thus, we classify the Thanetian succession into two T-R sequences as follows:

3.5.1. Sequence boundaries

The first sequence boundary occurs at the Selandian/Thanetian (S/T) boundary. According to the International Subcommission on Paleogene Stratigraphy, the boundary is located at the base of Chron26n, which lies within the NP6 Zone (Schmitz et al., 2011). The reduced thickness of the *Heliolithus kleinpellii* (NP6) Zone in the present study is reported also in most localities of Egypt (Faris and Farouk, 2012) suggests a hiatus across the S/T boundary. This paleontological break, characterized by an absence or shortened interval of Zone NP6 is recorded in various localities of Egypt (e.g., Bassiouni et al., 1991; Tantawy, 1998; Faris and Abu Shama, 2007; Faris and Farouk, 2012). The hiatus across the S/T boundary may be not noticeable in the planktic foraminiferal record, but is apparent in the calcareous nannofossil stratigraphy, which provides finer resolution for this interval (Strougo, 1986; Aubry et al., 1999). In most parts of Egypt, this hiatus occurs at the maximum regressive surface between the vertical facies change at the boundary between the Dakhla Shale and Tarawan Chalk Formations. Notable changes in sedimentation patterns in the late Paleocene have been documented at various Egyptian localities. These changes in sedimentation correlate well with this physical boundary, which is observed by intensive branched *Thalassinoides* burrows or thin conglomerate beds at Western Desert of Egypt (El-Azabi and Farouk, 2011).

The Tarawan Chalk/Esna Shale boundary (the second T/R sequence boundary) is also associated with notable vertical facies changes in Egypt. The boundary is well known in Egypt as the “Velascoensis Event” (Strougo, 1986). It is marked by accentuated uplift of the Mediterranean coast and includes the emergence and erosion of several positive structures and increased subsidence in internal depocenters (Strougo, 1986). The event that produced these changes is believed to be primarily tectonic but coupled with global sea-level fall. In the present study, it correlates to the P4b/

P4c subzonal boundary. The Tarawan Chalk Formation, which has a variable thickness in Sinai from 1 to 4 m, reflects the tectonic changes at the end of the Selandian age (P4a Subzone).

The third sequence boundary occurs at the P/E boundary. The base of the Eocene (sample 124) is characterized by an absence of benthic foraminifera, which could be due to carbonate dissolution and/or dilution caused by increased detrital input (Speijer and Wagner, 2002; Khozyem et al., 2013). A marked faunal turnover of planktic species occurs in the basal part of the Eocene sequence, which is characterized by the inception of small planktic foraminifera, especially *Acarinina* spp. There is also a large change in the benthic foraminiferal assemblage, which changes from the *Cibicidoides pseudoacutus* biofacies to the *Gavelinella danica* biofacies reflects a relative sea-level rise. Dramatic changes in the foraminiferal population occur above the sequence boundary. The P‰ reaches 99‰ and the total foraminiferal number reaches approximately 5500 s/g. The decrease in benthic species richness to approximately 7 species per sample reflects an upper bathyal environment and a new transgressive phase. Comparison with the Dababiya GSSP near Luxor in southern Egypt (Dupuis et al., 2003; Aubry et al., 2007) suggests that the lowermost Eocene is not complete at Gebel Matulla (bed-1 to bed-3 in the Dababiya GSSP is missing from the Gebel Matulla section). In general, the Dababiya beds that include the complete P/E boundary are reduced or missing in the Sinai.

3.6. Transgressive-Regressive (T-R) Sequences

3.6.1. T-R sequence 1

The transgressive phase of sequence 1 consists of foraminiferal wacke-packstone (lower part of the Tarawan Chalk Formation). It is characterized by a P‰ of up to 90 and a total foraminiferal number ranging from 2500 to 3500 s/g. *Angulogavelinella avnimelechi* biofacies dominates, with low to medium species richness of approximately 7–15 benthic species per sample dominated by small-sized epifaunal Rotallina, indicating eutrophic deep outer neritic to upper bathyal environments.

The regressive phase of T-R sequence 1 consists of foraminiferal lime-mudstone with a decrease in P‰ from 90 to 60 associated with an increase in the shallower *Cibicidoides pseudoacutus* biofacies from ~20‰ to ~40‰ and a total foraminiferal number from 3500 to 400 s/g with only rare foraminiferal tests near the top of the Tarawan Chalk Formation. Decreases of the deeper dwelling Paleocene taxa such as *Gavelinella danica*, *Nuttallides truempyi*, *Pullenia coryelli*, suggests that the regressive phase was not deeper than 100 m during upper part of P4c Subzone (Fig. 6).

3.6.2. T-R sequence 2

This sequence is recorded within the lower part of the Esna Shale Formation. It is bounded at the base by vertical facies changes near the Tarawan Chalk/Esna Shale boundary. There is a change in P‰ and total foraminiferal number with benthic foraminiferal species richness and diversity. The transgressive phase of sequence 2 is dominated by an *Angulogavelinella avnimelechi* and *Gavelinella danica* biofacies with a P‰ of up to 90‰, and TFN from 400 to 3300 s/g, in addition to benthic foraminiferal species richness of approximately 7–10 species per sample, which indicates upper bathyal conditions. During the regressive phase, P‰ decreases from 90 to 60‰ and the total foraminiferal number drops from 4300 to 150 s/g. There is also a decrease in the deeper *Angulogavelinella avnimelechi* biofacies from 52‰ to 39‰ and an increase in the shallower *Cibicidoides pseudoacutus* biofacies from 24‰ to 36‰. In addition there are increases of acarininids and subbotinids with decreased the morozovellids. (Fig. 6). The T-R sequence 2 is bounded at the top by the P/E boundary. Above this boundary, there is an

up to 95% increase in planktic species and the total foraminiferal number reaches 5500 s/g. The *Gavelinella danica* biofacies also becomes dominant, representing up to 70% of the microfauna (Fig. 3). These changes reflect a new transgressive phase.

4. Discussion

The maximum regressive phases correspond well to the eustatic chart of Haq et al. (1987). In addition, the European sea-level curve (Hardenbol et al., 1998) is in good agreement with the Se2/Th1, Th4, and Th6/Yp0 sequence boundaries, while the Th2, Th3 and Th5 boundaries do not correspond with those from the Hardenbol et al. (1998) chart. The sequences identified in Egypt are also close to sequences from the New Jersey passive continental margin (Miller et al., 2005), except that the Selandian/Thanetian boundary is not defined in the New Jersey record. In Egypt, this boundary is well established at many different localities (Lüning et al., 1998). It reflects the global nature of the three boundaries required between the T-R sequences. We note that there are some differences between the sequences we propose and those defined in the Nile Valley of Egypt. For instance, our T-R sequence 2 combines DB8 and DB9 in the Nile Valley (King, 2013).

5. Conclusions

The interval spanning the Thanetian succession in the Gebel Matulla section consists of condensed hemipelagic silty marl intercalated with chalk limestone and shale. Three benthic biofacies, of *Cibicidoides pseudoacutus*, *Angulogavelinella avimelechi* and *Gavelinella danica*, reflect a greater water depth during the Thanetian (ranging from outer neritic to upper bathyal) than at other Egyptian localities. Fluctuations in the foraminiferal population and benthic biofacies during the Thanetian succession at Gebel Matulla provide evidence for two T-R sequences associated with eustatic sea-level changes. These sequences are delimited by the maximum regressive surface at the Selandian/Thanetian boundary, a boundary within the Thanetian succession, and the Thanetian/Ypresian boundary. A clear drop in P% and total foraminiferal number, along with an increase in benthic foraminiferal species richness, occurs during regressive phases and is associated with an increase in the *Cibicidoides pseudoacutus* biofacies. The first T-R sequence boundary occurs at the Selandian/Thanetian stage boundary and is associated with major discontinuities and notable changes in sedimentation patterns at the Dakhla Shale/Tarawan Chalk formational boundary. The second boundary occurs within the Thanetian succession at the Tarawan Chalk/Esna Shale formational boundary, and is synchronous with the observed sea-level fall during the upper part of P4b Subzone which well-known “*Velascoensis* Event” in Egypt, which was primarily caused by tectonic changes that accentuated uplift of the Mediterranean coast. The third boundary occurs with the Esna Shale at the Paleocene/Eocene boundary, where dramatic shifts linked to the Paleocene/Eocene Thermal Maximum (PETM) are observed. The regressive phase of both sequences is characterized by a decrease in the total foraminiferal number and planktic percentage and an increase in benthic foraminiferal species richness. All three T-R sequences are in good agreement with other eustatic sea-level curves.

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