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Late Paleocene–Early Eocene Foraminiferal Paleobathymetry and Depositional Environments and Their Sequence Stratigraphic Implications of Gebel Duwi, Red Sea, Egypt

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THE current work is based on quantitative and qualitative analyses of the foraminifera of the Late Paleocene-Early Eocene sequence at Gebel Duwi, Quseir region, Red Sea, Egypt. Two rock units are studied in the Late Paleocene–Early Eocene sequence: Esna Formation at the base and Thebes Formation at the top. Four planktonic foraminiferal biozones are identified; Late Paleocene P5 zone and Early Eocene E1–E3 zones. The foraminiferal parameters such as total foraminiferal number (TFN), benthic foraminiferal number (BFN), planktonic foraminiferal number (PFN), Planktonic/Benthic ratio (P/B%), Epifaunal/ Infaunal ratio (E/I%), Calcareous/ Arenaceous ratio (C/A%), abundance, diversity, and Benthic Foraminiferal Oxygen Index (BFOI) in addition to fieldwork and the microfacies investigation were incorporated to divide the studied sequence into three transgressive-regressive depositional sequences bounded with four sequence boundaries. The morphological characteristics and assemblages of benthic foraminiferal are heavily influenced by variations in oxygen concentrations at the sediment water interface; these variations are reflected at the wall thickness and size of recorded taxa. These taxonomic and variations were quantified as a dissolved oxygen indicator. Three types of benthic foraminifera were classified into dysoxic, suboxic, and oxic indicators. These indices are then used for paleoenvironmental interpretations. The environments ranged from inner neritic to upper bathyal (150–300 m deep) during the deposition of the Late Paleocene–Early Eocene succession.

Keywords: Foraminifera, Paleoenvironment, Late Paleocene, Early Eocene, sequence, Gebel Duwi, Egypt.

Introduction

The Paleocene Eocene Thermal Maximum (PETM), one of the most dramatic and sudden warming events ever recorded in geologic history, occurred approximately fifty-five million years ago and caused an abrupt climate change on Earth (Kennett and Stott, 1991; Zachos et al., 1993). At low latitudes, the PETM event caused an increase in sea surface temperature of roughly 5°C (Zachos et al., 2003; Trpati and Elderfield, 2004) and high latitude is about 8°C (Thomas and Shackleton, 1996; Thomas et al., 2002). This event influenced organisms at a global scale of the ocean, leading to a fast and sudden turnover of planktonic and benthic organisms. Whilst through this boundary the deep sea calcareous benthic foraminiferal assemblages have been exposed to a great extinction (Thomas, 1990a),the assemblages of benthic foraminiferal at marginal and epicontinental basins were suffered the temporary assemblage changes or/and lower extinction (Speijer et al., 1996; Alegret et al., 2005; Alegret and Ortiz, 2006; Ernst et al., 2006; Stassen et al., 2013; Hewaidy et al., 2019a).

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Through the P/E boundary event, the planktonic foraminiferal fauna displays faunal turnover and temporary diversification, visibly represented through a group rich with planktonic foraminifera of tropical which contain elements of the distinguishing planktonic foraminiferal excursion taxa, as *Morozovella allisonensis*, and *Acarinina sibaiyaensis* (Berggren et al, 2003; Ouda et al, 2012; Pardo et al, 1999; Hewaidy et al., 2019a). The paleobathymetry and depositional environment depended on species composition, abundance, morphogroups and foraminiferal diversity could be providing excellent tools for reconstruction of the paleowater depth of climate changes or/and depositional sequences (Alegret and Ortiz, 2007; Alegret and Thomas, 2009; Alegret et al., 2012; Farouk and Jain, 2016; Farouk et al., 2019). Morphogroup analysis is advanced in a try to assess paleobathymetric and sediment trends (habitat of life; epifaunal, infaunal) reflected by benthic foraminiferal assemblages, and that technique was applied in many studies of both shallow and deep-water positions (Koutsoukos and Hart, 1990; Tyszka and Kaminski, 1995; Ashckenazi-Polivoda et al., 2018).

The present work attempts to: (1) establish a high-resolution biostratigraphic framework of the Late Paleocene- Early Eocene sequence using planktonic foraminifera of the study area; (2) establish the paleowater depth depended on lithofacies types and foraminiferal palaeobathymetry; (3) expose the response of relative sea level changes utilizing variations of foraminifera assemblages; (4) increasing our understanding to how assemblages of benthic foraminifera evolve beneath fluctuation bottom water oxygen; (5) introduce a sequence stratigraphic classification for the studied Upper Paleocene- Early Eocene succession.

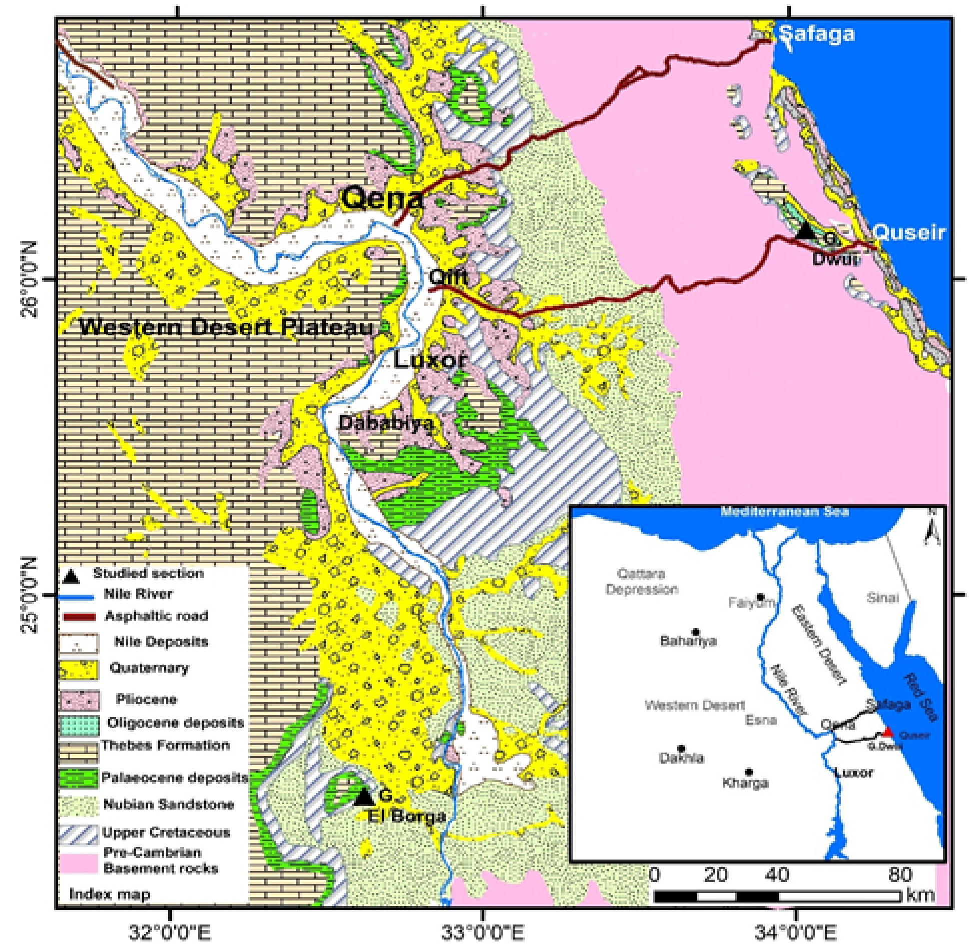


Fig. 1. Location and geologic map of Gebel Duwi showing the studied section.

Geological Settings

Gebel Duwi lies about 5 km west of the Qift-Quseir Road, 20 km from Quseir, Red Sea coast, between latitudes 26° 06’ 2”N and longitudes 34º 05’ 10”E (Fig. 1).

The investigated sediments are deposited in an epicontinental basin at the Tethys Ocean’s southern edge, northwestern edge of the Arabian Nubian shield. The research region situates on Egypt’s stable shelf that is distinguished by little structural distortion (Said, 1962). Normal faults have been distinctly oriented NE-SW, indicating that they are closely associated with the tectonic events parallel to the Red Sea - Gulf of Suez rifting. This trend referred to Late Cretaceous to the recent; dextral-shear resulted in right-lateral transcurrent movement among Laurasia and Africa (Meshref, 1990). The depositional sequence has been distinguished to the Taref Formation Coniacian–Santonian (Issawi et al., 1999) at the base; follow upwards by Quseir Formation early Campanian (Hermina (1990); Duwi Formation late Campanian- early Maastrichtian (Baioumy and Tada, 2005); Dakhla Formation Late Maastrichtian Middle Paleocene (Khalil et al., 2016); Tarawan Formation Middle Paleocene (Khalil et al., 2016); Esna Formation late Paleocene early Eocene (Khalil et al., 2016) and Thebes Formation early Eocene (Saida, 1962) at the top. The Paleocene/Eocene boundary at the studied section is placed within the lowermost portion of the Esna Formation.

Materials and Methods

Methodology

The present study focuses on a well–exposed part of the Gebel Duwi, Qusseir area, Red Sea (26° 06’ 2”N and 34º 05’ 10”E) the sequence is measured, sampled, and described)Fig.(1. with a high-resolution for the sampling is about 50 cm thirty-three samples have been collected with the various rock units. About 50 g of each sample has prepared according to the following standard methods (Rückheim et al., 2006), the samples have been disaggregated in water with diluted H_2O_2, and then washed to obtain clean fossils. After drying the residue was divided into three- fractions 63 **µ**m, 125-630 **µ**m, and 630 **µ**m to easier Handel the foraminifera. Benthic foraminifera is picked from a split of the 125-630 **µ**m fraction. Counting 200 to more than 300 benthic foraminiferal specimens, using an Otto micro splitter and determined using a binocular-microscope at the micropaleontology and stratigraphy laboratory of the Matrouh University, Marsa Matrouh, Egypt, and permanently stored in micropaleontological slides. About eight thin-sections have been prepared and examined to study their depositional texture and microfossil assemblages, for the terminology of limestones, the classification of (Dunham, 1962).

Statistical analysis and calculating parameters

Using the benthic and planktonic foraminiferal number (number per gram sediment), the total foraminiferal number (TFN) (number of benthic and planktonic tests per gram sediment) was calculated. TFN was considered as representing water-depth; however, it has been revealed that the availability of nutrients (organic matter) has a greater impact on foraminiferal assemblages (Jorissen et al., 2007; Zaky et al., 2020). TFN must be used with a combination of other foraminiferal parameters such Planktonic/ Benthic ratio (P/B%), Calcareous/ Arenaceous ratio (C/A%), and Epifauna/ Inifauna ratio (E/I%) as a more reliable evaluation the changes of paleo-environmental. The Planktonic/Benthic ratio (P/B%) was expressed as number of planktonic/number of planktonic and benthic X100. PAST software was used to calculate benthic foraminiferal diversity (Di), Fisher_alpha, Shannon_H, and Shannon-Weaver (Hammer et al., 2001(. Bottom water paleo-oxygenation has been evaluated, depending on the Benthic Foraminiferal Oxygen Index (BFOI) (Kaiho, 1994a). The calculation of BFOI, identified benthic foraminifera are defined into three-types, Dysoxic (D), Suboxic (S), and Oxic (O). BFOI is calculated as the following equation: $BFOI= O/ (O+ D+ S/2) \times 100$.

Lithostratigraphy

The lithostratigraphic sequence of Gebel Duwi includes Coniacian-Eocene succession but the current study restricted to these two units only. This interval contains two lithostratigraphic units, the Esna Formation at the base and Thebes Formation at the top (Fig. 2).

The measured section of the Esna Formation attains about ~ 14 m thick at Gebel Duwi. It is laminated, dark grey to greenish, brownish/ blackish grey shale, marl, and sandy shale, either as fissile or/and massive, and some gypsum veinlets shale. The Thebes Formation consists of mainly chalk. In the upper part of the Thebes Formation Layers of chert nodules and siliceous limestones are common. It consists of ~ 2.5 m thick of yellowish-white, moderately hard, and massive limestone in the uppermost part of the studied section.

Fig. 2. A panoramic field view in the Gebel Duwi area shows the Esna and Thebes formations.

Results

Planktonic Foraminiferal Biostratigraphy

The abundance, diversity, and preservation of planktonic foraminifera are diverse. The biozones have been identified in the studied Late Paleocene - Early Eocene interval depending on the zonal scheme of Berggren and Pearson (2005). These zones used the lowest and highest occurrence (LO and HO) of the index species at the study section from oldest to youngest as the following:

Morozovella velascoensis Zone (P5)

This zone is defined as the partial range of HO of *Globanomalina pseudomenardii* and LO of *Acarinina sibaiyaensis.* It occurs within the ~ 2 m of Shale from the lower part of the Esna Formation (samples 1 - 4; Fig. 3). The assemblages are dominated by *Morozovella subbotinae*; another common constituents include *M. aequa*, *M. velascoensis*, *M. acuta*, *M. pasionensis*, *M. occlus*, *M. gracilis*, *Acarinina nitida*, *A.soldadoensis* , *A. mckannai, A. triplex*, *Igorina albeari*, *Subbotina velascoensis*, *S. triangularis*, *Parasubbotina varians,* and *Globanomalina chapmani*.

Acarinina sibaiyaensis Zone (E1)

This zone is defined as the interval between LO of *Acarinina sibaiyaensis* and LO of *Pseudohastigerina wilcoxensis.* It exists in ~2.5 m from the lower part of Esna Formation (samples 5 -9; Fig. 3). The assemblages are dominated by *Acarinina sibaiyaensis* another common constituent includes *Subbotina triangularis*, *S. velascoensis*, *S. patagonica, Acarinina soldadoensis*, *A. triplex*, *A. wiilcoxensis*, *Morozovella velascoensis*, *M. allisonensis*, *M. acuta*, *M. subbotinae*, *M. gracilis*, *M. marginodentata*, and *M. edgari*. The usage of the Sparnacian Stage as the lowest Eocene stage (Aubry et al., 2005), put the Sparnacian Stage among the Ypresian Stage and the Thanetian Stage. This prevents the dropping of the Ypresian Stage base with about 1 million years to synchronize the recently determined GSSP of the base of the Eocene Series. This zone is thinner than the 2.20 m thick Dababiya portion in Egypt (Berggren and Ouda, 2003).

Pseudohastigerina wilcoxensis/ Morozovella velascoensis (E2)

This zone is defined the concurrent range from LO of *Pseudohastigerina wilcoxensis* to HO of *Morozovella velascoensi*s. It is represented by ~ 3.5 m of the upper part of the Esna Formation (sample 10 - 14; Fig. 3). This interval characterized by the abundance of planktonic foraminifera and high diversity with well preservation. Assemblage is dominated by *Pseudohastigerina wilcoxensis* another common constituent includes *Subbotina triangularis, S. velascoensis, Acarinina wilcoxensis, A. soldadoensis, Morozovella occlusa, M. subbotinae, M. parva, M. gracilis, and M. velascoensis.*

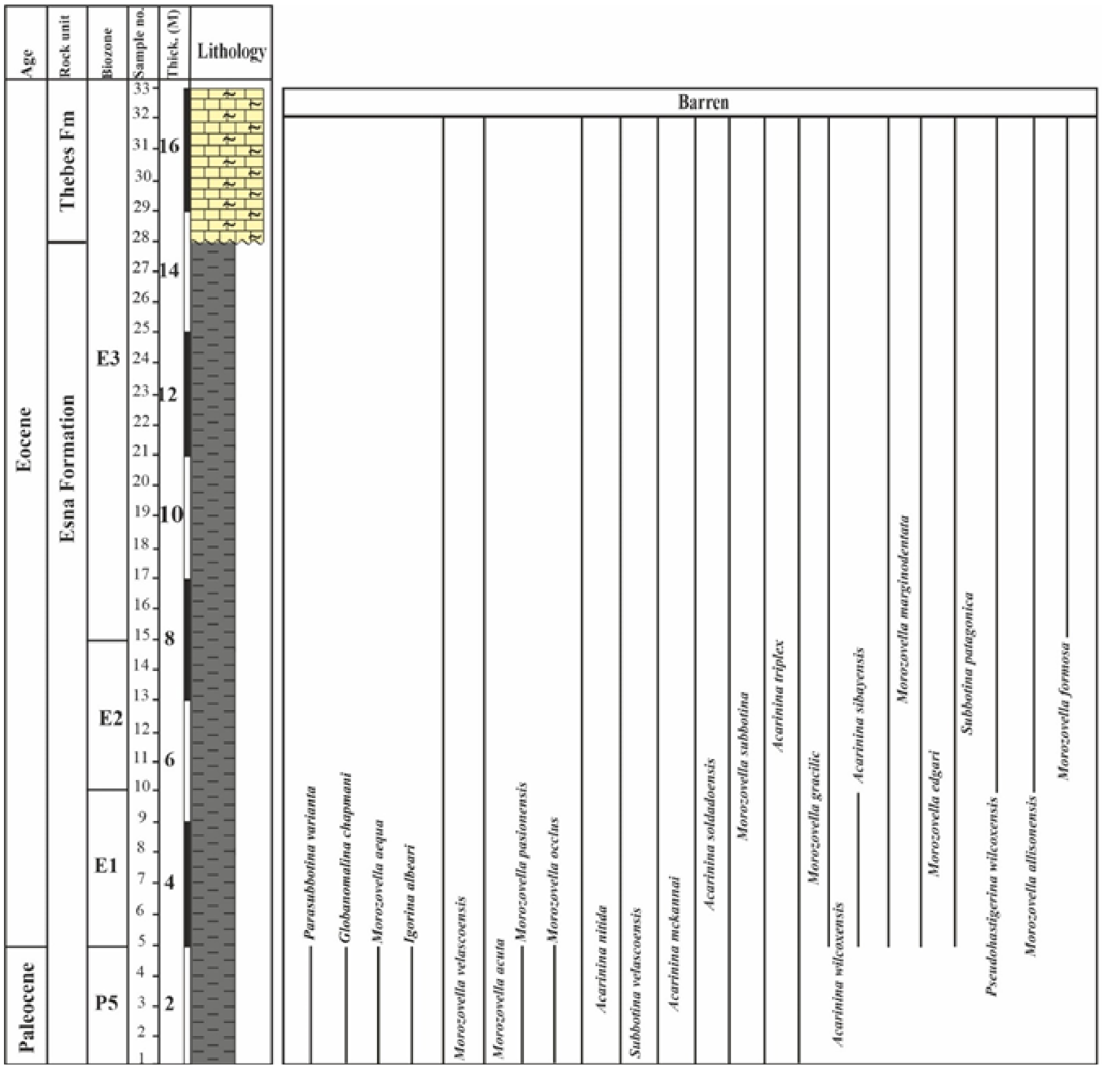


Fig. 3. The Gebel Duwi section's chronostratigraphy and planktonic foraminiferal distribution chart.

Morozovella marginodentata Zone (E3)

This zone is defined as the partial range the HO of the *Morozovella velascoensis* and the LO of *Morozovella formosa*. It occurs within ~ 10 m from the upper part of Esna and lower part of Thebes Formations (from sample 15 to 33; Fig. 3). The assemblage is dominated by *Morozovella formosa* another common constituent includes *Acarinina soldadoensis, Morozovella edgari*, *M. marginodentata*, *M. gracilis*, *M. aequa,* and *M. subbotinae*. This zone is equivalent to the P6 Zone (Warraich et al., 2000), the *Globorotalia rex* Zone (Dorreen, 1974), and the *A. wilcoxensis berggreni* Zone (Afzal, 1997).

Benthic Foraminiferal palaeobathymetry

Foraminiferal palaeobathymetry displays an efficient method to interpret paleoenvironments, and can use to record the paleowater depth and so the changes of relative sea level (Murray, 1976; Posamentier et al.,1988; Miller et al., 1997; Farouk, 2016; Farouk et al., 2016; Farouk et al., 2018). This section discusses BFN, PFN, P/B%, TFN, C/A%, E/I%, the benthic foraminiferal assemblages, diversity, and BFOI in 1 gram of dry sediment.

Total foraminiferal number (TFN)

TFN is represented by the number of total foraminiferal specimens (planktonic and benthic) in one gram of dry sediment. Commonly, the dominance of favorable conditions for the foraminiferal community results in an increase of the total number of foraminifera. Thus, TFN reflects the state of paleo-water depth. The TFN shouldn't be considered alone since it isn't an independent parameter but it should be coupled with other parameters. In the Gebel Duwi section, TFN varies between 0.3 and 5335 s/g in samples 1-33 (Fig. 4 and Supplementary Material Table 1). In the P5 zone, TFN values increase from 819.2 to 896 s/g (samples 1-4) except in sample 2 reaches a maximum value of 2716.2 s/g. In samples 5-9, TFN values range between 0.86 and 908.8 s/g (E1 Zone). TFN values decrease from 3625 to 0.38 s/g in the E2 zone (samples 10-14). In the E3 zone, TFN values fluctuate (samples 15- 33) and reach a maximum of 5335 s/g in sample 18. In sample 33 TFN values are barren.

Planktonic/Benthic ratio (P/B%)

The P/B% were determined from random square counting by the picking tray and were expressing P/ (P +B) X 100. In Gebel Duwi section, The P/B% values range from 40 to 88.8% in samples 1-33 (Fig. 4 and Supplementary Material Table 1).

In the P5 zone, P/B% values vary from 65.2 to 73.5% (samples 1-4). P/B% is high in samples 5-9, it reaches to a maximum of 88.8% in the E1 zone. In samples 10-14, P/B% values decrease and reach a minimum (0) in sample 14 because absent planktonic (E2 zone). P/B% values display rapid fluctuations in the E3 zone (samples number 15-33). In sample 33, P/B% is drops reach to 0% (zero) because rare. P/B% ranges from low to high indicating shifting from shallow to open marine environments.

Diversity indices

Diversity

Species richness of benthic foraminiferal tests is broadly utilized as an indicator of paleobathymetry and paleoenvironment (Buzas and Gibson, 1969; Murray, 2001). In the current study, low to high values of the diversity of 3 to 32 species per sample at the Gebel Duwi section (samples 1- 33; Fig. 4 and Supplementary Material Table 1). Diversity measurements [Fisher's-alpha fluctuates between 0.7 and 11.6, and Shannon H oscillates among 0.2 and 2.9].

A high value of diversity occurred in the P5 zone 1-25 species per sample (samples 1-4). In the E1 zone, low to moderate values of the diversity of benthic foraminifera were observed of the Early Eocene 3-15 species per sample (samples 5-9). A high value of the diversity of benthic foraminifera are appearance in the early E2 zone (samples 10-12) with 21-27 species per sample and it stars to decrease relative to fewer values of 6- 4 species per sample (samples 13-14) in late E2 zone. The diversity of benthic foraminifera in samples 15-32 fluctuations from 4 to 32 species per sample (E3 zone). In sample 33, the diversity of benthic foraminifera is barren.

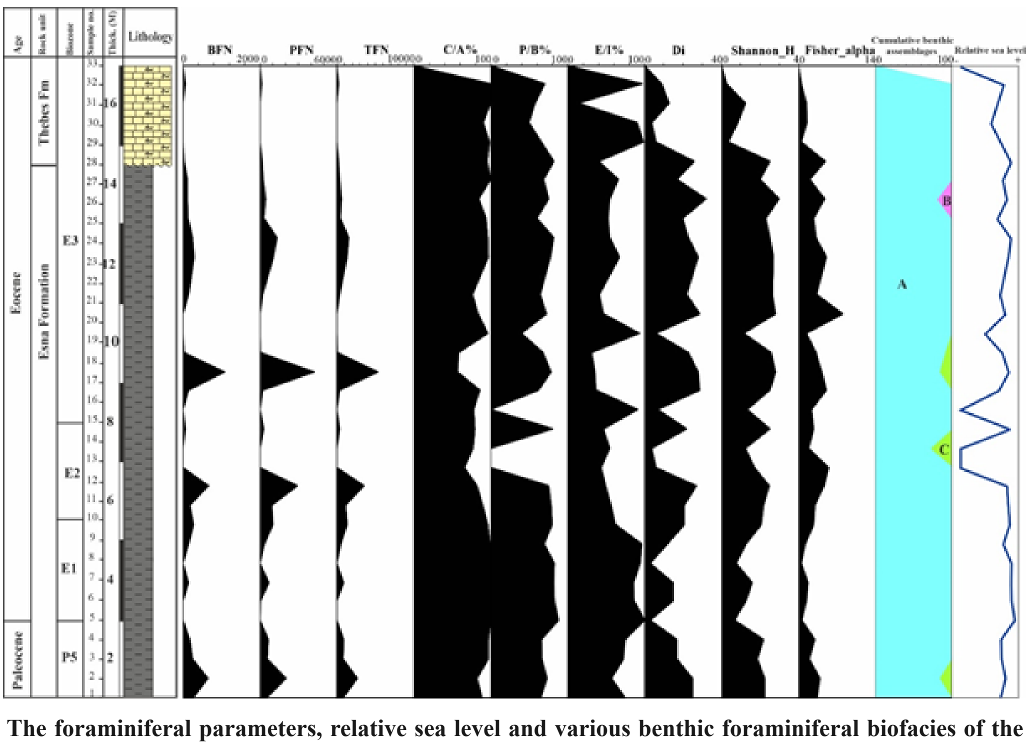


Fig. 4. The foraminiferal parameters, relative sea level and various benthic foraminiferal biofacies of the Gebel Duwi section.

TABLE 1. Parameteries in Gebel Duwi section.

Sample number	Depth	BFN	PFN	TFN	C/ A%	P/ B%	E/ I%	Diveristy	Shannon_H	Fisher_alpha
33	-16.5	0	0	0	0	0	0	0	0	0
32	-16	68.48	158.4	226.88	100	70.5	97.1	9	0.287	0.7948
31	-15.5	9.8	12.6	22.4	100	58.3	14.6	13	1.248	2.097
30	-15	0.22	0.08	0.3	90.9	50	90.9	4	0.8856	2.261
29	-14.5	1.68	10.98	12.66	98.8	66.6	98.8	6	0.3846	0.8742
28	-14	38.88	185.76	224.64	95.9	82.6	41.1	26	2.539	6.989
27	-13.5	129.92	311.04	440.96	100	69.2	66.5	17	2.033	3.065
26	-13	129.28	466.56	595.84	84.6	75.7	55.4	32	2.996	6.836
25	-12.5	136.96	316.8	453.76	94.3	60.4	52.8	20	2.34	4.074
24	-12	259.84	1359.36	1619.2	96.5	82.5	55.1	23	2.539	4.697
23	-11.5	309.76	1071.36	1381.1	97.1	78.5	68.1	28	2.704	7.388
22	-10.5	160.64	256	416.64	76.8	64.7	42.2	22	2.66	4.772
21	-10	2.36	13.68	16.04	83.8	73.1	47.4	29	2.837	11.6
20	-9.5	0.64	0.36	1	96.9	40	93.7	6	1.179	2.18
19	-9	34.88	72	106.88	58.7	68.4	31.6	23	2.59	4.604
18	-8.5	1095.68	4239.36	5335	57.7	78.6	35.7	28	2.833	6.095
17	-8	160	249.6	409.6	86	62.3	37.2	29	2.546	7.298
16	-7.5	0.46	0.18	0.64	78.2	0	91.3	7	1.336	3.427
15	-7	64.64	316.8	381.44	79.7	81.4	47	22	2.53	4.138
14	-6.5	0.18	0.2	0.38	77.7	0	55.5	4	1.273	2.759
13	-6	0.18	0.36	0.54	66.6	0	44.4	6	1.735	7.867
12	-5.5	675.84	2949.12	3625	82.9	76.1	50.3	27	2.514	6.78
11	-5	192	960	1152	90	79.2	56.7	21	2.2	4.4
10	-4.5	291.84	1059.84	1351.7	96.4	80	62.7	21	2.076	4.005
9	-4	160.64	391.68	552.32	99.6	70.1	96.4	12	1.299	1.825
8	-3.5	0.72	3.6	4.32	100	83.3	94.4	3	0.7867	0.778
7	-3	160	748.8	908.8	100	82.5	86.4	15	1.604	2.62
6	-2.5	10	60	70	100	83.3	86.8	15	1.3	2.1
5	-2	0.14	0.72	0.86	100	88.8	100	3	0.6829	0.9354
4	-1.5	192	704	896	97.3	66.6	75	17	2.2	4.4
3	-1	258.56	587.52	846.08	97.5	67.1	73.2	17	1.891	2.815
2	-0.5	665.6	2050.56	2716.2	82.6	73.5	57.3	25	2.26	5.735
1	0	277.76	541.44	819.2	88.9	65.2	75.5	25	2.28	4.893

Fisher's alpha index

A low Fisher's α value is related to low diversity, while high values suggest high diversity (Phipps et al., 2010). The Paleocene succession at the Gebel Duwi section (samples 1–4) is characterized by low to moderate Fisher›s α values 2.815– 5.735 (Fig. 4 and Supplementary Material Table 1). Interestingly, an abrupt decreasing of Fisher›s α values 0.9354 –2.62 is observed with the Paleocene– Eocene boundary (samples 5–9). In the early E2 zone, Fisher›s α values increases from 4.005 (sample 9) to 7.867 (sample 13) then it decreases in the late E2 zone to 2.759 (sample 14). Fisher›s α values are represented by low to relatively high 2.18 - 11.6 in the early E3 zone (samples 15- 28) and it is oscillating upward from 2.261 to 0 at the late E3 zone.

Heterogeneity

The Shannon-Weaver index, H(S), is the index of heterogeneity, with high heterogeneity values suggesting high diversity (Murray, 1991). Values of the Shannon index are ranging from 0.287 to 2.996 in samples 1-33 reflecting medium heterogeneity (Fig. 4 and Supplementary Material Table 1).

Abundance (BFN, PFN):

In the present study, the abundance of benthic foraminifera fluctuations in samples 1-12 (0.14- 675.84 ind/g). In samples 13–14 the BFN is lower than 1 individual/gram. A BFN in samples 15 - 32 varies between 0.22 and 309.76 ind/g, except for sample 18 which reaches a maximum of 1095.68 ind/g (Fig. 4 and Supplementary Material Table 1). The abundance of planktonic foraminifera fluctuations in samples 1-12 (0.72- 2949.12 ind/g). In samples 13– 14, the PFN is lower than 1 ind/g. The PFN in samples 15 - 32 varies between 0.08 and 1359.36 ind/g except for sample 18 which reaches a maximum (4239.36 ind/g). In sample 33 the PFN is barren (Fig. 4 and Supplementary Material Table 1).

Epifaunal/ Infaunal ratio (E/I%)

Many studies are showing the relationship between the Epifaunal/ Infaunal% and the various microhabitats of benthic foraminifera (Corliss, 1985; Corliss and Chen, 1988; Jorissen et al., 1995). The E/I% might point to changes of the environment controlled by the benthic foraminifera assemblages (Table 2). The recorded epifauna and inifauna in the Paleocene/Eocene of Gebel Duwi section:

E/I% in Duwi section varies from 14.6 to 100% indicating mesotrophic conditions (Fig. 4, supplementary material Tables 1-2). In sample 31 an observed decrease in E/I% reaches 14.1% the interpretation of low oxygen and eutrophic conditions have been supported by the seafloor, and hence the increase of irregular to reach a maximum of 100% at sample 5 suggests a somewhat deeper condition together with increasing paleoproductivity.

Calcareous / Arenaceous benthic foraminiferal ratio (C / A%)

The arenaceous benthic formaminifera could be existed in various environments from extremely shallow marine to abyssal (Polski, 1959; Bandy and Arnal, 1960). The dominance of calcareous foraminifera suggests sedimentation hugely above the CCD line, of a zone well oxygenated, high in calcium carbonate, and distinguished by high temperature or/and normal salinity (Saint-Marc, 1986). The C/A % of the studied Gebel Duwi section was shown (Fig. 4 and Supplementary Material Table 1). The calcareous foraminiferal tests are dominated with irregular distribution ranging from 57.7 to 100% in samples 1- 33 of the Late Paleocene – Early Eocene succession.

Benthic foraminiferal assemblages

Utilizing the Mini tab software program, an R-mode cluster analysis was carried out on twenty-one species of benthic foraminifera that represent the Gebel Duwi section and a relative abundance of more than 5% program (Figs. 5- 6, and Supplementary Material Tables .(4, 3).

Three main benthic foraminiferal clusters are distinguished. The important benthic foraminiferal species in each cluster and frequency have been shown in distribution charts of the study section and have been presented with a relative abundance of more than 5% and 3% (Figs. 4 –6 and Supplementary Material Tables 3, 4). The cluster "A" displays high abundances of benthic foraminifera which are common during the Late Paleocene - Early Eocene. This cluster is well composed of calcareous and arenaceous benthic foraminifera dominated by epifaunal and infaunal species. This assemblage generally contains *Alabamina midwayensis*, *Anomalinioides midwayensis*, *Anomalinioides acuta*, *Bulimina farafrensis, Bulimina midwayensis*, *Bulimina reussi*, *Cibicidoides alleni*, *Cibicidoides decorates*, *Gaudryina pyramidata*, *Lenticulina*, *Loxostomoides applinae*, *Nodosaria*, *Oridosalis plummerae, Siphogenerinoides eleganta*,

TABLE 2. Habitat preferences of agglutinated and calcareous benthic foraminiferal morphogroups established in the studied section.

Epifaunal
EPIFAUNAL CALCAREOUS

Rounded trochospiral	**Biconvex trochospiral**	*Frondicularia nakkadyi*
Anomalinoides midwayensis	*Anomalinoides acuta*	**Milioline**
Valvulineria scrobiculata	*Anomalinoides affinis*	*Spiroloculina tenuis*
Planoconvex trochospiral	*Cibicidoides alleni*	**EPIFAUNAL AGGLUTINATED**
Alabamina midwayensis	*Cibicidoides* cf. *pseudoperlucides*	**Tubular**
Cibicidoides succedens	*Cibicidoides decorates*	*Bathysiphon arenaceous*
Gyroidinoides girardanus	*Cibicidoides pseudoacutus*	
Gyroidinoides subangulatus	*Lenticulina* sp	
Gyroidinoides tellburmaensis	*Oridorsalis plummerae*	
Osangularia plummerae	*Osangularia plummerae*	
Valvalabamina depressa	**Palmate**	
Valvalabamina planulata	*Neoflabellina* sp	

Inifaunal

INFAUNAL CALCAREOUS

Oval	*Stainforthia gafsensis*	*Nonionella insecta*
Pseudonodosaria pygmaea	*Stainforthia troosteri*	**Elongate multilocular**
Elongate	*Stainforthia* sp	*Pyramidulina latejugata*
Dentalina colei	*Tappanina selmensis*	*Pyramidulina raphinistrum*
Nodosaria affinis	*Vulvulina colei*	**INFAUNAL AGGLUTINATED**
Nodosaria longiscata	**Tubular or branching**	**Elongate multilocular**
Nodosaria vertebralis	*Ramulina tubensis*	*Gaudryina aissana*
Cylindrical tapered	**Flattened tapered**	*Gaudryina* cf. *ellisorae*
Pleurostomella paleocenica	*Astacolus* sp	*Gaudryina inflata*
Bulimina asperoaculeata	*Loxostomoides applinae*	*Gaudryina laevigata*
Bulimina farafraensis	*Marginulina carri*	*Gaudryina pyramidata*
Bulimina quadrata	*Marginulina pachygaster*	*Gaudryina rugosa*
Bulimina quadrata-ovata	*Marginulina wetherli*	*Gaudryina soldadoensis*
Bulimina midwayensis	*Vaginulinopsis midwayana*	*Karreria fallax*
Bulimina reussi	**Spherical/globose**	*Spiroplectinella dentata*
Turrilina brevispira	*Guttulina* sp	*Spiroplectinella esnaensis*
Siphogenerinoides eleganta	*Lagena apiculate*	*Spiroplectinella henyri*
Sitella cushmani	*Lagena hispida*	*Spiroplectinella knebeli*
Stilostomella midwayensis	*Lagena sulcate*	*Spiroplectinella spectabilis*
Stilostomella stephensoni	**Rounded planispiral**	*Tritaxia asper*

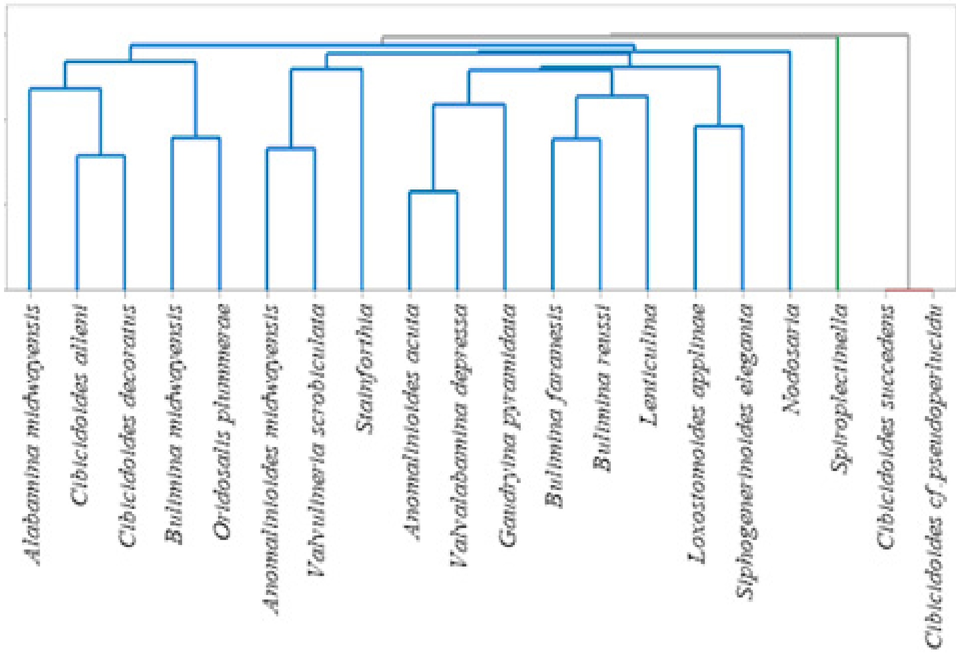


Fig. 5. An R–mode cluster analysis of the recorded benthic foraminifera species in the Gebel Duwi section.

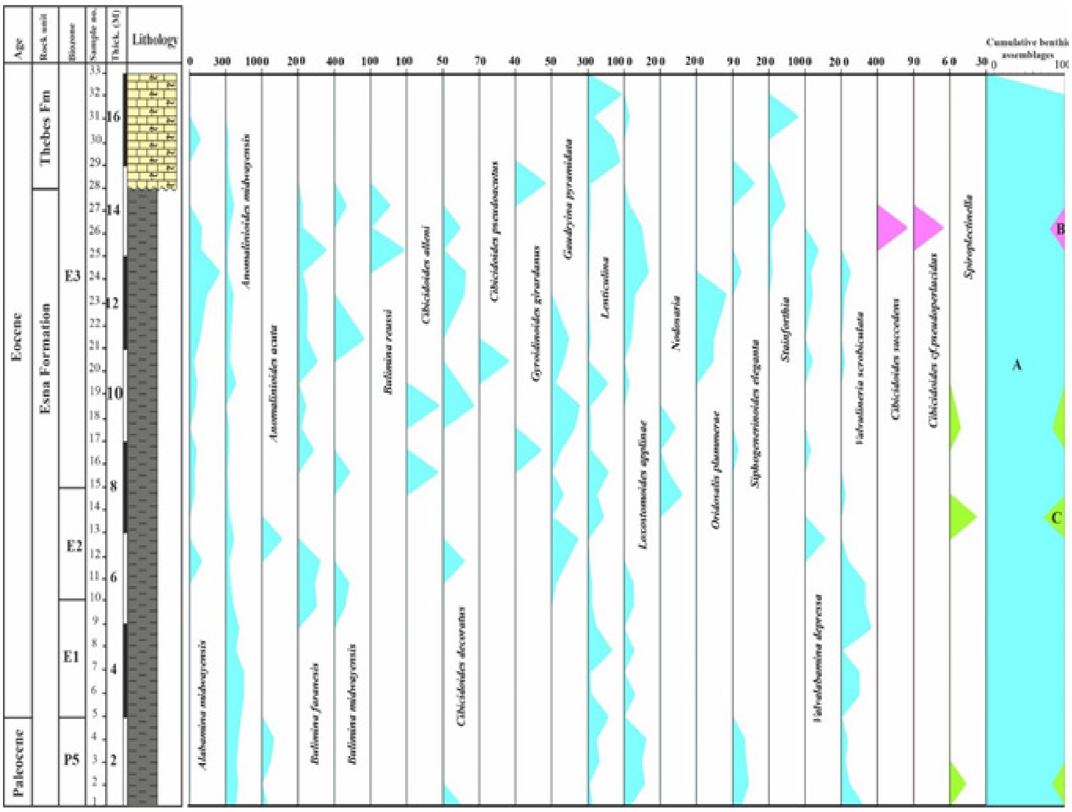


Fig. 6. Benthic foraminifera distribution chart (>3%) and relative cumulative abundance of different clusters.

Stainforthia, *Valvalabamina depressa* and *Valvulineria scrobiculata* assemblages indicating an inner neritic to bathyal environments (Speijer and Schmitz, 1998; Schnack, 2000; Hewaidy et al., 2019 b, c; Widmark and Speijer, 1997; Olsson & Wise, 1987; Miller et al., 2008, Zaky et al., 2020; Fig. 7).

The cluster “B” is marked with the low relative abundance of benthic foraminifera through the Early Eocene (E3 Zone). This cluster is also containing only calcareous benthic foraminifera dominated by epifaunal species. Among this taxon are *Cibicidoides succedens and Cibicidoides* cf. *pseudoperlucidus*. Assemblage compositions and diversity of benthic foraminifera are reflecting a middle neritic to outer neritic environment (Schnack, 2000; Fig. 7).

The cluster “C” has been defined by taxa common in the Early Eocene, and relative abundances are moderate. This cluster contains only arenaceous benthic foraminifera dominated by infaunal species. It is distinguished by the common occurrences of *Spiroplectinella*. The interpretation of this assemblage is that indicates outer neritic to upper bathyal environments (El Dawy and Hewaidy, 2003; Speijer, 2003; Holbourn et al., 2013; Hewaidy et al., 2018, Hewaidy et al., 2019b, c, Fig. 7). In the present

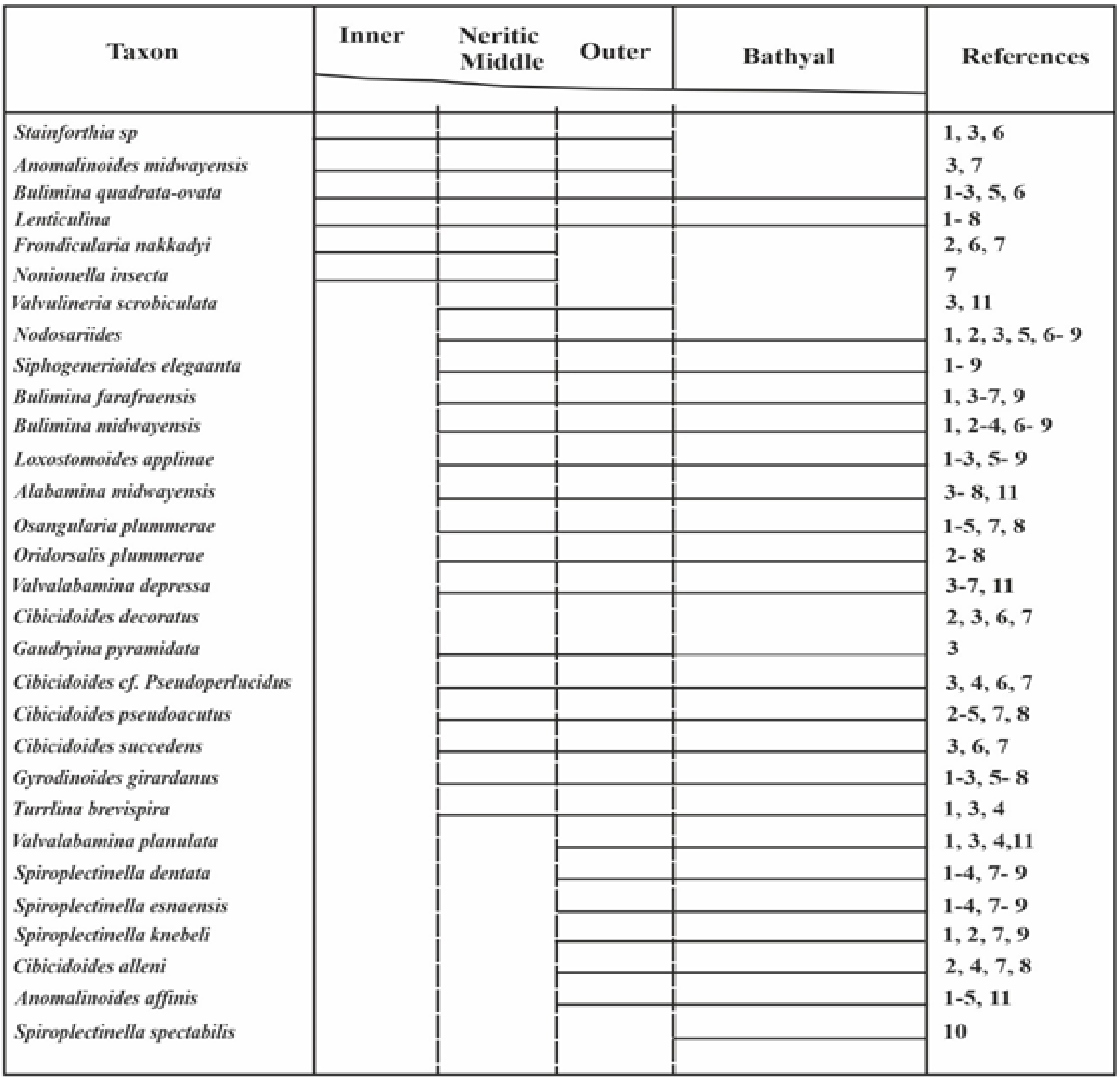


Fig. 7. Summary of chosen taxa’s preferred bathymetry based on previous studies. 1= Le Roy; 1953, 2= Luger; 1985, 3= Speijer; 1994, 4= Speijer; 1995, 5= Speijer and Van der Zawan; 1996, 6= Speijer et al.; 1996, 7= Schnack; 2000, 8= El Dawy; 2001, 9= Hewaidy; 1994, 10= Kaiho; 1992, 11= Speijer & Schmitz; 1998.

TABLE 3. Relative abundance (>5%) of the most common species and relative cumulative abundance of different clusters in Gebel Duwi section.

Sample number	Alabamina midwayensis	Anomalinioides midwayensis	Anomalinioides acuta	Bulimina faranesis	Bulimina midwayensis	Bulimina reussi	Cibicidoides alleni	Cibicidoides succedens	Cibicidoides cf.pseudoperlucidus	Cibicidoides decoratus	Gaudryina pyramidata	Lenticulina	Loxostomoides applinae	Nodosaria	Oridosalis plummerae	Siphogenerinoides eleganta	Spiroplectinella	Stainforthia	Valvalabamina depressa	Valvulineria scrobiculata	A	B	C
33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
32	0	0	0	0	0	0	0	0	0	0	0	94.3	0	0	0	0	0	0	0	0	100	0	0
31	0	0	0	0	0	0	0	0	0	0	0	13.8	0	0	0	0	0	81.2	0	0	100	0	0
30	9	9	0	0	0	0	0	0	0	0	0	72.7	0	0	0	0	0	0	0	0	100	0	0
29	0	7.1	0	0	0	0	0	0	0	0	0	90.4	0	0	0	0	0	0	0	0	100	0	0
28	0	12	0	0	0	0	0	0	0	0	0	5.7	0	0	0	12	0	27.1	0	0	100	0	0
27	0	22.1	0	5	0	5.4	0	0	0	0	0	7.3	0	0	0	0	0	46.7	0	0	100	0	0
26	10	12.3	0	5	0	0	0	7.4	5	0	0	6.4	10	0	0	0	0	7.4	0	0	80.4	19.6	0
25	9.3	6	0	30.8	0	9.3	0	0	0	0	0	0	11.6	0	0	0	0	6	7.4	0	100	0	0
24	25.1	6	0	5	0	0	0	0	0	5	0	0	13.7	0	0	5	0	10.3	0	10.8	100	0	0
23	14.4	21	0	10.3	0	0	0	0	0	0	0	0	6.1	0	7.4	0	0	0	0	0	100	0	0
22	8.3	14	0	10	8.3	0	0	0	0	0	14.3	8.7	5	0	5	0	0	0	0	0	100	0	0
21	0	11	0	21.1	0	0	0	0	0	0	10.1	0	0	0	0	0	0	0	0	0	100	0	0
20	6.3	28.1	0	0	0	0	0	0	0	0	0	56.3	0	0	0	0	0	0	0	0	100	0	0
19	5	0	0	9.1	0	0	5	0	0	6	23	5.5	0	0	0	0	5	0	0	0	91.4	0	8.6
18	0	9.8	0	0	0	0	0	0	0	0	19.1	9.3	0	8.4	0	0	8.8	0	0	0	84.1	0	15.9
17	5.6	10.4	0	16.8	0	0	0	0	0	0	8	8.8	0	0	0	0	0	0	0	0	100	0	0
16	4.3	0	0	0	0	0	0	0	0	0	0	56.5	0	0	0	0	0	0	0	0	100	0	0
15	3.9	7.4	0	0	0	0	0	0	0	0	9.9	24.7	0	12	0	0	0	0	0	5	100	0	0
14	0	11.1	0	0	0	0	0	0	0	0	0	44.4	0	0	0	0	22.2	0	0	0	71.4	0	28.6
13	0	22.2	11	0	0	0	0	0	0	0	22.2	0	0	0	0	0	0	0	11.1	0	100	0	0
12	10.2	10.1	0	24.2	0	0	0	0	0	0	12.8	5	0	0	0	0	0	0	0	7.5	100	0	0
11	0	13.3	0	18.6	0	0	0	0	0	0	0	12.6	5.2	0	0	0	0	0	0	26.7	100	0	0
10	0	21	0	21	0	0	0	0	0	0	0	11.8	5.2	0	0	0	0	0	0	26.7	100	0	0
9	0	37.8	0	0	0	0	0	0	0	0	0	24.3	0	0	0	0	0	0	0	33.1	100	0	0
8	0	27.7	0	0	0	0	0	0	0	0	0	66.6	5.5	0	0	0	0	0	0	0	100	0	0
7	0	50.1	0	0	0	0	0	0	0	0	0	6	0	0	0	0	0	0	0	19.7	100	0	0
6	0	50.8	0	0	0	0	0	0	0	0	0	10	6	0	0	0	0	0	0	20	100	0	0
5	0	42.8	0	0	0	0	0	0	0	0	0	57.1	0	0	0	0	0	0	0	0	100	0	0
4	0	35.6	6.6	0	0	0	0	0	0	0	0	24.3	12	0	0	6.6	0	0	0	6.6	100	0	0
3	0	29.7	5	0	0	0	0	0	0	0	0	32.6	10	0	0	7.4	0	0	0	5	100	0	0
2	0	34.2	0	0	0	0	0	0	0	0	0	5.3	11.5	0	0	8.8	13.4	0	0	9.2	83.7	0	16.3
1	0	27.6	0	0	0	0	0	0	0	0	0	13	0	0	0	5	0	0	0	24	100	0	0

TABLE 4. Relative abundance (3%<) of the most common species in Gebel Duwi section.

Sample number	Depth	Alabamina midwayensis	Anomalinioides midwayensis	Anomalinioides acuta	Bulimina faranesis	Bulimina midwayensis	Bulimina reussi	Cibicidoides alleni	Cibicidoides decoratus	Cibicidoides pseudoacutus	Gyroidinoides girardanus	Gaudryina pyramidata	Lenticulina	Loxostomoides applinae	Nodosaria	Oridosalis plummerae	Siphogenerinoides eleganta	Stainforthia	Valvalabamina depressa	Valvulineria scrobiculata	Cibicidoides succedens	Cibicidoides cf.pseudoperlucidus	Spiroplectinella
33	-16.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
32	-16	0	0	0	0	0	0	0	0	0	0	0	94.3	0	0	0	0	0	0	0	0	0	0
31	-15.5	0	0	0	0	0	0	0	0	0	0	0	13.8	3	0	0	0	81.2	0	0	0	0	0
30	-15	9	9	0	0	0	0	0	0	0	0	0	72.7	0	0	0	0	0	0	0	0	0	0
29	-14.5	0	7.1	0	0	0	0	0	0	0	0	0	90.4	0	0	0	0	0	0	0	0	0	0
28	-14	0	12	0	0	0	0	0	0	0	4.1	0	5.7	0	0	0	12	27.1	0	0	0	0	0
27	-13.5	0	22.1	0	5	3.4	5.4	0	0	0	0	0	7.3	3	0	0	0	46.7	0	0	0	0	0
26	-13	10	12.3	0	5	0	0	0	3.4	0	0	0	6.4	10	0	0	0	7.4	0	0	7.4	5	0
25	-12.5	9.3	6	0	30.8	0	9.3	0	0	0	0	0	3.7	11.6	0	0	0	6	7.4	0	0	0	0
24	-12	25.1	6	0	5	0	0	0	4.4	0	0	0	3	13.7	0	0	5	10.3	3	10.8	0	0	0
23	-11.5	14.4	21	0	10.3	0	0	0	4.1	0	0	0	0	6.1	0	7.4	0	0	4.1	4.1	0	0	0
22	-10.5	8.3	14	0	10	8.3	0	0	0	0	0	14.3	8.7	4.3	0	4.3	0	0	0	0	0	0	0
21	-10	3.3	11	0	21.1	0	0	0	0	3.3	0	10.1	0	0	0	4.2	0	0	4.2	4.2	0	0	0
20	-9.5	6.3	28.1	0	0	0	0	0	3.1	0	0	3.1	56.3	3.1	0	0	0	0	0	0	0	0	0
19	-9	4.5	0	0	9.1	0	0	4.5	6	0	0	23	5.5	0	0	0	0	0	0	0	0	0	4.5
18	-8.5	0	9.8	0	3.2	0	0	0	0	0	0	19.1	9.3	0	8.4	0	0	0	0	0	0	0	8.8
17	-8	5.6	10.4	0	16.8	0	0	0	0	0	3.6	8	8.8	0	0	0	3	0	3	0	0	0	0
16	-7.5	4.3	4.3	0	0	4.3	0	4.3	0	0	0	0	56.5	0	4.3	0	0	0	0	0	0	0	0
15	-7	3.9	7.4	0	0	0	0	0	0	0	0	9.9	24.7	0	12.3	0	0	0	0	5	0	0	0
14	-6.5	0	11.1	0	0	0	0	0	0	0	0	0	44.4	0	0	0	0	0	0	0	0	0	22.2
13	-6	0	22.2	11.1	0	0	0	0	0	0	0	22.2	0	0	0	0	0	0	11.1	0	0	0	0
12	-5.5	10.2	10.1	0	24.2	0	0	0	4.1	0	0	12.8	5	0	0	0	0	0	0	7.5	0	0	0
11	-5	0	13.3	0	19	4	0	0	0	0	0	3.3	12.6	5.2	0	0	0	0	0	26.7	0	0	0
10	-4.5	0	21	0	21	3	0	0	0	0	0	0	11.8	5.2	0	0	0	0	0	26.7	0	0	0
9	-4	0	37.8	0	0	0	0	0	0	0	0	0	24.3	0	0	0	0	0	0	33.1	0	0	0
8	-3.5	0	27.7	0	0	0	0	0	0	0	0	0	66.6	5.5	0	0	0	0	0	0	0	0	0
7	-3	0	50.1	0	0	0	0	0	0	0	0	0	6	0	0	0	0	0	0	19.7	0	0	0
6	-2.5	0	50.8	0	0	0	0	0	0	0	0	0	10	6	0	0	0	0	0	20	0	0	0
5	-2	0	42.8	0	0	0	0	0	0	0	0	0	57.1	0	0	0	0	0	0	0	0	0	0
4	-1.5	0	35.6	6.6	0	0	0	0	0	0	0	0	24.3	12	0	0	٧	0	0	٦,٦	0	0	0
3	-1	0	29.7	5	0	0	0	0	0	0	0	0	32.6	10	0	0	7.4	0	0	5	0	0	0
2	-0.5	0	34.2	0	0	0	0	0	0	0	0	0	5.3	11.5	0	0	8.8	0	0	9.2	0	0	13.4
1	0	0	27.6	3.2	0	0	0	0	3.6	0	0	0	13	3.6	0	0	5	0	0	24	0	0	0

study, the species in this assemblage attains its maximum abundance 8.6– 28.6%.

Microfacies study

The depositional environments of the different rock units have been interpreted, on the base field observations as well as the vertical differences in the microfacies, biofacies, and lithofacies of the examined sequence in the Gebel Duwi region.

Foraminiferal wackestone microfacies (Facies Type 1 "FT1"):

This facies type is recorded in Esna Formation of Gebel Duwi (Fig. 8). Esna Formation is characterized by the black dark gray color and moderately hard) Fig. 8(8. Petrographically, it is mud supported with moderately sorted foraminifera randomly scattered within a micrite binding material. The allochems are composed mainly of planktonic and benthic foraminifera, bioclasts, and bird eyes porosity is embedded within the micritic matrix (Pl. a, d and g(.

Dolomitic lime- mudstone microfacies (Facies Type 2 "FT2"):

This facies is recorded at Esna Formation in Gebel Duwi (Fig. 8). Lithologically, Esna Formation is characterized by the black dark gray color and is moderately hard Fig.(8). Petrographically, it consists mainly of lime mud matrix enriched in dolomite with fine-grained rock, clay minerals, Quartz, feldspars, iron oxides and calcite (Pl. b, c and h).

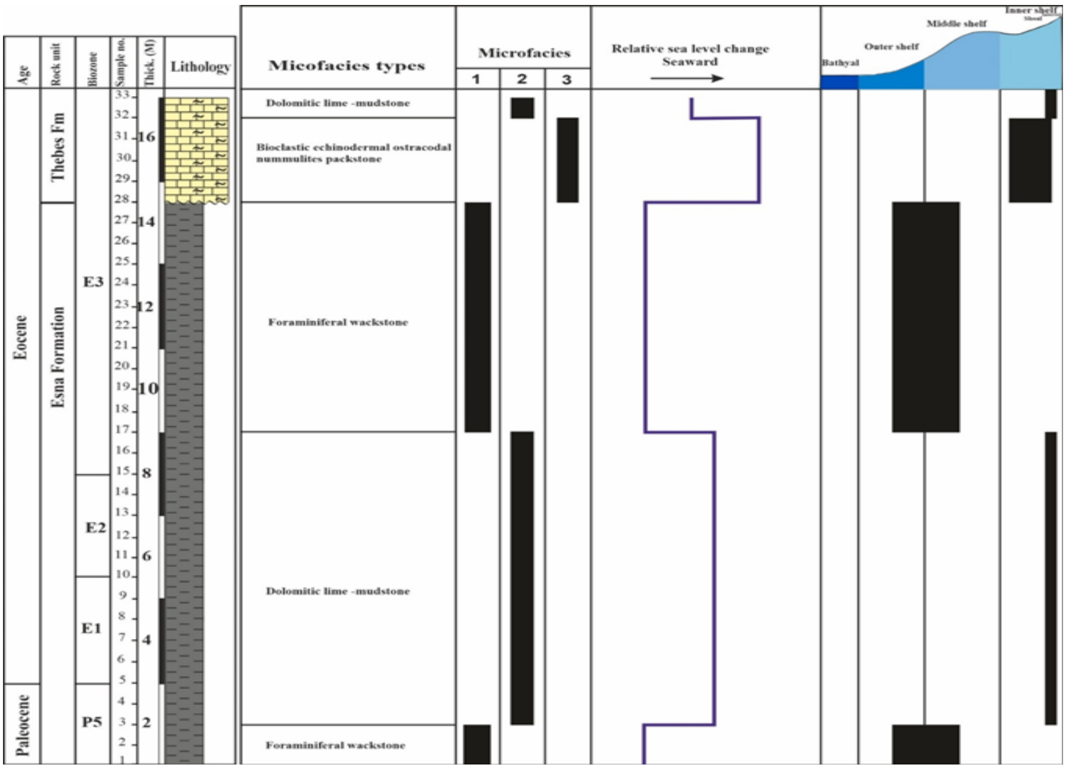


Fig. 8. Representative stratigraphic section of the exposed Esna and Thebes formations at Gebel Duwi section, showing their microfacies types and sedimentary environments.

Plate:

(a) Abundant foraminiferal tests slightly packed within a lime-mud matrix. foraminiferal wackestone, Esna Formation at Gebel Duwi, sample 28.

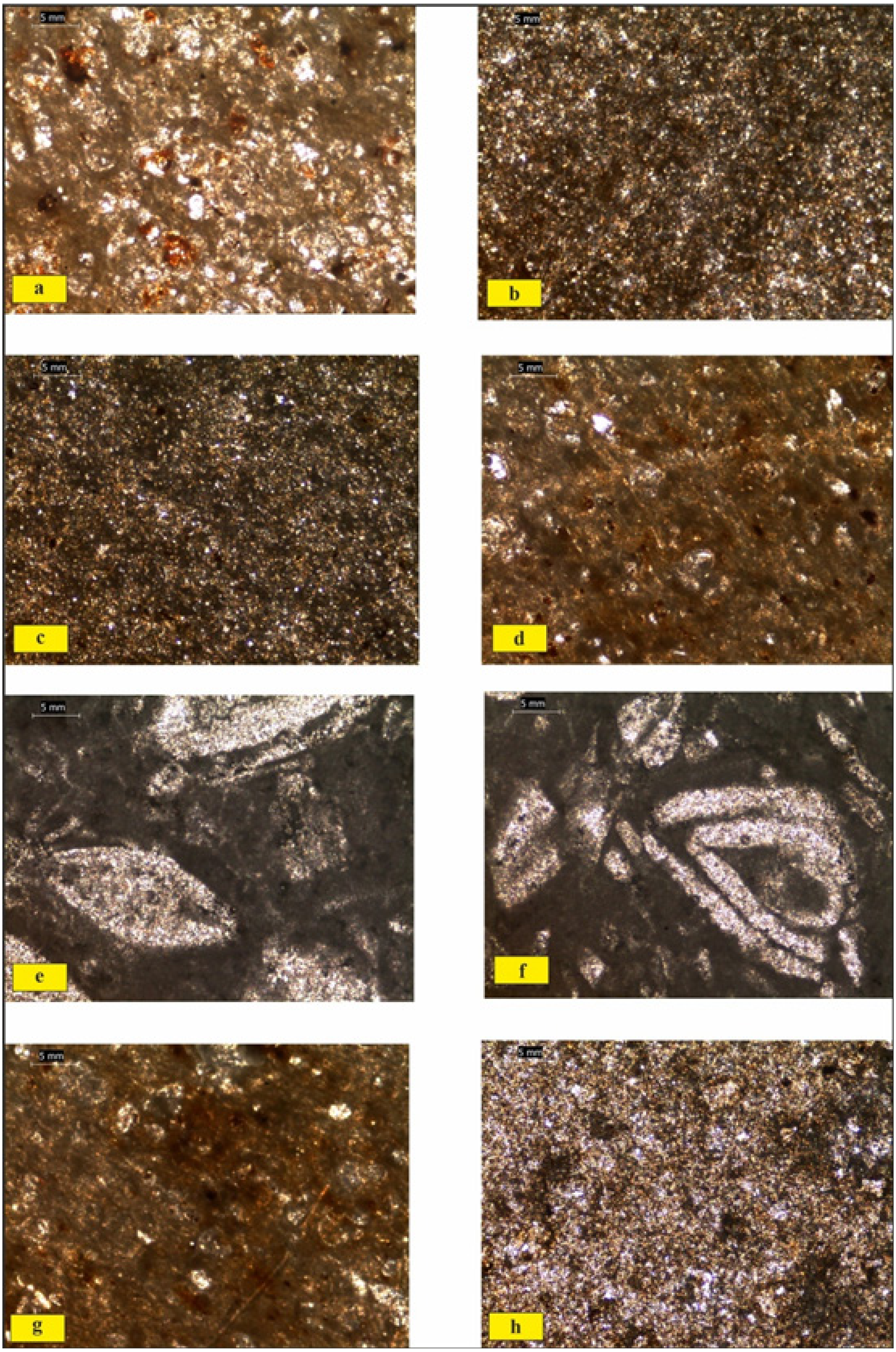
(b, c) Dolomitic lime- mudstone, Gebel Duwi, samples 7, 33.

(d) Abundant foraminiferal tests slightly packed within a lime-mud matrix. foraminiferal wackestone, Esna Formation at Gebel Duwi, sample 1.

(e, f) Bioclastic echinodermal ostracodal nummulites packstone microfacies at Gebel Duwi, sample 29.

(g) Abundant foraminiferal tests slightly packed in a lime mud matrix. foraminiferal wackestone, Esna Formation, Gebel Duwi, sample 2.

(h) Dolomitic lime- mudstone, Gebel Duwi, sample 3.


5 mm
a
b
c
d
e
f
g
h

Bioclastic echinodermal ostracodal Nummulites packestone microfacies (Facies Type 3 "FT3"):

This facies is recorded at Thebes Formation in Gebel Duwi (Fig. 8). Lithologically, this microfacies, at the outcrop level, represents fine to medium grained light to black dark gray limestone with minor interbeds of shale and moderately hard (Fig. 8. Petrographically, this microfacies is distinguished with diversified bioclasts of the echinodermal fragments with the presence of the genera of ostracodes and larger benthic foraminifers including Nummulites (Pl. e and f). All these allochems, of microfacies, are embedded in a micritic matrix.

Benthic foraminiferal Oxygen Index (BFOI)

Benthic foraminifera represented one of the most sentient indexes to dissolved oxygen levels and, may thus be utilized for the interpretation of old sediment. Standards of evaluation oxygen depended on test size, wall thickness, foraminiferal morphology, or indicating taxa. So, by the standards, the specific benthic foraminifera were gathered to three types: dysoxic, oxic, and suboxic indicators (Fig. 9; Tables: 5 and 6). BFOI relies upon foraminiferal properties which are reflected in aspects of these processes. The composition of benthic foraminiferal fauna in calcareous taxa, and data from living foraminifera, might be used to determine an oxygenation index (Kaiho; 1991, 1992, 1994a, 1994b, 1999).

The calcareous benthic foraminifera are divided into oxic, suboxic, and dysoxic indicators by the taxonomic characteristics of the benthic foraminifera and morphologic (Kaiho, 1994a). The following formula may be used to calculate BFOI, BFOI is defined as O/ (O+ D+ S/2) x 100, where O, D, and S are the numbers of oxic, dysoxic, and suboxic foraminifera, which are epifauna with large size and thick walls. The lower portion from the studied section is distinguished by an increase in the abundance of suboxic and oxic indicators. Dysoxic indicators have occurred with low percentage values. This interval displays the highest percentage values of *Anomalinioides midwayensis* and the lowest percentage values of the inifaunal taxa.

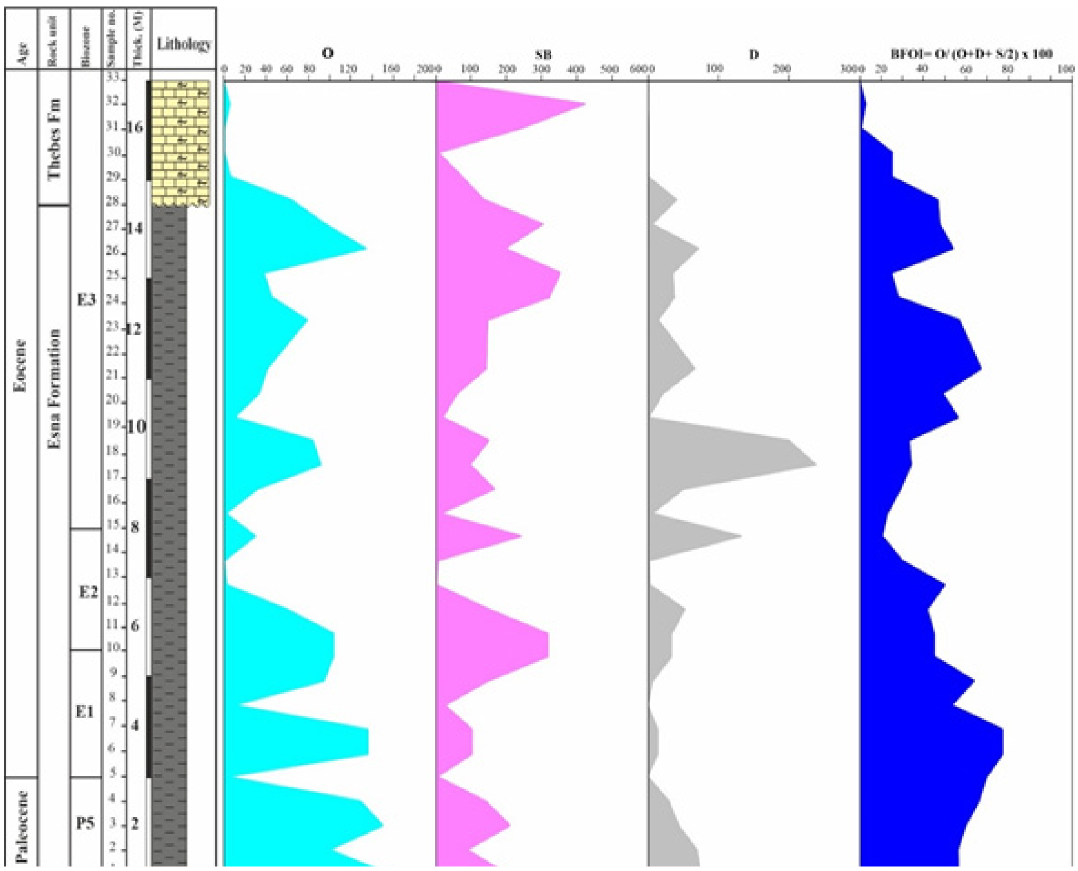


Fig. 9. Types of oxygen availability: Oxic (O), Suboxic (SB), and Dysoxic (D).

TABLE 5. Classification of benthic foraminiferal species into Oxic (O), Suboxic (SB) and Dysoxic (D) types, According to Kaiho (1994a).

Benthic foraminiferal species	Group	Benthic foraminiferal species	Group	Benthic foraminiferal species	Group
Cibicidoides cf. *pseudoperlucidus*	O	*Marginulina pachygaster*	SB	*Nodosaria vertibralis*	D
Cibicidoides decorates	O	*Marginulina wetherli*	SB	*Dentalina colei*	D
Cibicidoides pseudoacutus	O	*Gyroidinoides girardanus*	SB	*Dentalina* sp	D
Cibicidoides sp.	O	*Gyroidinoides subangulatus*	SB	*Gaudryina aissana*	D
Cibicidoides succedens	O	*Gyroidinoides tellburmaensis*	SB	*Gaudryina* cf. *ellisorae*	D
Cibicidoides megaloperforatus	O	*Lagena apiculata*	SB	*Gaudryina inflate*	D
Cibicidoides mircus	O	*Lagena hispida.*	SB	*Gaudryina laevigata*	D
Anomalinoides acuta	O	*Lagena sulcata.*	SB	*Gaudryina pyramidata*	D
Anomalinoides affinis	O	*Lenticulina*	SB	*Gaudryina rugosa*	D
Anomalinioides midwayensis	O	*Loxostomoides applinae*	SB	*Gaudryina soldadoensis*	D
Anomalinoides sp.	O	*Nonionella insecta*	SB	*Gaudryina* sp	D
Frondicularia nakkadyi	O	*Oridorsalis plummerae*	SB	*Guttulina* sp.	D
Neoeponides sp	O	*Pyramidulina latejugata*	SB	*Bathysiphon arenaceous*	D
Osangularia plummerae	O	*Pyramidulina raphinistrum*	SB	*Karreriella tenius*	D
Ramulina tubensis	O	*Sitella cushmani*	SB	*Pseudonodosaria pygmaea*	D
Tappanina selmensis	O	*Stainforthia gafsensis*	SB	*Pleurostomella paleocenica*	D
Alabamina midwayensis	SB	*Stainforthia troosteri*	SB	*Pleurostomella* sp.	D
Alabamina wilcoxensis	SB	*Stainforthia sp*	SB	*Siphogenerinoides eleganta*	D
Astacolus sp.	SB	*Stilostomella midwayensis*	SB	*Neoflabellina* sp	D
Bulimina asperoaculeata	SB	*Stilostomella stephensoni*	SB	*Spiroloculina tenuis*	D
Bulimina farafraensis	SB	*Turrilina brevisipra*	SB	*Spiroplectinella esnaensis*	D
Bulimina midwayensis	SB	*Valvalabamina depressa*	SB	*Spiroplectinella henryi*	D
Bulimina quadrata	SB	*Valvalabamina planulata*	SB	*Spiroplectinella knebeli*	D
Bulimina quadrata-ovata	SB	*Valvulineria scrobiculata*	SB	*Spiroplectinella dentate*	D
Bulimina reussi	SB	*Vulvulina colei*	SB	*Spiroplectinella spectabilis*	D
Bulimina sp.	SB	*Nodosaria affinis*	D	*Tritaxia asper*	D
Marginulina carri	SB	*Nodosaria longiscata*	D		

TABLE 6. Calculation of the BFOI in the studied succession from the following formula "BFOI= O/ (O+ D+ S/2) x 100".

Sample NO.	O	SB	D	BFOI= O/ (O+D+ S/2) x 100
33	0	0	0	0
32	6	422	0	2.76
31	1	243	1	0.8
30	1	9	1	15.3
29	7	76	1	15.2
28	64	138	41	36.7
27	96	304	6	37.7
26	134	198	72	43.9
25	38	354	36	15.1
24	46	322	38	18.3
23	79	148	15	47
22	41	143	67	57.3
21	34	62	22	39
20	10	21	1	46.5
19	84	152	200	23.3
18	92	98	238	24.2
17	32	167	51	19.2
16	2	15	6	12.9
15	30	242	132	10.6
14	1	6	2	20
13	3	3	3	40
12	60	151	53	31.8
11	104	318	34	35
10	104	318	34	35
9	95	149	7	53.8
8	10	26	0	43.4
7	136	103	14	67.4
6	136	103	14	67.4
5	3	4	0	60
4	129	141	30	56.2
3	150	210	44	50.1
2	100	90	70	46.5
1	156	202	76	46.8

BFOI values range from 43.4 to 67.4 in samples 1-9. In E2 Zone, BFOI values began to decrease from 40 to 31.8. This interval shows the increase in the abundance of suboxic and dysoxic indicators. Oxic indicators decrease in this interval. This interval is showing the high percentage values of inifaunal taxa of *Bulimina faranesis*, *Gaudryina pyramidata*, *Loxostomoides applinae,* and moderates percentage values of the epifaunal taxa. In samples 14-19, this interval was distinguished with a falling in the abundance of oxic indicators and, an increasing in dysoxic and suboxic indicators. BFOI values are decreased to reach a minimum value of 10.6 in sample 15. BFOI values increase again in the abundance of oxic and suboxic indicators. Dysoxic indicators have occurred with low percentage values. This interval is showing the low percentage values of the inifaunal taxa and, the high percentage values of *Anomalinioides midwayensis, Alabamina midwayensis,* and *Bulimina faranesis*. BFOI values range from 39 to 57.3 in samples 20- 23. BFOI values decrease in samples 24-25 to reach 15.1. BFOI values range from 36.7 to 43.9 in samples 26- 28. In the late E3 Zone, BFOI values decrease again to reach a minimum value of 0.8 in sample 31. BFOI values are zero in sample 33 because benthic foraminifera is absent.

Discussion

Paleocene/Eocene boundary

The Global Stratotype Section and Point (GSSP) through the Paleocene/Eocene (P/E) boundary have been located at the deserted Quarry of Dababiya, southeast Esna, in the base of the Dababiya Quarry Beds (DQB) which are found within the lower Esna Formation, near Luxor, Egypt. This provides an excellent record of the Paleocene Eocene Thermal Maximum (PETM) and the Carbon Isotope Excursion (CIE) (Aubry et al., 2007; Berggren et al., 2012). The P/E boundary was correlated on the base of the P5/E1 zones of planktonic foraminifera (Berggren and Pearson, 2005) and between the NP9/NP10 zonal boundary, that was determined by the LO of *Tribrachiatus bramlettei* (Martini, 1971), or the LO of *Discoaster diastypus* (Okada and Bukry, 1980).

Many events took place through the P/E boundary including alterations in oceanic circulation (Miller et al., 1987; Thomas, 1990a, b, 1993), global warming (Stott and Kennett, 1990; Kennett and Stott, 1991), and reduction in atmospheric circulation (Rea et al., 1990). Major shifts in the bathyal and abyssal benthic foraminifera coincided with these PETM-related occurrences (Benthic Extinction Event BEE) (Tjalsma and Lohmann, 1983; Thomas, 1990a, b).

In Egypt, the P/E boundary has been placed through the planktonic foraminiferal species from the last occurrence of *Morozovella velascoensis* or the first occurrence of the *Pseudohastigerina wilcoxensis* (Masters, 1984; Strougo, 1986; Haggag, 1992; Shahin, 1998; Tantawy, 1998; Obedaillah, 2000; El Nady and Shahin, 2001; Saad, 2001; Scheibner et al., 2001; Samir, 2002; Youssef and Saida, 2012; Hefny and Youssef, 2015). In the investigated region, the calcareous shale of the Esna Formation is the predominant lithology across the P/E boundary in Gebel Duwi. Biostratigraphically, it synchronizes by the zonal boundary between P5 and E1. In this study, PETM was seen in the poorly to moderately recorded basal Eocene foraminiferal assemblages. Assemblages of planktonic foraminifera recorded at these deposits are dominated with flat-spired *Acarinina*, containing *A. sibaiyaensis* and, relevant taxa typical to the PETM. P/ E lies within the Esna Formation between samples 5/6 in the present study.

Paleobathymetry

Benthic foraminifera are very useful as paleobathymetric indicators as their distribution in the oceans is controlled by multiple variables, including water depth, productivity (food supply), and oxygen concentration (Alegret et al., 2001; Culver, 2003; Leckie and Olson, 2003; Alegret and Thomas, 2004; Frontalini et al., 2016).

The amount of dissolved oxygen and the organic matter flux significantly affected the benthic foraminiferal population (Jorissen et al., 2007). The major environmental parameters such as characteristics of the sediment, turbidity currents, and water depth are also the other physicochemical factors that may be affected the TFN (Murray, 1991). The pre/post depositional dissolution in the water column or/at the sea floor produced the change in the TFN (De Villiers, 2005).

The high P/B% ratio may imply a deeper paleodepth; however, it is important to take into account the dominating taxa, which may reflect the various paleoecological conditions (King, 2012). Paleobathymetry can be inferred using variations in the P/B% as a proxy (Herkat and Ladjal, 2013).

High proportions of calcareous taxa may point to comparatively deeper paleo-environments, whereas assemblages dominated by agglutinated taxa may indicate shallow or/and marginal marine paleo-environments (Gooday, 1994). When the water-depth is increased in bathyal to abyssal environments, the C/A% shows a linear decline that approaches 0% near the CCD (Frontalini et al., 2018a, b). E/I% is expressed as the number of epifaunal benthic foraminifera/total number of epifaunal + inifaunal benthic foraminiferal X 100. The potential benthic foraminiferal microhabitat preferences could be extremely dependent on shell morphology (Jorissen et al., 1995). The rounded trochospiral, milioline, biconvex, and planoconvex, coiled flattened, and tubular tests, were epifaunal lived on the bottom substrate morphogroups, while the infaunal lived within bottom of the substrate morphogroups comprises of spherical, rounded planispiral, globular unilocular, elongate multilocular, flattened ovoid, cylindrical or/and flattened tapered tests (Alegret et al., 2003). E/I% could be using to reconstruct paleo-environmental variables as oxygenation of the seawater, and the food supply to the sea floor (Fontanier et al., 2002). The increase of the Epifaunal morphotypes could be related to low organic matter influxes or/and high oxygenation conditions (Bernhard, 1986; Kaiho, 1994a; Kaminski, 2012). While infaunal species are characterized by abundant under high organic matter fluxes or/and low oxygen conditions (Alve and Bernhard, 1995; Geslin et al., 2004). More study employing deep geologic-time paleo-environments is needed (Thomas et al., 2000; Holbourn et al., 2001; Cetean et al., 2011). The number of all recorded benthic foraminiferal species is diversity, whereas the Fisher_alpha index provided a better and more reliably estimated of the paleo-environmental changes and the diversity as well as it is accounted of the relative abundances of species. The low diversity indicated oxygenate conditions with very low organic matter influx (Friedrich and Hemleben, 2007). The proportion of a species in the entire assemblage is used to calculate relative the abundances expressed.

Microfacies analysis

The FT1 is highly diverse of foraminiferal tests and its distribution pattern indicates deposition in intertidal environments (Flügel, 1982). Based on the abundance of planktonic foraminifera in fine-grained matrix reflects the middle to an outer shelf below the normal wave base. This microfacies occurs in facies belt 7 – 8 (Wilson's, 1975). The FT2 is fine-grained indicating deposition in the intertidal environment (Flügel, 1982). Dolomitized mudstones with very rare faunal elements occur in restricted environments of the shallow subtidal (Höntzsch et al., 2011). The FT3 is elongated shell form, thinner test walls, and abundance of mud matrix propose that the microfacies deposits in highly deep oligophotic zone, under the fair-weather wave bottom (Pomar et al. 2004; Payros et al. 2010).

Benthic foraminiferal Oxygen Index (BFOI)

The dissolved oxygen concentration which differences at the sediment or and/water interface related to many factors plays an important role for controlling of the composition the benthic foraminiferal assemblages, and morphotypic properties including the test of size, morphology, and wall thickness (Perez and Machain, 1990). These different taxonomic and morphologic factors were determined by (Kaiho, 1994a) in terms of the BFOI. The benthic foraminifera was classified as oxic, suboxic, and dysoxic indicators on the base of relations between particular morphologic properties, benthic foraminiferal microhabitat, and oxygen levels (Kaiho, 1994a). The BFOI was calculated as the following equation (Kaiho, 1994a):

$$BFOI= O/ (O+ D+ S/2) \times 100$$

Where;

O, D, and S which represented oxic number, dysoxic, and suboxic foraminifer, were epifauna with a large size >350m and the thick wall.

Bottom water paleoxygenation is assessed depending on the BFOI of (Kaiho, 1994a).

In the present area, BFOI values within the lower portion of the studied section are distinguished with an increase in the abundance of oxic and suboxic indicators reflecting oligotrophic and well-oxygenated conditions. In E2 Zone shows an increase in the abundance of suboxic and dysoxic indicators. This interval of BFOI values is moderate and reflects mesotrophic and medium-oxygenated conditions. BFOI values in E3 Zone fluctuated and reached a minimum of 0.8% in sample 31 the interpretation of low oxygen and eutrophic conditions have been supported.

Sequence Stratigraphy

Three third order depositional sequences bounded by four sequence boundaries have been recognized in the studied Late Paleocene–Early Eocene succession. It is differentiated and recognized into their systems tracts according to change in the sea level and interpreted into the paleobathymetric analysis of the various foraminiferal factors (R mode cluster analyses, P/B%, abundance, and diversity), in addition to the fieldwork, and lithofacies examination, where the established sequences are mainly composed of TST and HST (Fig. 10).

The established depositional sequences are briefly discussed below, taking into account their age, the nature of their SBs, and the descriptions of their systems tracts.

Depositional sequence 1 (SQ1)

SQ1 occurs in the lower Paleocene (Samples 1-4, P5 zone; Fig. 10) at the Gebel Duwi section.

Transgressive systems tract (TST1): This TST1 is composed mainly of FT1 and an increasing of foraminiferal palaeoproductivity (P/B% up to 73.5%; TFN between 819.2 and 2716.2 s/g; species richness is 25 species/sample; Shannon index ranges from 2.26 to 2.28; and Fisher's ranges between 4.893 and 5.735; Fig. 10, table 4). The benthic assemblage was dominated by Cluster A (83.7–100%), and Cluster C (16.3%). Furthermore, the high percentage of *Anomalinoides midwayensis* and *Valvulineria scrobiculata* assemblages reflect deep inner to middle neritic environments (Schnack, 2000; Sprong et al., 2012).

The maximum flooding surface (MFS1) occurs at the highest relative proportion of the *Anomalinioides midwayensis* assemblages in the middle part of the P5 Zone between the vertical facies change from FT1 to FT2 (sample 3, Fig. 10). *Spiroplectinella* indicate deep-up features in the fauna and facies which are characteristic of TST.

Highstand systems tract (HST1):

The HST in Gebel Duwi (samples 3- 4; P5 zone) is characterized by a TFN ranging from ~846.08 to 896 s/g and P/B% of up to 67.91%, where BFN is ranging between 258.56 and 192 s/g and PFN is ranging between 587.52 and 704 s/g (Fig. 10, Table 1). It is associated with the cluster "A" assemblages that are dominated by E/I % ranging from 73.2 to 75 %, C/A% that reaches a maximum of 97.5% and reflects middle to outer shelf. This HST is characterized by a medium diversified fauna wherever the Fisher's ranges between 2.815 and 4.4; species richness is 17 species/sample and Shannon index ranges

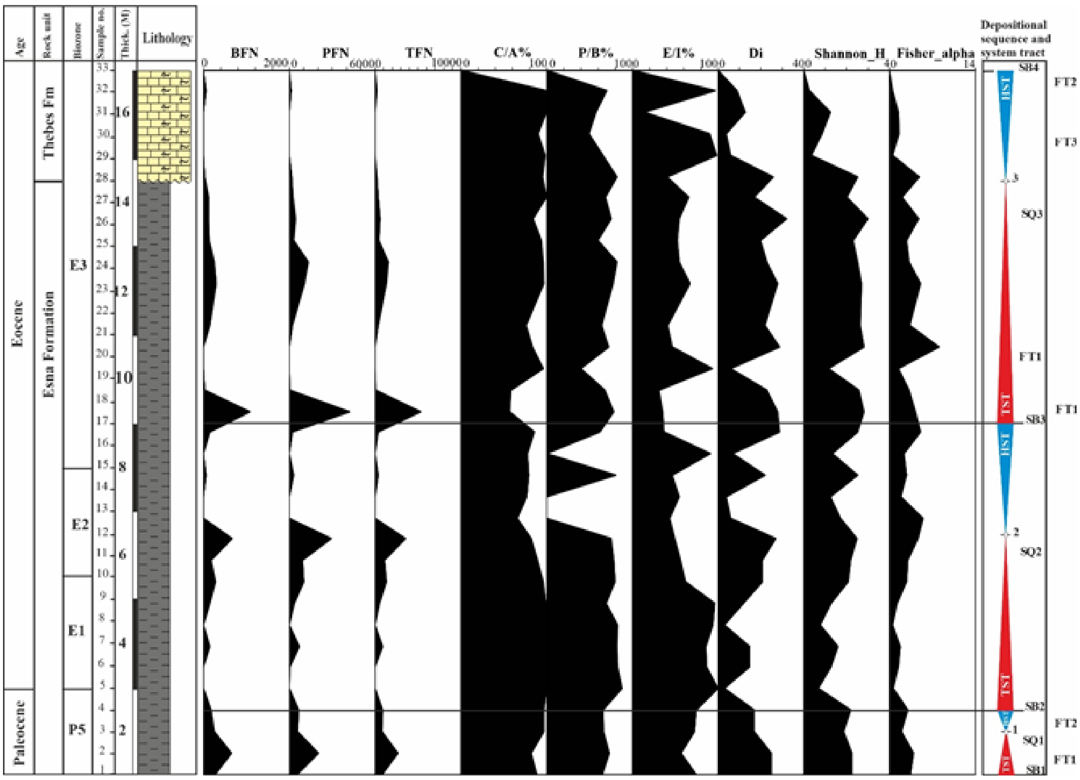


Fig. 10. Showing the foraminifera paleobathymetry of sequence stratigraphic interpretation of the Paleocene-Eocene sequence revealed in the Gebel Duwi section.

from 1.891 - 2.2. *Siphogenerinoides eleganta* and *Anomalinioides midwayensis*

indicate shallow-up features in fauna and facies which are characteristic of HST.

Depositional sequence 2 (SQ2(

The base of SQ2 was distinguished by Paleocene/ Lowermost Eocene in Fig. 10 SB2 lies below P/E boundary. It is characterized by an anoxic event, that was placed at the *Acarinina sibaiyaensis* Zone occurs at the base of the Dababiya Quarry bed, and is known as Paleocene/ Eocene Thermal Maximum (PETM). The SB1 synchronizes with a worldwide sea level fall that occurred with the bottom of the P5 Zone in the Paleocene/Eocene cyclic chart (Haq *et al*., 1988). A relatively age equivalent sea level drop is described at the central-east Sinai by (Lüning et al., 1998) and at the Galala plateaus by (Kuss *et al*., 2000). The correlation of the sequence boundary has occurred by the base of Subzone P6b (now E4 Zone, Berggren and Pearson, 2005) in the global eustatic sea level curves of (Haq *et al*., 1988).

Transgressive systems tract (TST2):

At the P5/E1 zonal boundary, the base of the Eocene is distinguished by a well-known transgression that is documented by a significant lithological change in which the clay below is replaced by calcareous clay and clayey marl, where the $CaCO_3$ and 13C increase culminates in the lowest portion of Thanetian sequence. The changes in the diversity, type and frequency of foraminifera are accompanied by an increase in TFN and P/B% (Fig. 10, table 1). This transgressive phase is characterized in the Gebel Duwi section (samples 5-12; E1 and E2 Zones) by a P/B% of up to 88.8% and TFN ranging from 0.86 to 3625 s/g, where BFN ranging from 0.14 to 675.84 s/g, PFN ranging between 0.72 to 2949.12 s/g. It is associated with the cluster "A" assemblages that are dominated by E/I% reach a maximum of 100%, and C/A% reaches a maximum of 100% reflecting the middle to outer shelf environment. The TST is distinguished between low and medium diverse fauna with species richness of 3-27 species/sample; the Shannon index is ~ 0.7-2.5 and Fisher's is ~ 0.8 to 6.8.

The MFS2 is positioned between the vertical facies foraminiferal wackestone (FT1) and the *Bulimina farafraensis* assemblages with the highest relative ratio in the E2 Zone (sample 12).

Highstand systems tract (HST2):

At the upper section of Esna Shale Formation, the shallowing upwards trend within the lower part of the E1 zone. In the top part of the Esna Shale Formation, the second negative excursion is connected to a second sea level decline. In the deeper water, benthic foraminifera disappear or appear infrequently (eg. *Gavelinella rubiginosus* and *Angulogavelinella avnimelechi*) and increase the dominance of the cluster "A" assemblages, a decline in P/B%, TFN, a highly oxidized reworked foraminiferal fauna, and modifications in the frequency, type, and diversity of foraminifera all point to a shallowing tendency (Fig. 10, table 1).

The HST in Gebel Duwi (samples 13-16; E2 and E3 Zones) is characterized by a P/B% in samples 13-14, 16 drops (0) because very rare planktonic and reaches a maximum of 81.4% in sample 15 and TFN ranging from 0.38 to 381.44 s/g, where BFN ranging from 0.18 to 64.64 s/g, PFN ranging between 0.18 to 316.8 s/g (Fig. 10, table 1). It is associated with the cluster "A" assemblages that are dominated by E/I% reaching a maximum of 91.3%, C/A% reaching a maximum of 79.7% reflecting middle to outer shelf. The HST is distinguished between low and medium diverse fauna with Fisher's ranges between 2.8 and 7.9, the species richness of about 4-22 species/sample, and the Shannon index ranges from 1.3 to 2.5.

Depositional sequence 3 (SQ3)

Third depositional sequence SQ3 exists in the E3 zone (Fig. 10). It is bordered from the base by SB3, and exists among the lithological transition from shale to limestone.

Transgressive systems tract (TST3)

The TST in Gebel Duwi (Samples 17-32; E3 Zone) is characterized by the P/B% with a maximum of 82.6%, and TFN ranging between 0.3 and 5335 s/g, where BFN ranging between 0.22 and 1095.68 s/g, PFN ranging between 0.08 to 4239.36 s/g (Fig. 10, table 4). It is associated with the cluster "A, B and C" assemblages that are dominated by E/I% ranging from 14.6 to 97.1%, and C/A% reaches a maximum of 100% reflecting middle to outer shelf. The TST is distinguished between low and high diverse fauna with Fisher's ranges between 0.8 and 7.4, the species richness of about 4- 32 species per sample, and the Shannon index ranges from 0.2 - 2.9.

The MFS3 is placed within the E3 Zone between the vertical facies foraminiferal wackestone (FT1) and Bioclastic echinodermal ostracodal Nummulites packestone microfacies)FT3) (sample ,(28 existing among lithological alteration from shale to limestone.

Highstand systems tract (HST3):

It attains about 0.5 m thick at the Gebel Duwi section (sample 33, Fig. 10). This system tract is marked by the absence of benthic and planktonic foraminifera. The absence of planktonic forms suggests a drop in the relative sea level which indicates on regressive phase. This system tract is suggested to be deposited in a littoral environment with very few oscillations to a shallow inner neritic environment (Fig. 10, Table 1). HST consists mainly of barren shale.

This point to the being indicative of low conditions of oxygen. HST of Depositional sequence SQ3 deposited on shallower slope environments. Larger foraminifera are limited to the comparatively shallow well lighted sea bottom, and if they aren't transported, their existence usually indicates of depths <30 m (Hallock, 1986). Bioclastic echinodermal ostracodal nummulites packstone microfacies are mainly composed of Nummulitids. Towards the top portion of this system tract, the diversity of skeletal components gradually decreases. By retrograding the Thebes Formation's shallower marine limestone, the upper sequence boundary can be clearly and simply identified.

Conclusion

The foraminiferal content of the Late Paleocene-Early Eocene transition at the Gebel Duwi section, Quseir area, Red Sea, Egypt was examined to estimate the dominant paleoecological conditions. Four planktonic foraminiferal zones have been identified. These are the P5, E1, E2 and E3 zones of the Late Paleocene and Early Eocene ages, respectively. P/E boundary is recorded within the lower part of the Esna Formation. Depending on the R-mode cluster analyses, there are three main clusters (A, B, and C), of the benthic foraminiferal assemblages that can be distinguished and point to three benthic foraminiferal assemblages reflecting depositional paleoenvironment ranging from shallow inner neritic to upper bathyal environments.

During the Late Paleocene, a paleoenvironmental transition from inner neritic to upper bathyal environments occurred, with moderate organic matter influx and well oxygenated conditions related to the rise of sea level, as evidenced with high values of P/B%, TFN, C/A%, E/I%, Di, and Fisher's. The uppermost Eocene is characterized by high moderate organic matter and/or low oxygen input into inner neritic–upper bathyal paleoecological conditions, as well as a modest rise in the sea level, as deduced by moderate to high P/B%, TFN, C/A%, E/I%, Di, and Fisher's values.

Three transgressive-regressive sequences (SQ1, SQ2, and SQ3) bounded by four sequence boundaries (SB1, SB2, SB3, and SB4), have been recognized in the Late Paleocene–Early Eocene succession. These depositional sequences are recognized and divided into their systems tracts according to the sea level variations and interpreted to the paleobathymetric analysis of the various foraminiferal factors (abundance, diversity, R mode cluster analyses, abundance, and P/B%), furthermore microfacies examination and fieldwork. SQ1 covered the interval of the P5 zone. SQ2 covered the interval of the Paleocene/Lowermost Eocene sequence boundary (SB2) and was bordered at the base by the SB2 at the P/E. SQ3 covers the interval of the E3 zone and is occupying the top part of the studied section.

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الأعماق القديمة والبيئات الترسيبية لفورامينفرا الباليوسين المتأخر-الأيوسين المبكر والتتابع الرسوبي في جبل الضوي، البحر الأحمر، مصر

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تعتمد الدراسة الحالية على التحليلات الكمية والنوعية للفوراميني‍فيرا الجيرية في الفترة الزمنية من العصر الباليوسين المتأخر إلى الأيوسين المبكر في جبل الضوى، منطقة القصير، البحر الأحمر، مصر. تم دراسة وحدتين صخريتين في تتابع العصر الباليوسين المتأخر - الأيوسين المبكر: مكون الإسنا في الأسفل ومكون الطيبة في الأعلى. تم التعرف على أربعة نطاقات بيوستراتيجرافى للبلانكتون فورامنيفرا؛ نطاق العصر الباليوسين المتأخر P5 ونطاق الأيوسين المبكر E1 – E3. عوامل الفورامنيفرا التي تتحكم في البيئة مثل العدد الكلي للفورامنيفرا (TFN)، عدد الفورامنيفرا القاعية (BFN)، عدد الفورامنيفرا الهائمة (PFN)، نسبة البلانكتون/ البنثك (B / P٪)، نسبة الإبيفونا/ الأنيفونا٪ (I / E%)، نسبة الجدار الجيرى/ الجدار الرملى٪ (A / C%)، والوفرة، والتنوع، ومؤشر الأكسجين للبنثك فورامنيفرا (BFOI) بالإضافة إلى العمل الميداني والميكروفيشز لتقسيم التتابع المدروس إلى ثلاثة متواليات من الدرجة الثالثة من الترسيب يحدها أربعة حدود تسلسلية. تتأثر الخصائص المورفولوجية وتجمعات الفورامنيفرا القاعية بشدة بالتغيرات في تركيزات الأكسجين عند السطح البيني لمياه الرواسب؛ تنعكس هذه الاختلافات في سمك الجدار وحجم الأصناف المسجلة. تم قياس هذه الاختلافات التصنيفية والمورفولوجية كمؤشر للأكسجين المذاب. تم تصنيف ثلاثة أنواع من المنخربات القاعية إلى مؤشرات dysoxic وsuboxic وoxic. ثم يتم استخدام هذه المؤشرات لتفسيرات البيئة القديمة. تراوحت البيئات من بيئة ضحلة داخلية إلى بيئة أعلى عمقاً bathyal upper to neritic inner (عمق ١٥٠-٣٠٠ متر) أثناء ترسيب تتابع الباليوسين المتأخر - الأيوسين المبكر.