TÜBİTAK

Turkish Journal of Earth Sciences

http://journals.tubitak.gov.tr/earth/

Research Article

Turkish J Earth Sci
(2015) 24: 585-606

doi:10.3906/yer-1411-25

Calcareous nannofossils of the Paleocene–Eocene transition in four sections from Egypt

Mahmoud FARIS[1], Sherif FAROUK[2,*]
[1]Geology Department, Faculty of Science, Tanta University, Egypt
[2]Egyptian Petroleum Research Institute, Nasr City, Egypt

Received: 26.11.2014 • **Accepted/Published Online:** 16.09.2015 • **Printed:** 30.11.2015

Abstract: A detailed analysis of calcareous nannofossil assemblages was carried out across the Paleocene–Eocene transition in four outcrops in Egypt (the Gebel Matulla, Markha, El-Quss Abu Said, and Gebel Duwi sections) that span the *Discoaster multiradiatus* (NP9) to *Discoaster binodosus* (NP11) zones. The Paleocene–Eocene (P/E) boundary is placed in the lower part of the Esna Shale Formation based on the LOs of the Calcareous Nannofossil Excursion Taxa (CNET or RD) that define the base of NP9b. The studied sections are considered complete and document the Paleocene–Eocene Thermal Maximum (PETM). The occurrences of long-armed and asymmetrical discoasters (e.g., *D. araneus*, *D. anartios*) and rhomboasters (e.g., *R. intermedia*, *R. bitrifidia*, and *R. spineus*) are characteristic of the PETM interval. A sharp decrease in the diversification of *Fasciculithus* is noted at the onset of PETM. The abundance of *Zygrhablithus bijugatus* increases and corresponds with the dramatic decline in the oligotrophic *Fasciculithus* above the Paleocene/Eocene boundary and appears to be a significant global event. The *Discoaster*, *Fasciculithus*, and *Rhomboaster* species reflect relatively warm and, probably, oligotrophic surface waters. A minor hiatus in most of the studied sections near the upper part of Zone NP10 has been recorded in many parts of the world and reflects a global sea level drop.

Key words: Paleocene/Eocene, calcareous nannofossils, biostratigraphy, Egypt

1. Introduction

Gradual global warming during the late Paleocene through early Eocene led to the warmest climatic conditions of the last 90 million years. This includes one of the most abrupt and significant global warming events in the geologic record at the Paleocene/Eocene (P/E) boundary. This interval was also characterized by elevated nannoplankton evolutionary rates, with turnover higher than for any other time in the history of the group (Bown, 2005). However, relatively few shallow marine sections spanning the P/E boundary have been identified or studied for calcareous nannofossils although the Paleocene–lower Eocene successions in Egypt are marked by widely distributed, rich calcareous planktonic faunal assemblages that span the Global Stratotype Section and Point (GSSP) at the base of the Eocene in the Dababiya Quarry, Luxor, Egypt. The P/E boundary is placed at the base of the Carbon Isotope Excursion (CIE) in the Dababiya Quarry section (Aubry and Ouda, 2003). The primary goals of the present study were to 1) document a high-resolution biostratigraphic and semiquantitative analysis of the nannofossil assemblages in the study sections; 2) discuss the turnover of the calcareous nannofossil assemblages across the P/E boundary; and 3) elucidate the change in paleoclimate at the Paleocene–Eocene boundary.

2. Materials and methods

Four sections representing near continuous depositional sequences across the Paleocene/Eocene boundary were sampled in different parts of Egypt to add more information on the calcareous nannofossil evolutionary changes. One hundred and fifty-six samples were collected from four sections (Figure 1), two in Sinai (1, at Gebel Matulla [29°01′ 02′ N, 33°12′ 45′ E], and 2, at Markha [29°00′ 56′ N, 33°14′ 06′ E]), one in Farafra Oasis (3, at El-Quss Abu Said [between 27°6′ 23′ and 27°51′ 33′]), and one in the Eastern Desert (4, at Gebel Duwi [25°58′ 45′ N and 34°09′ 33′ E]). The samples were taken at close intervals (5–20 cm) near the boundary.

For calcareous nannofossils smear slides were prepared using techniques described in Bramlette and Sullivan (1961) and Hay (1964) and observed via light microscopy at a magnification of 1250×. They were identified following the taxonomic schemes of Perch-Nielsen (1985). The

* Correspondence: geo.sherif@hotmail.com

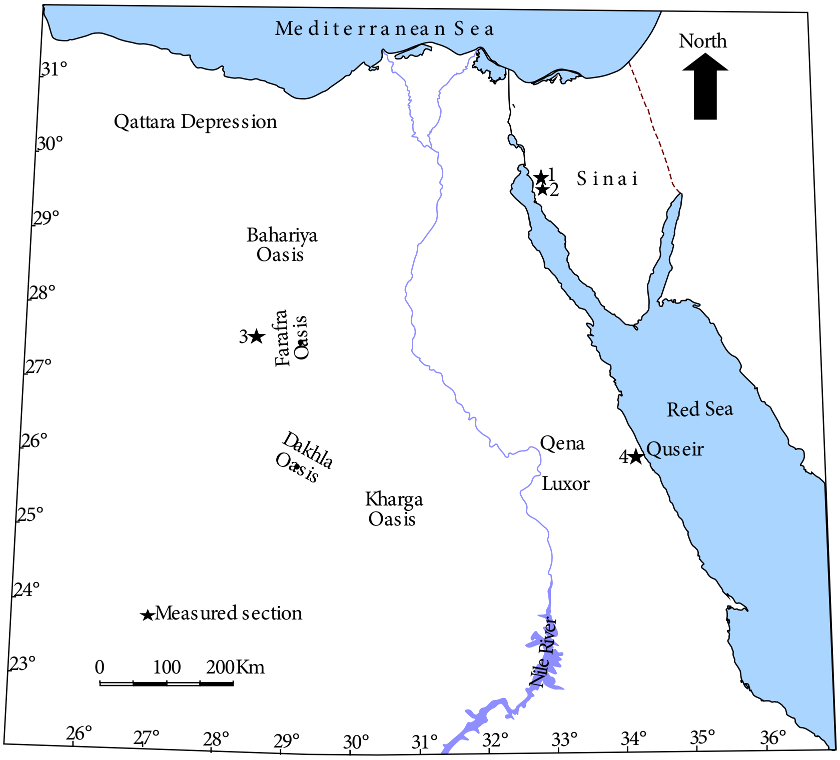


Figure 1. Location map of Egypt showing the location of the studied sections. 1: Gebel Matulla, 2: Markha, 3: El-Quss Abu Said, 4: Gebel Duwi.

primary zonation scheme followed is that of Martini (1971).

3. Lithostratigraphy of the study sections

The upper Paleocene–lower Eocene Esna Formation consists mainly of gray to greenish calcareous shales and marls. It is characterized by intercalated argillaceous limestone near the upper part. At the Gebel Matulla and Markha sections four conspicuous ledges (stringers) due to differential weathering of sandstones are recorded. The thickness of the Esna Formation at Sinai is about 20 m with an observed increase in thickness towards the Farafra Oasis (Figure 2). It conformably overlies the Tarawan Formation and underlies the Thebes Formation. The Esna Formation is subdivided into the Thanetian El Hanadi Member, the lowermost Eocene Dababiya Quarry Member, and the lower Eocene Mahmiya and Abu Had members (Aubry et al., 2007). At the P/E boundary in the four examined sections a ledge of argillaceous limestone rich in phosphate particles and coccoliths debris is equivalent to the Dababiya Quarry Member. The Dababiya Quarry Member is reduced in thickness because the lower part of the unit pinches out toward northern Egypt.

4. Results

4.1. Nannofossil preservation and abundances

Calcareous nannofossils preservation in general is moderate to good with minor to moderate etching and minor overgrowth. The assemblages are rich and well diversified throughout the study interval. Abundances were determined by counting 300–400 specimens/slide. In addition, one random traverse of the slide was scanned for rare species. The relative abundance of nannofossils was determined as follows: A (abundant) = >5 specimens per one field of view, C (common) = 1–5 specimens per one field of view, F (frequent) = one specimen per 2–5 fields of view, R (rare) = one specimen per 6–10 fields of view, VR (very rare) = one specimen per >10 fields of view, and B (barren) = no specimens. For preservation of nannofossil assemblages, the following letters are used: G (good) = little or no overgrowth and/or dissolution, M (moderate) = little or some overgrowth and/or dissolution, and P (poor) = abundant overgrowth and/or dissolution.

4.2. Nannofossil biostratigraphy

Some representative taxa are illustrated in Figures 3–5. Brief accounts of the different nannofossil biozones identified in the four study sections are given. The abbreviations used are LO = lowest occurrence and HO = highest occurrence. The nannofossil distribution charts are shown in Tables

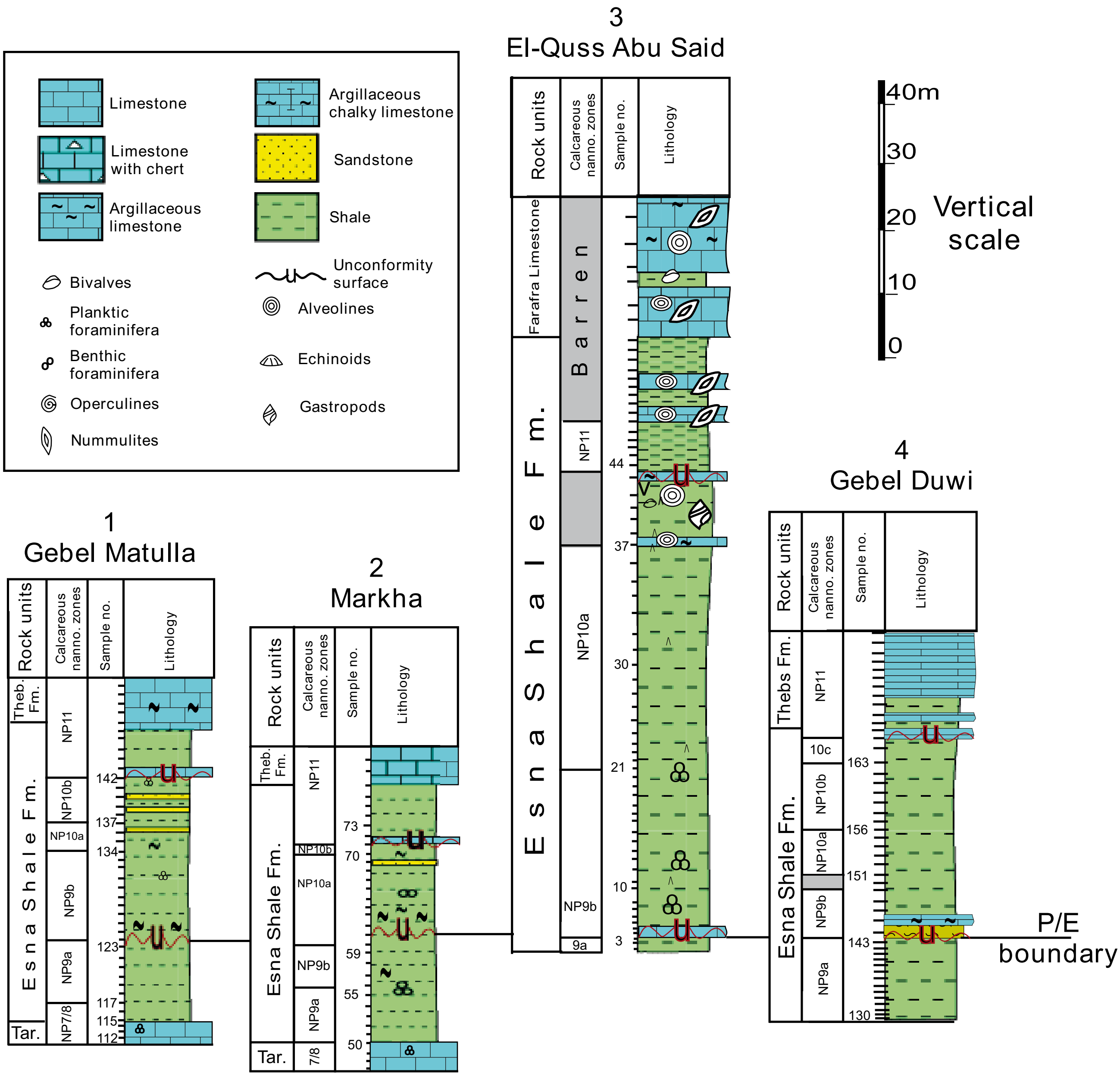


Figure 2. Lithostratigraphic correlation between the studied sections.

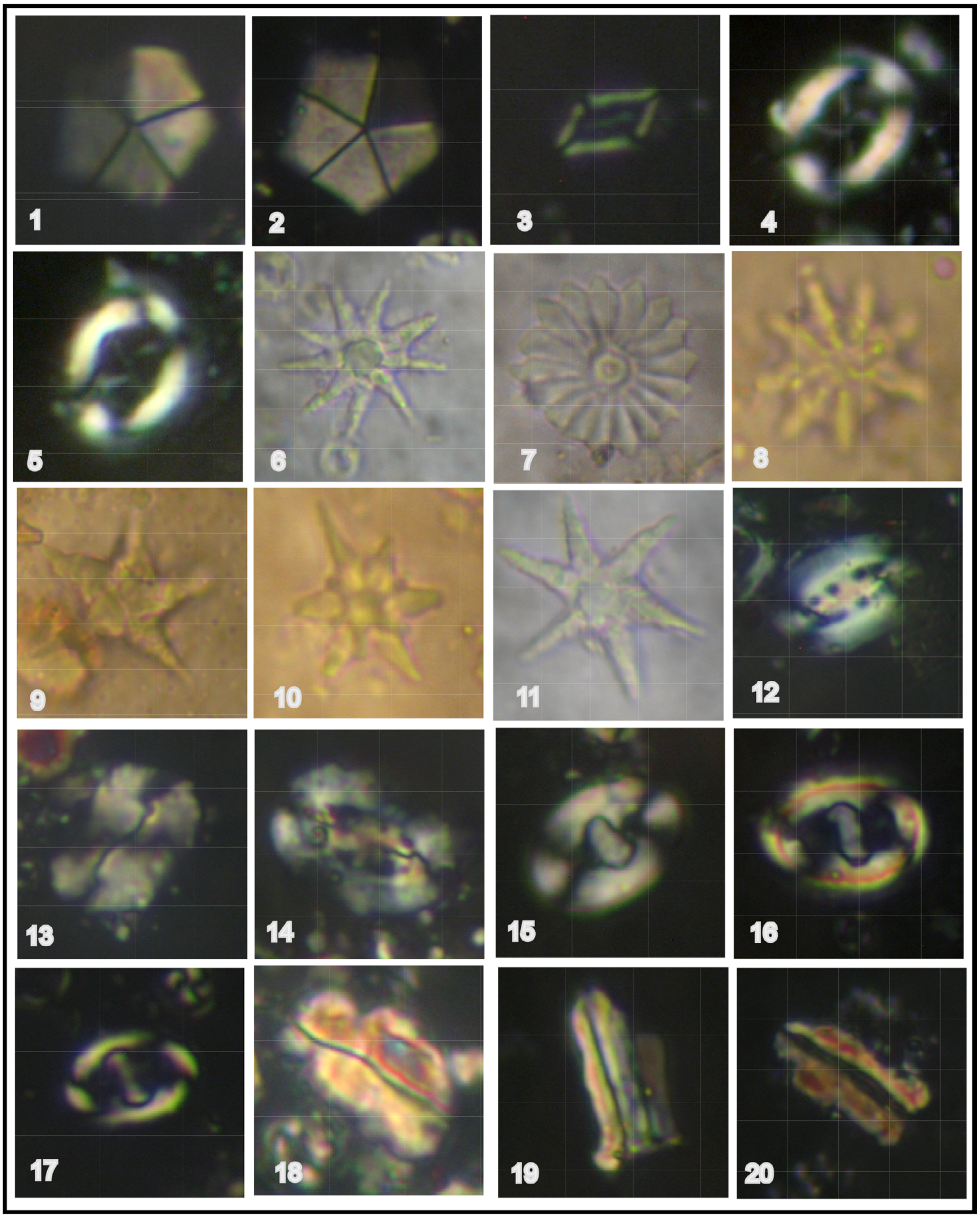
1–4, while the identified calcareous nannofossil taxa are listed in the Appendix.

4.2.1. Gebel Matulla section (Table 1)

Three nannofossil zones are recognized across the upper Paleocene–lower Eocene transition

4.2.1.1. *Discoaster multiradiatus* Zone (NP9)

The base of this zone is well defined by the LO of *Discoaster multiradiatus*, and its top is approximated here by the LO of *Tribrachiatus bramlettei*. This zone can be divided into two subzones, NP9a and NP9b, with the base of NP9b defined by the LO of *Rhomboaster intermedia* (sample 124). Other taxa, *R. spineus* and *Discoaster paelikei*, first appear at a higher level (sample 125). The LO of *Zygrhablithus bijugatus* occurs below the PETM at most sites and appears to be significantly time transgressive across latitudes and between ocean basins (Pospichal and Wise, 1990; Bralower, 2005; Agnini et al., 2007). In the present section, *Z. bijugatus* first occurs in the lower part of Subzone NP9a (sample 119). *Coccolithus bownii* occurs in considerable numbers in sample 124 (base NP9b, early Eocene). *Discoaster araneus* first appears slightly above the



10μm

Figure 3. 1–2: *Braarudosphaera bigelowii* (Gran and Braarud, 1935); 1: sample 25, El-Quss Abu Said section; 2: sample 20, El-Quss Abu Said section. 3: *Calciosolenia aperta* (Hay and Mohler, 1967); sample 1, El-Quss Abu Said section. 4–5: *Chiasmolithus solitus* (Bramlette and Sullivan, 1961); sample 155, Gebel Duwi section. 6: *Discoaster araneus* Bukry (1971); sample 128, Matulla section. 7: *Discoaster multiradiatus* Bramlette and Reidel (1954); sample 120, Gebel Matulla section. 8: *Discoaster falcatus* Bramlette and Sullivan (1961); sample 145, Duwi section. 9–10: *Discoaster mahmoudii* Perch-Nielsen (1981); 9: sample 58, Markha section, 10: sample 144, Gebel Duwi section. 11: *Discoaster paelikei* Agnini and Fornaciari (2008); sample, 128, Gebel Matulla section. 12: *Ellipsolithus distichus* (Bramlette and Sullivan, 1961); sample 134, Gebel Matulla section. 13–14: *Ellipsolithus macellus* (Bramlette and Sullivan, 1961); 13: sample 51, Markha section, 14: sample 2, El-Quss Abu Said section. 15: *Zygolithus sheldaniae* Bown, 2005, sample 130, Gebel Duwi section. 16, 17: *Zygodiscus plectopons* Bramlette and Sullivan (1961); 16: sample 130, Gebel Duwi section, 17: sample 71, Markha section. 18–20: *Zygrhablithus bijugatus* (Deflandre *in* Deflandre & Fert, 1954); 18: sample 68, Markha section, 19: sample 126, Gebel Matulla section, 20: sample 119 Gebel Matulla section.

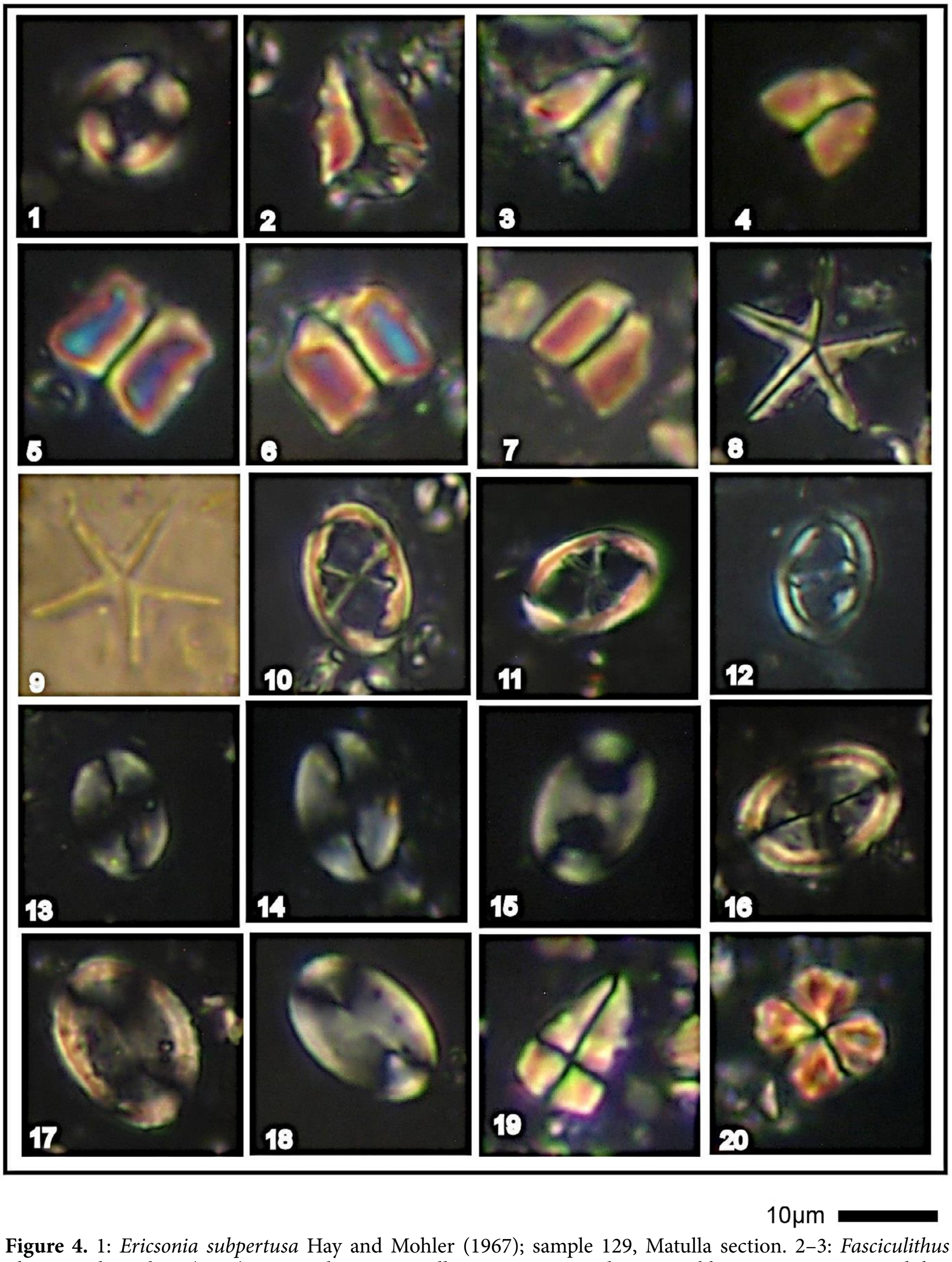


Figure 4. 1: *Ericsonia subpertusa* Hay and Mohler (1967); sample 129, Matulla section. 2–3: *Fasciculithus alanii* Perch-Nielsen (1971); 2: sample 121, Matulla section, 3: sample 55, Markha section. 4: *Fasciculithus clinatus* Bukry (1971); sample 138, Gebel Duwi section. 5: *Fasciculithus involutus* Bramlette & Sullivan (1961); sample 5, El-Quss Abu Said section. 6–7: *Fasciculithus tympaniformis* Hay and Mohler in Hay et al. (1967); 6: sample 130, Gebel Duwi section, 7: sample 53, Markha section. 8–9: *Micrantholithus vesper* Deflandre (1950); 8: sample 156, Gebel Duwi section, 9: sample 21, El- Quss Abu Said section. 10–11: *Neochiastozygus junctus* (Bramlette and Sullivan, 1961), 10: sample 9, El-Quss Abu Said section, 11: sample 160, Gebel Duwi section. 12: *Placozygus sigmoides* (Bramlette and Sullivan, 1961), sample 63, Markha section. 13–14: *Pontosphaera plana* (Bramlette & Sullivan, 1961), 13: sample 58, Markha section, 14: sample 145, Gebel Duwi section. 15: *Pontosphaera exilis* (Bramlette and Sullivan, 1961), sample 12, El-Quss Abu Said section. 16–18: *Pontosphaera versa* (Bramlette and Sullivan, 1961), 16: sample 135, Matulla section, 17: sample 165, Gebel Duwi section, 18: sample 14, El-Quss Abu Said section. 19: *Sphenolithus radians* Deflandre in Grasse; sample 148, Matulla section. 20: *Sphenolithus primus* Perch-Nielsen (1971); sample 56, Markha section.

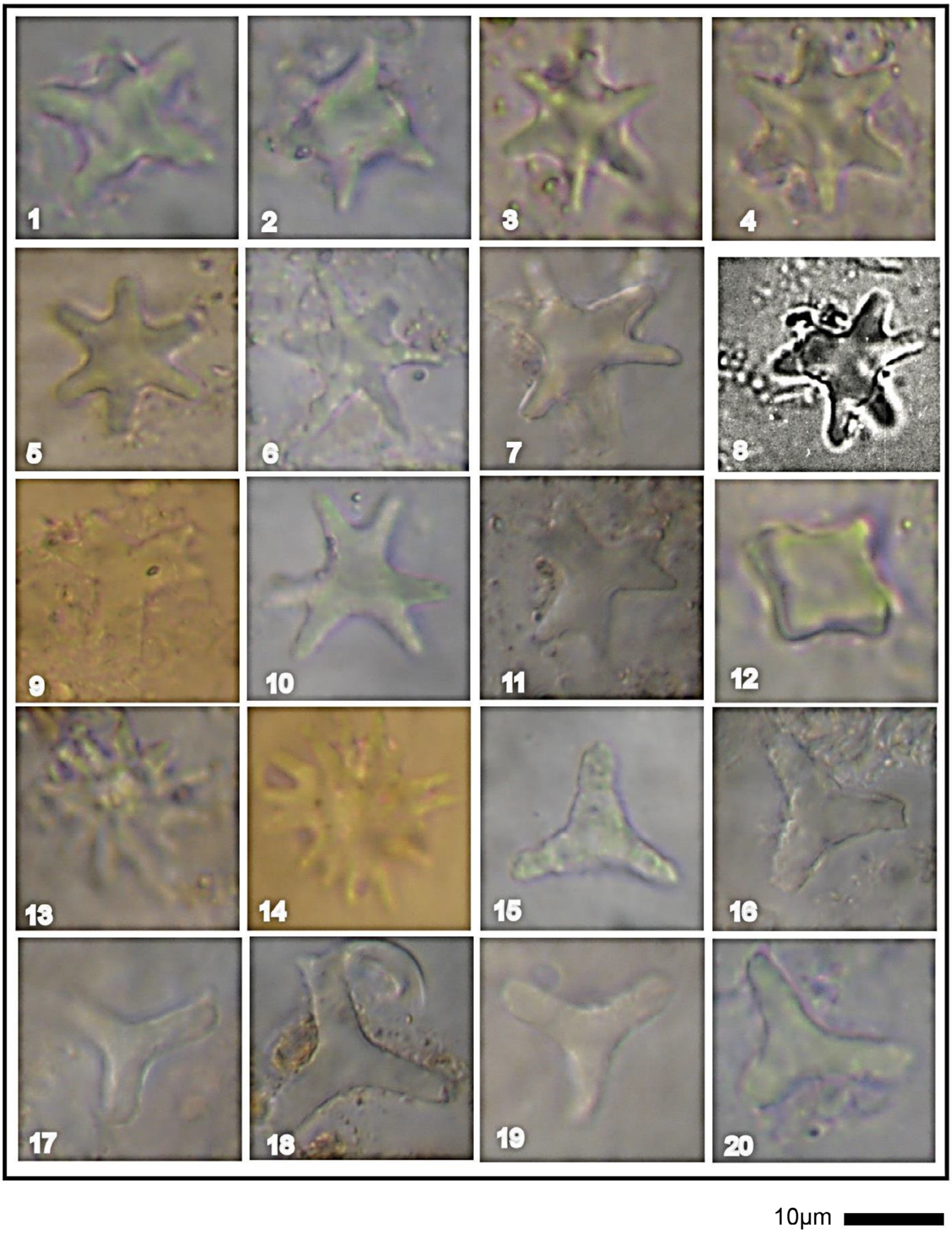


Figure 5. 1–2: *Rhomboaster bitrifida* Romein (1979); 1: sample 16, El-Quss Abu Said section, 2: sample 144, Gebel Duwi section. 3–6: *Tribrachiatus bramlettei* (Bronnimann and Stradner, 1960); 3: sample 59, Markha section, 4: sample 135, Matulla section, 5: sample 22, El-Quss Abu Said section, 6: sample 152, Gebel Duwi section. 7–8: *Tribrachiatus contortus* (Stradner, 1958); 7: sample 164, Duwi section, 8: sample 165, Duwi section. 9–11: *Tribrachiatus digitalis* Aubry (1996), 9: sample 138, Matulla section, 10; sample 162, Gebel Duwi section, 11: sample 71, Markha section. 12: *Rhomboaster cuspis* Bramlette & Sullivan (1961); sample 18, El-Quss Abu Said section. 13–14: *Discoaster anartios* Bybell & Self-Trail (1995); 13: sample 3, El-Quss Abu Said section, 14: sample 128, Matulla section. 15–20: *Tribrachiatus orthostylus* Sharmrai (1963); 15: sample 166, Duwi section, 16: sample 45, El-Quss Abu Said section, 17: sample 73, Markha section, 18: sample 148, Matulla section, 19: sample 170, Gebel Duwi section, 20: sample 143, Matulla section.

Table 1. Stratigraphic distribution of the identified calcareous nannofossil species, Gebel Matulla section.

Late Paleocene						**Early Eocene**											**Age**
Esna Shale																	**Rock unit**
118	119	120	121	122	123	124	125	126	127	128	129	130	131	132	133	134	**Sample no.**
F	F	F	F	VR	R	F	F	R	F	C	A	F	A	VR	C	C	**Abundance**
G	**M**	**M**	**M**	**M**	**M**	**M**	**M**	**M**	**M**	**M**	**M**	**M**	**G**	**M**	**M**	**G**	**Preservation**
NP9																	**Nannofossil zones**
NP9a						**NP9b**											**Subzones**
VR	VR	VR	VR	VR		A	F	R	VR	R	R	VR	R	VR	R	VR	***Coccolithus pelagicus***
R	R	VR		VR	VR			R	VR			R			R	R	***Ericsonia cava***
R	R	VR	R	VR	R		R	R	VR	R	F	R	R	VR	F	R	***Ericsonia subpertusa***
VR	R	VR															***Ericsonia universa***
VR	R	VR	VR	VR	VR												***Ericsonia robusta***
R	F	F	R	R	R			R	VR	R	R	R	R		R	R	***Sphenolithus primus***
R	R	R	F	VR	R	VR	VR	VR		VR							***Fasciculithus involutus ****
R	R	R	F	VR	R	VR	VR	VR									***Fasciculithus tympaniformis***
VR									F	F	F	F	F		F	F	***Neochiastozygus junctus***
VR		VR	R		VR												***Fasciculithus clinatus***
VR		R	VR	VR	VR												***Teweius pertusus***
VR	VR				VR					VR							***Lithoptychius bitectus ****
VR		R	R		VR		VR										***Toweius eminens***
VR				VR	VR	VR				R	VR	R	VR			VR	***Discoaster multiradiatus***
	VR																***Discoaster mohleri****
	VR	VR	VR		VR											R	***Chiasmolithus consuetus***
	VR	VR	R	VR	R												***Fasciculithus richardii***
	VR	VR	R														***Fasciculithus schaubii***
	VR	VR			VR	F	F	F	F	F		F	F		R	R	***Zygrhablithus bijugatus***
	VR	VR	R		VR												***Fasciculithus alanii***
		VR					VR									VR	***Neochiastozygus chiastus***
		R	R														***Toweius tovae***
			VR		VR												***Chiasmolithus bidens***
			VR														***Fasciculithus thomsii***
			R		VR	VR				R							***Discoaster lenticularis***
					VR												***Discoaster splendidus***
						R	R	R		VR						R	***Rhomboaster intermedia****
						C	F								VR		***Coccolithus bownii***
						F	F			R							***Discoaster araneus****
						VR	VR			VR					VR		***Discoaster falcatus***
						F	F	F		VR		VR				VR	***Rhomboaster bitrifida****
							VR										***Discoaster backmanii***
							R	R									***Rhomboaster spineus****
							R	R		VR							***Discoaste paelikei***
								R									***Rhomboaster calcitrapa****
										R							***Discoaster anartios****
											VR	VR					***Discoaster mahmoudii****
												VR	VR		R	R	***Pontosphaera plana***
															R	R	***Campylosphaera eodela****
															VR	R	***Discoaster mediostus***
																VR	***Ellipsolithus distichus***
																VR	***Ellipsolithus macellus ****
																VR	***Pontosphaera exilis***
																VR	***Chiasmolithus eograndis***

Table 1. (Continued).

Esna Shale																			**Rock unit**
135	136	137	138	139	140	141	142	143	144	145	146	147	148	149	150	151	152	153	**Sample no.**
C	A	R	F	A	A	A	A	F	F	C	C	F	C	F	F	F	R	F	**Abundance**
G	G	M	M	G	G	G	G	M	M	M	M	M	G	M	M	M	M	M	**Preservation**
NP10								**NP11**											**Nannofossil zones**
NP10a			**NP10b**																**Subzones**
R	R	R	VR	C	C	F	R	R	F	VR	VR	R		VR	R	R	VR	R	***Coccolithus pelagicus***
R	R	R	VR			F	R	R	R	VR	R	R			R	R	VR	F	***Ericsonia cava***
R	R					F	R	R	F	R	R	R		F		F	VR	R	***Ericsonia subpertusa***
VR	VR	VR	VR	VR	VR	R	VR	VR	VR		R	R	R						***Ellipsolithus macellus ****
F	F	VR	VR	F	R	R	VR										R		***Neochiastozygus junctus***
R	R	VR	VR	R	R	R	R	R	R	VR	F	F	F	F	F	R	VR	R	***Sphenolithus primus ****
VR			VR	VR	VR	VR				VR	VR							R	***Discoaster multiradiatus****
R	R			R	R	R		R			VR								***Discoaster mediosus***
R	R			R	R	VR													***Rhomboaster bitrifida****
VR	VR		VR		VR	VR		VR	VR	VR									***Campylosphaera eodela****
R	R	R	R	R					VR	VR	R	R	R	VR				R	***Zygrhablithus bijugatus***
VR				VR															***Discoaster falcatus***
VR	R		VR	R	R														***Rhomboaster intermedia****
VR																			***Discoaster mahmoudii****
VR	VR																		***Neochiastozygus chiastus***
VR																			***Zygodiscus plectopons***
VR																			***Pontosphaera versa***
VR	VR			R	VR														***Tribrachiatus bramlettei *(x)***
VR																			***Fasciculithus involutus ****
	VR			VR															***Discoaster paelikei***
	VR		R	R	VR	R	VR				VR		VR						***Discoaster binodosus***
	VR			VR			VR												***Tribrachiatus bramlettei (+)***
	VR	VR			VR								VR						***Discoaster diastypus****
			R	VR	VR	R	R												***Tribrachiatus digitalis ****
				F		R		VR											***Coccolithus bownii***
				VR	VR	VR	VR				VR								***Pontosphaera exilis***
						VR					VR		VR						***Discoaster barbadensis***
								R		R	R	VR	F						***Tribrachiatus orthostylus****
										R	R	VR	VR		VR			R	***Sphenolithus radians****
										VR	VR							R	***Sphenolithus edltus***
										R									***Discoaster deflandrei***
										R	VR	VR							***Lophodolithus nascens***
											VR		VR						***Chiasmolithus consuetus***
											VR			VR		VR		R	***Pontosphaera plana***
													VR	VR		VR		R	***Coronocyclus bramlettei***
														VR					***Blackites solus***
														VR					***Teweius pertusus***
														VR			VR	R	***Toweius eminens***

(x)= Short arms; (+)= Long arms

NP9a/ NP9b zonal boundary in the studied section, as well as in west central Sinai (Faris and Salem, 2007).

Fasciculithus alanii occurs directly below the P/E boundary, and is restricted to NP9a (Dupuis et al., 2003). This highest occurrence close to the CIE was also encountered in other Egyptian sections such as Gebel Aweina, Gebel Duwi, and Gebel Abu Had (Aubry, 1998; von Salis et al., 1998), in the Contessa section in Italy (Galeotti et al., 2010), and in the Zumaya and Alamedilla sections in Spain (Monechi et al., 2000a, 2000b). The HO of *Fasciculithus alanii* coincides with the NP9a/NP9b subzonal boundary in the Gebel Matulla section. However, *Fasciculithus alanii* is recorded slightly above the NP9a/ NP9b boundary in Gebel Mishiti, east central Sinai (Faris and Abu Shama, 2007), and therefore seems to represent a reliable event for the top of the Paleocene (NP9a). The last appearance of *F. clinatus* occurs in Subzone NP9a below the P/E boundary. The LO of *Discoaster mahmoudii* occurs within Subzone NP9b with its HO within Subzone NP9b (sample 130).

4.2.1.2. *Tribrachiatus contortus* Zone (NP10)

This zone includes the biostratigraphic interval from the LO of *Tribrachiatus bramlettei* to HO of *Tribrachiatus contortus*. Aubry (1995) subdivided Zone NP10 into four subzones (NP10a, b, c, d), based on the *Tribrachiatus* lineage. NP10a is defined by the lowest occurrence of *T. bramlettei*, NP10b by the total range of *T. digitalis*, and NP10c by the absence of *T. digitalis* and *T. contortus*, and *T. bramlettei* and *T. contortus* are the marker species for NP10d.

Tantawy (1998), on the other hand, subdivided Zone NP10 into three subzones: NP10a from the LO of *T. bramelttei* to the LO of *T. digitalis*, NP10b from the LO of *T. digitalis* to the LO of *T. contortus*, and NP10c for the total range of *T. contortus*. In the present study, we followed Tantawy's (1998) subdivision but only two subzones, NP10a and NP10b, were identified. The base of Subzone NP10a is delineated by the LO of *T. bramelttei* (short arms) in sample 135. The LO of *T. digitalis* was used to approximate the base of Subzone NP10b in sample 138. *Tribrachiatus bramelttei* (long arms) was recorded within subzones NP10a and NP10b. *Discoaster diastypus* is first recorded within of Subzone NP10b (sample 136). A considerable hiatus was detected at the NP10b/NP11 boundary as a result of the absence of Subzone NP10c in the Gebel Matulla section.

In the Gebel Matulla section *D. binodosus* first appears in the lowermost part of NP10a. This taxon first occurs at the base of Zone NP10 in some other sections in Egypt as noted by Faris (1993) at the Gurnah section, Nile Valley; Taramsa, west of Qena; El Serai, east of Qena; and at Gebel Duwi, Quseir area. This author used the LO of this species to delineate the NP9/ NP10 zonal boundary at Gebel El Ain and Gebel El Falig in northeast Sinai. In Bolle et al. (2000) and Monechi et al. (2000a, 2000b), *Discoaster binodosus* appears in the middle of Zone NP10.

4.2.1.3. *Discoaster binodosus* Zone (NP11)

Zone NP11 includes the biostratigraphic interval from the HO of *T. contortus* to the LO of *D. lodoensis*. The LO of *T. orthostylus*, however, is used here to approximate the base of Zone NP11 due to the complete absence of *Tribrachiatus contortus*, whose HO is used to define the top of Zone NP10. Several additional bioevents have been identified within Zone NP11, namely the LOs of *Sphenolithus radians*, *S. editus*, *D. deflandrei*, and *Lopdolithus nascens*.

4.2.1.4. Paleocene/Eocene boundary

In the Gebel Matulla section, the lowest occurrences of *Discoaster araneus*, *Rhomboaster bitrifida*, and *R. intermedia* were used to delineate the Paleocene/Eocene boundary (NP9a/NP9b). Moreover, *D. falcatus* first appears at the base of NP9b. At Dababiya the NP9a/NP9b transition coincides with the PETM dissolution interval that is followed by the first appearances of *Rhomboaster cuspis* and *R. bitrifida* plus *D. araneus* and *D. anartios*, whereas *Campylosphaera eodella* appears earlier in NP9a and *R. spineus* later in NP9b (Khozyem et al., 2014). The dominant nannofossil species at the Paleocene–Eocene transition in our sections are shown in Figure 6.

4.2.2. Markha section (Table 2)

4.2.2.1. *Discoaster multiradiatus* Zone (NP9)

This zone is defined as the interval from the LO of *D. multiradiatus* to the LO of *Tribrachiatus bramlettei*. Aubry et al. (2000) delineated the NP9a/b boundary by the simultaneous lowest occurrences of several taxa, i.e. *Rhomboaster* species, *Discoaster araneus*. The NP9a/ NP9b subzonal boundary is delineated here at the level of the LO of Calcareous Nannofossil Excursion Taxa (CNET), i.e. *C. bownii*, *R. bitrifida*, and *R. intermedia*. The taxon *D. araneus* exhibits great morphologic variability within NP9b in this section. Aubry and Salem (2012) subdivided Zone NP9 into three subzones (NP9a, NP9b, NP9c) on the basis of the sequential HO of *F. alanii* and LO of *P. minuta*, respectively. The first specimens of *Z. bijugatus* have been detected within Subzone NP9a (late Paleocene). The HO of *Fasciculithus alanii* coincides with the NP9a/NP9b subzonal boundary in this section, and its HO biohorizon can be considered a reliable bioevent. *Discoaster mahmoudii* has its lowest occurrence (LO) at about 3.5 m above the P/E boundary (within NP9b), a level that correlates with the top of the CIE and is located in the lower third of NP9b (Dupuis et al., 2003). Here in the Markha section *Discoaster mahmoudii* has its LO within the upper NP9b and its HO within NP10a (Table 2).

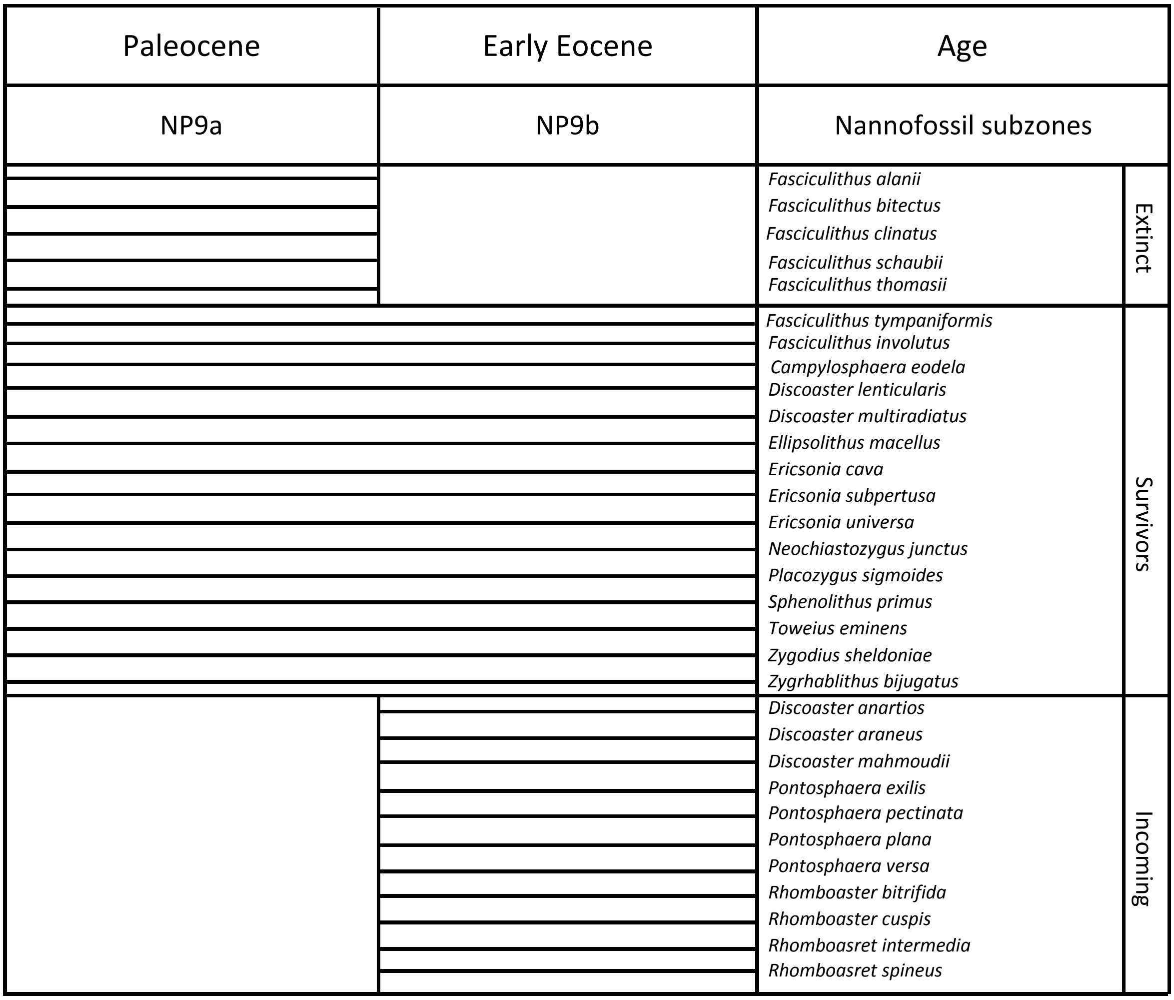


Figure 6. The dominant calcareous nannofossil species at the Paleocene–Eocene transition in the studied sections.

4.2.2.2. *Tribrachiatus contortus* Zone (NP10)

In the present section, this zone includes the biostratigraphic interval from the entry of *T. bramlettei* to the LO of *T. orthostylus*. Two subzones were identified, namely NP10a and NP10b. NP10a is defined as before as the interval from the LO of *T. bramltteii* to the LO of *T. digitalis* (samples 59 to 70). The NP10b occupies the interval from the LO of *T. digitalis* to the LO of *T. contortus*, and it is represented by a very short interval (only sample 71). The LO of *T. bramlettei* (short arms) first occurs at the base of NP10a (sample 59) and just below the first appearance of *T. bramlettei* (long arms) recorded in sample 66. Bolle et al. (2000) recorded the HOs of *Fasciculithus tympaniformis* and *F. involutus* in the lower part of the NP10 Zone. The HOs of *F. alanii, F. clinatus* and *F. schaubii* occur at the P/E boundary between the NP9a/NP9b zonal boundary. The LO of *Discoaster mahmoudii* occurs in the upper Subzone NP9b and its HO in Subzone NP10a (sample 60). The pontosphaerid group was recorded in Subzone NP9b (early Eocene). The first representative of *Campylosphaera* (*C. eodela*) occurs within Subzone NP9a (late Paleocene).

4.2.2.3. *Discoaster binodosus* Zone (NP11)

The base of NP11 is traditionally delineated by the HO of *Tribrachiatus contortus* and its top by the LO of *Discoaster lodoensis.* In the Markha section, the base of Zone NP11 is defined by the LO of *Tribrachiatus orthostylus* due to the absence of *T. contortus* whose HO traditionally defines the base of Zone NP11. The top of NP11 is not defined precisely owing to the absence of *Discoaster lodoensis.* One stratigraphically important bioevent identified in the upper part of the Esna Formation (Zone NP11) is the LO of *Sphenolithus radians.*

4.2.2.3. Paleocene/Eocene boundary

The LOs of the Calcareous Nannofossil Excursion Taxa (CNET), *Coccolithus bownii*, *R. bitrifida*, and *R. intermedia* are used to approximate the NP9a/NP9b (P/E boundary). *Fasciculithus alanii* is restricted to NP9a (Dupuis et al.,

Table 2. Stratigraphic distribution of the identified calcareous nannofossil species, Markha section.

Late Paleocene					**E. Eocene**						**Age**
Esna Shale											**Rock unit**
51	52	53	54	55	56	57	58	59	60	61	**Sample no.**
C	C	C	_	A	A	B	F	F	C	C	**Abundance**
	M	M	_	M	M	_	M	M	M	M	**Preservation**
NP9a					**NP9b**			**NP10a**			**Nannofossil zones**
F	R	R		R	R			R	VR	R	***Sphenolithus primus***
VR	VR				F						***Ericsonia universa***
R	R	F		F	R		F	F	F	F	***Ericsonia cava***
VR	R	R		R	VR			VR	VR	VR	***Fasciculithus involutus **
VR	R	R		R	VR			VR	VR	VR	***Fasciculithus tympaniformis **
VR	VR	VR		VR	F		VR		VR	VR	***Coccolithus pelagicus***
VR								VR	VR	VR	***Chiasmolithus consuetus***
VR	VR										***Discoaster mohleri***
VR											***Ellipsolithus macellus***
VR					F		F	F	F	F	***Neochiastozygus junctus***
R	VR	R		R	F		R		R	F	***Ericsonia subpertusa***
VR											***Lithoptychius bitectus **
VR								VR			***Toweius eminens***
VR	VR			VR							***Fasciculithus thomasii***
VR	R	R		R				VR	VR		***Discoaster multiradiatus***
VR	VR			VR							***Fasciculithus clinatus***
		VR		VR	F		F	F	F	F	***Zygrhablithus bijugatus***
		VR		VR				VR		VR	***Campylosphaera eodela***
		VR		VR							***Fasciculithus schaubii***
		VR		VR							***Fasciculithus alanii***
					F		F	R	F	R	***Coccolithus bownii***
					F		VR	VR		VR	***Rhomboaster bitrifida***
					F		VR	VR		VR	***Rhomboaster intermedia***
							VR	VR	VR	R	***Pontosphaera plana***
							VR	VR		R	***Pontosphaera pulchra***
							VR	VR	VR		***Discoaster mahmoudii***
								VR	VR		***Tribrachiatus bramlettei* (short arms)***
								VR			***Ellipsolithus distichus***
									VR		***Toweius pertusus***
										VR	***Discoaster mediostus***
										VR	***Zygodiscus adamas***
										VR	***Chiasmolithus bidens***

Table 2. (Continued).

E. Eocene																		**Age**
Esna Shale																		**Rock unit**
62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	**Sample no.**
C	C	C	VR	A	F	F	C	C	C	C	C	_	F	C	__	C	C	**Abundance**
G	M	M	M	M	M	M	M	M	M	M	M	_	M	M	__	M	M	**Preservation**
NP10										**NP11**								**Nannofossil zones**
NP10a									**NP10b**									**Subzones**
F	F	R	VR	F	R	F	F	VR	F	R	R			VR				***Neochiastozygus junctus***
R	F	R	R	F	F	F	F	F	F	R	F		R	F		F	F	***Ericsonia cava***
R																		***Pontosphaera plana***
R	F	R	R	R	R	R	R	F	R	R	R		R	F		R	R	***Sphenolithus primus***
VR	VR	VR				VR				VR				VR			VR	***Chiasmolithus consuetus***
VR		R		VR	VR		R	VR										***Rhomboaster intermedia****
VR																		***Pontosphaera versa***
VR	VR	VR																***Chiasmolithus bidens***
VR		VR			VR													***Discoaster multiradiatus***
VR	VR	VR																***Fasciculithus involutus ****
VR																		***Sphenolithus anarrhopus***
VR	VR	VR																***Fasciculithus tympaniformis***
	VR	VR		VR														***Discoaster mediosus***
	VR	VR			VR	VR	VR	VR										***Tribrachiatus bramlettei* (x)***
	VR						VR	R	VR		VR		R					***Discoaster binodosus***
	VR	VR			VR	VR		VR		VR	R		VR	R		VR	VR	***Ellipsolithus macellus ****
	VR																	***Placozygus sigmoides***
	VR									VR								***Pontosphaera pulchra***
		VR		VR			R	VR										***Rhomboaster bitrifida***
			VR			R	F	R	R	R	R			R		R	R	***Ericsonia subpertusa***
				R		VR	VR	VR	VR	VR	R			VR		VR	VR	***Coccolithus pelagicus***
				VR		VR	VR	VR										***Tribrachiatus bramlettei* (+)***
					VR				VR		VR							***Campylosphaera eodela***
						VR					VR		VR	VR		VR	VR	***Zygrhablithus bijugatus***
								VR			VR							***Discoaster diastypus****
									VR									***Zygodiscus plectopons***
									R									***Tribrachiatus digitalis***
										VR	VR							***Discoaster barbadensis***
										VR								***Ellipsolithus distichus***
										VR	R		R	R		VR	VR	***Tribrachiatus orthostylus****
											R		R	R		R	R	***Sphenolithus radians***
														VR		VR	VR	***Toweius eminens***
														R		R	R	***Sphenolithus moriforms***

(x)= Short arms; (+)= Long arms

2003). The HO of this taxon has also been reported in several areas in Egypt such as Gebel Aweina, Gebel Duwi, and Gebel Abu Had (Aubry, 1998; von Salis et al., 1998), Wadi Nukhul in west central Sinai (Khozyem et al., 2013), and in the Zumaya and Alamedilla sections in Spain (Monechi et al., 2000a, 2000b). The HO of *F. alanii* at the Markha section can be used to approximate the P/E boundary.

4.2.3. Gebel Duwi section (Table 3)

4.2.3.1. *Discoaster multiradiatus* Zone (NP9)

This zone includes the interval from the LO of *D. multiradiatus* to the LO of *T. bramlettei*. The LOs of *Discoaster araneus*, *Rhomboaster bitrifida*, and *R. spineus* were used to subdivide Zone NP9 into two subzones: NP9a and NP9b. Here *Ericsonia subpertusa* is vary rare to frequent within Subzone NP9b. An increased abundance of *Neochiastozygus junctus* characterizes the base of NP9b (early Eocene).

Discoaster mahmoudii has its lowest occurrence (LO) above the P/E boundary (Dupuis et al., 2003). At the Duwi section the LO of *Discoaster mahmoudii*, however, is represented only by rare numbers at the base of NP9b simultaneous with the lowest occurrences of *R. bitrifida* and *R. spineus*. This may indicate the presence of a small hiatus at the NP9a/NP9b zonal boundary (P/E boundary) in this section. The absence of *Discoaster mahmoudii* in the Ghanima section, Western Desert, may indicate the existence of a minor hiatus at the Paleocene/Eocene boundary (NP9a/NP9b) (Khalil, and Al Sawy, 2014). It is important to note that the LO of *Z. bijugatus* rarely occurs in the upper Subzone NP9a, and it becomes frequent at the base of the Eocene (base NP9b). In other sections around the world, *Ericsonia subpertusa* and *Z. bijugatus* show low abundances in the upper Paleocene interval and increased abundances during the PETM (Bralower, 2002). The abundance of *Z. bijugatus* increases at the PETM and can be easily correlated with the final abundance decrease of *Fasciculithus* spp. in this section. Subzone NP9b is overlain immediately by an interval barren of nannofossils (samples 149, 150, 151); thus it is not clear whether these samples belong to Subzone NP9b and/or to Subzone NP10a.

4.2.3.2. *Tribrachiatus contortus* Zone (NP10)

The LO of *Tribrachiatus bramlettei* marks the base of Zone NP10 in sample 152. Zone NP10 is subdivided here into three rather than just two subzones: NP10a, NP10b, and NP10c on the basis of the sequential appearance of *T. bramlettei*, *T. digitalis*, and *T. contortus* (Tantawy, 1998). As defined by Tantawy (1998) Subzone NP10a includes the interval from the LO of *T. bramlettei* to the LO of *T. digitalis*, NP10b is defined as the interval from the LO of *T. digitalis* to the LO of *T. contortus*, and NP10c encompasses the interval from the LO to the HO of *T. contortus*. In the Duwi section, the *Tribrachiatus digitalis* morphotype is rare in only a few samples but is still present in Subzone NP10c. It is quite clear and well documented from detailed studies across several Paleocene–early Eocene sections in Egypt that *T. digitalis* is absent. This may be the result of a hiatus covering at least NP10b, and poor preservation and taxonomic problems of *T. digitalis*, or perhaps a consequence of insufficient sample resolution in this interval. The LOs of *Discoaster barbadiensis* and *D. diastypus* occur in Subzones NP10a and NP10b, respectively. In Bolle et al. (2000) and Monechi et al. (2000a, 2000b), *Discoaster binodosus* appears in the middle of Zone NP10, whereas in the Duwi section, it appears in the base of NP10a.

4.2.3.3. *Discoaster binodosus* Zone (NP11)

The HO of *Tribraciatus contortus* in sample 165 marks the base of Zone NP11 in the Duwi section. *Tribrachiatus orthostylus* first appears above the base of Zone NP11 (sample 166). The LO of *S. radians* has been proposed as an alternative biohorizon to approximate the base of Zone NP11 when the key marker (*T. contortus*) is missing (Perch-Nielsen, 1985; Backman, 1986). The LO of *Sphenolithus radians* is virtually coincident with the LO of *T. orthostylus* (Raffi et al., 2005; Agnini et al., 2006). In our Duwi section, very rare specimens of *S. radians* occur within Zone NP11 (sample 170).

4.2.3.4. Paleocene/Eocene boundary

The Paleocene/Eocene boundary is placed at the LOs of *D. araneus*, *R. bitrifida*, and *R. spineus.* As previously mentioned, *D. mahmoudii* first appears in the upper part of Subzone NP9b simultaneously with RD assemblages at the base of NP9b (early Eocene). This may indicate the presence of a stratigraphic gap at the P/E boundary. The HO of *F. schaubii* occurs in Subzone NP9a, below the P/E boundary.

4.2.4. El-Quss Abu Said section (Table 4)

4.2.4.1. *Discoaster multiradiatus* Zone (NP9)

As applied here, this is the interval from the LO of *Discoaster multiradiatus* to the LO of *Tribrachiatus bramlettei*. Aubry et al. (1999) subdivided Zone NP9 into two subzones (NP9a and NP9b), based on the LOs of *Rhomboaster* taxa and *D. araneus*. We base this subdivision in the present section on the LOs of *R. bitrifida*, *R. spineus*, and *D. araneus*. Based on the LO of *Campylosphaera eodela*, Okada and Bukry (1980) subdivided the CP8 Zone into CP8a (*Chiasmolithus bidens*) and CP8b (*Campylosphaera eodela*). In the El-Quss Abu Said section, the LO of *C. eodela* occurs within the NP9a Subzone. In addition to the marker taxon (*Discoaster multiradiatus*) for the base of Zone NP9,

Table 3. Stratigraphic distribution of the identified calcareous nannofossil species, Gebel Duwi section.

Thanetian														**Early Eocene**								**Age**
Esna Shale																						**Rock unit**
130	131	132	133	134	135	136	137	138	139	140	141	142	143	144	145	146	147	148	149	150	151	**Sample no.**
C	A	A	B	C	F	A	C	C	F	A	F	R	F	C	C	B	B	F	B	B	B	**Abundance**
M	M	M	_	M	M	M	M	M	M	M	M	M	M	G	M	_	_	M	_	_	_	**Preservation**
NP9																						**Nannofossil zones**
NP9a														**NP9b**					**?**			**Subzones**
R	C	F		F	R	R	F	F	R	R	R	VR	F	R	R			R				***Coccolithus pelagicus***
R	C	F		F	R	R	F	F	R	F	R	VR	F	C	F			R				***Ericsonia cava***
F	F	F		R		F			VR		VR				VR							***Zygodiscus plectopons***
R	F	VR		VR	R	R	VR		R	R				R	F			VR				***Discoaster multiradiatus***
R	VR	R		VR	VR	R	VR	R	VR		VR			VR	VR			VR				***Fasciculithus tympaniformis***
F	R	VR			F	F	R	R														***Chiasmolithus bidens***
VR		VR			VR	VR			VR			VR	VR									***Fasciculithus alanii***
VR	R	R		VR		R																***Zygodiscus adamas***
F	F	R		R			VR	R			VR			F	F			F				***Neochiastozygus junctus***
VR	R	VR		VR	R																	***Discoaster lenticularis***
R		F					F		VR	R												***Chiasmolithus californicus***
VR	VR	VR													VR							***Neochiastozygus chiastus***
R	R	R									VR							VR				***Chiasmolithus consuetus***
VR							VR	VR	VR													***Fasciculithus clinatus***
VR								VR	R						VR							***Zygolithus sheldaniae***
R																						***Discoaster megastypus***
VR																						***Discoaster mohleri***
R	VR		VR		VR	VR			VR	VR		VR		R	VR							***Fasciculithus involutus***
	R	VR		VR	R	F	R	R	VR	VR	VR	VR	VR	VR	VR							***Sphenolithus primus***
	VR	VR		VR									VR		VR							***Ellipsolithus distichus***
	F									R	R			F	F			VR				***Ericsonia subpertusa***
		R		VR	R	R	R	R	VR		VR											***Neococcolithes protenus***
		VR		VR									VR									***Toweius craticulus***
		R					F		VR	R												***Toweius eminens***
						R				VR					VR							***Discoaster lenticularis***
						VR				R	VR											***Fasciculithus schaubii***
							VR				VR			VR								***Fasciculithus bobii***
										VR	VR											***Toweius pertusus***
										VR		VR	VR	F	F			VR				***Zygrhablithus bijugatus***
										VR				VR	VR							***Discoaster falcatus***
														R	R							***Pontosphaera pulchra***
														F	R							***Discoaster araneus***
														F	R							***Rhomboaster bitrifida***
														F	*R*							***Rhomboaster spineus***
														F	R							***Discoaster mahmoudii***
														F	VR							***Discoaster paelikei***
															VR							***Discoaster beckmanii***
															VR			VR				***Pontosphaera plana***

Table 3. (Continued).

Eocene																				Age
Esna Shale																				Rock unit
152	153	154	155	156	157	158	159	160	161	162	163	164	165	166	167	168	169	170	171-176	Sample no.
R	F	B	F	F	C	B	C	A	B	F	F	F	C	C	R	B	C	F	B	Abundance
M	M	_	M	M	G	_	G	G	_	M	M	M	G	G	M	_	G	M	———	Preservation
NP10														NP11						Nannofossil zones
NP10a					NP10b							NP10C							?	Subzones
VR	R		R	R	R		R	F		R	VR	R	F	R	R		F	R		*Coccolithus pelagicus*
R	R		R	R	F		F	F		F	VR	R	F	R	R		F	R		*Ericsonia cava*
R	F		F	F	C		C	C		F	R	R	F	F			F	VR		*Neochiastozygus junctus*
VR			VR																	*Discoaster multiradiatus* *
VR	R		VR		R		R	R		VR	VR									*Tribrachiatus bramlettei* *(x)
VR	VR		VR		VR		R	R		R	VR									*Tribrachiatus bramlettei* (+)
	VR																			*Sphenolithus primus* *
	VR																VR			*Zygrhablithus bijugatus*
	VR		VR		R															*Rhomboaster bitrifida*
	VR		VR					VR												*Neochiastozygus chiastus*
	VR				VR		R	VR		R		R	R	R						*Pontosphaera puclhra*
	R			VR	R		R	R		R	VR	VR	VR				VR			*Discoaster binodosus*
			VR																	*Ellipsolithus distichus*
			VR	VR	VR		R													*Pontosphaera plana*
			VR																	*Chiasmolithus solitus*
			VR	VR																*Lopdolithus nascens*
			VR				VR							VR						*Ellipsolithus macellus* *
			VR											VR			VR			*Pontosphaera pectinata*
			VR				R			VR	VR	VR	R	VR				VR		*Discoaster barbadiensis*
				VR	VR													VR		*Micrantholithus vesper*
					VR			VR					R					VR		*Discoaster diastypus*
					R		R			R	R	R	R							*Tribrachiatus digitalis* *
					VR		R	VR		R		R	R	R						*Pontosphaera exilis*
							R	R				VR	VR					VR		*Sphenolithus moriformis*
							VR						VR	VR						*Pontosphaera versa*
							VR	VR												*Campylosphaera dela*
										VR										*Zygodiscus plectopons*
										VR										*Rhomboaster intermedia*
												R	R							*Tribrachiatus contortus* *
														R			VR	R		*Tribrachiatus orthostylus*
																		R		*Pontosphaera formosa*
																		VR		*Sphenolithus radians*

Table 4. Stratigraphic distribution of the identified calcareous nannofossil species, El-Quss Abu Said section.

L.Eocene Paleocene			Early Eocene																		**Age**
Esna Shale																					**Formation**
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	**Sample no.**
C	C	A	A	A	C	C	C	A	C	C	C	C	C	C	R	R	R	VR	C	C	**Abundance**
G	G	G	G	G	G	G	G	M	G	G	G	G	G	G	G	G	G	M	M	M	**Preservation**
NP9a			**NP9b**																		**Nannofossil zones**
R	**R**	**R**	**R**	**F**	**R**	**R**	**R**	**R**													***Ericsonia cava***
R	R	VR	R	R					VR	VR	VR	VR	VR	VR	VR				VR	VR	***Sphenolithus primus***
R	R		VR																		***Fasciculithus thomasii***
R	R	VR																			***Fasciculithus alanii***
R	R	R	VR	R																	***Fasciculithus involutus***
R	R	R	VR	R																	***Fasciculithus tympaniformis***
VR	VR	VR	VR	VR	VR			VR	VR	VR					VR	VR			VR	VR	***Teweius pertusus***
VR	VR																				***Fasciculithus clinatus***
VR	VR							VR	VR			VR			VR				VR	VR	***Ellipsolithus macellus***
VR		VR	VR	VR	VR	VR	VR														***Discoaster falcatus***
R	F	R	R	R	R	R	R	R	VR	VR	VR	VR		VR					VR		***Discoaster multiradiatus***
VR	VR	VR	VR																		***Calciosoleaia aperta***
	VR		VR		VR	VR	R	VR	VR	VR	VR		VR						VR	VR	***Campylosphaera eodela***
	R		VR	R	R				VR		VR		VR								***Chiasmolithus consuetus***
	R		VR	VR	VR		VR		VR	VR											***Toweius eminens***
	VR		VR																		***Fasciculithus richardii***
	VR		VR	R	R	R	VR	VR	VR		VR			VR					VR	VR	***Zygrhablithus bijugatus***
	VR				VR					VR	VR										***Ellipsolithus distichus***
	VR	VR	VR																		***Placozygus sigmoides***
			VR	VR				VR	VR				VR								***Discoaster anartios***
		R	F		F	F	F	F	VR	VR	R	VR	VR	R	VR	VR	VR	VR	VR	R	***Neochiastozygus junctus***
		R	R		R	R	R	R	R	R	VR	R	R	R	VR		VR		VR	VR	***Ericsonia subpertusa***
		VR	VR	VR															VR		***Zygolithus sheldaniae***
			R	R	VR	VR															***Rhomboaster intermedia***
			VR	VR																	***Discoaster paelikei***
			VR																		***Discoaster araneus***
			R		R			VR	VR						VR		VR				***Rhomboaster bitrifida***
			VR	VR																	***Rhomboaster spineus***
			VR	VR	VR	R	VR		VR												***Discoaster mahmoudii***
				VR	VR	R	R	R	F	F	F	F		R				VR	F	VR	***Pontosphaera plana***
				VR					VR	VR											***Toweius tovae***
				VR	VR		VR	VR	VR												***Discoaster mediosus***
				R																	***Discoaster lenticularis***
					VR	VR															***Zygodiscus plectopons***
						VR	VR	VR	VR				R			VR	R	VR	VR	F	***Micrantholithus vesper***
						VR															***Pontosphaera pulchra***
									R	R	VR	R	R	R	VR	VR	VR		VR		***Coccolithus pelagicus***
									VR				VR		VR		VR		VR	VR	***Braarudosphaera bigelowii***
									F	F	F	F	F	R	VR			VR	F		***Pontosphaera versa***
									VR	VR	VR								VR		***Blackites solus***
									VR		VR					VR	VR				***Rhomboaster cuspis***
										VR	VR			VR							***Chiasmolithus bidens***
										VR										VR	***Discoaster binodosus***
											VR		VR	VR							***Pontosphaera exilis***
															VR	R	R	VR	VR	F	***Micrantholithus atlenutes***
																				VR	***Zygolithus herlynii***

Table 4. (Continued).

Early Eocene																												**Age**
Esna Shale																												**Formation**
22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48		**Sample no.**
F	F	F	F	R	R	F	R	R	VR	VR	F	VR	R	R	B	B	B	B	B	B	F	R	VR	VR	R	F	VR	**Abundance**
M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	_	_	_	_	_	_	M	M	M	M	M	M	M	**Preservation**
NP10a																					**NP11**							**Nannofossil zones**
F	R	R	R	VR	VR	R		VR	R	VR	F	R	R	VR								F	R					***Micrantholithus vesper***
VR	VR	VR	VR		VR	F	R	VR	VR		R	R	R	R							R	R	R	VR	R	F	VR	***Teweius pertusus***
VR		VR	VR	VR					VR		VR		VR	VR							VR	VR				VR		***Braarudosphaera bigelowii***
R	VR		VR		VR	VR	VR	VR		VR	VR		VR	VR								VR		VR		VR		***Neochiastozygus junctus***
VR	VR	VR								VR	VR	VR	VR								VR	VR	VR	R	R	VR	VR	***Ericsonia cava***
VR	VR	VR																										***Coccolithus pelagicus***
VR						VR					VR											VR						***Tribrachiatus bramlettei***
VR						VR		VR					VR	VR									VR					***Rhomboaster cuspis***
VR		VR																										***Chiasmolithus consuetus***
VR			VR	VR		VR		VR		VR	VR		VR										VR					***Sphenolithus primus***
VR		VR	VR		VR					VR	VR												VR			VR		***Pontosphaera plana***
VR						VR					VR		VR								VR	VR		*R*				***Discoaster multiradiatus***
F	R	R	R			R					VR												VR		VR			***Micrantholithus attenuatus***
VR			VR											VR												VR		***Discoaster binodosus***
VR																												***Pontosphaera versa***
VR																												***Chiasmolithus bidens***
	VR										VR		VR													VR		***Zygrhablithus bijugatus***
		VR								VR	F	R									F							***Ellipsolithus macellus***
				VR							VR										VR		VR					***Ericsonia subpertusa***
				VR			VR				VR															VR		***Pontosphaera exilis***
					VR																							***Zygolithus herlynii***
						VR							VR													VR		***Pontosphaera rimosa***
						VR																						***Micrantholithus bramlettei***
						VR																						***Rhomboaster bitrifida***
											VR													VR				***Lophodolithus nascens***
											VR		VR													VR		***Campylosphaera dela***
														VR								VR						***Discoaste paelikei***
																					VR	VR	VR					***Tribrachiatus orthostylus***
																										VR		***Discoaster barbadiensis***

other nannofossil species were recorded, among them *F. involutus*, *F. thomasii*, *F. alanii*, and *D. falcatus*. The base of Subzone NP9b is delineated here by the lowest occurrences of *D. paelikei*, *D. araneus*, *R. bitrifida, R. intermedia*, and *D. mahmoudii.* On the other hand, *D. binodosus* occurs in small numbers in the topmost Subzone NP9b (Table 4).

4.2.4.2. *Tribrachiatus contortus* Zone (NP10)

As mentioned previously, Tantawy (1998) subdivided this zone into three subzones. In the El-Quss Abu Said section, only subzone NP10a was distinguished, and it is overlain unconformably by a bank of large foraminfers (nummulites, operculines).

4.2.4.3. *Discoaster binodosus* Zone (NP11)

The LO of *T. orthostylus* was used to locate the base of Zone NP11, but its top cannot be delimited accurately due to the absence of the marker taxon (*Discoaster lodoensis*) for the base of Zone NP12. In this section the base of Zone NP11 is also placed at the LO of *Tribrachiatus orthostylus*, which is in agreement with Perch-Nielsen (1985) and Faris and Strougo (1998).

4.2.4.4. Paleocene/Eocene boundary

The P/E boundary (NP9a/NP9b) is delineated at the LOs of *R. spineus*, *R. bitrifida*, *Discoaster anartios*, and *D. areneus*. Other taxa that first appear at the base of the early Eocene (base of NP9b) include *D. paelikei* and *D. mahmoudii*. In addition, the HO of *Fasciculithus alanii* occurs below the P/E boundary and can be used as an alternative bioevent to locate this boundary. *Discoaster mahmoudii* has its lowest occurrence (LO) above the P/E boundary (Dupuis et al., 2003). The co-occurrence of *D. mahmoudii* simultaneous with the RD taxa (rhomboasters, *D. anartios* and *D. areneus*) may indicate the presence of a minor hiatus at the P/E boundary in such sections. Above the P/E boundary, *Neochastozygus junctus* is quite prominent.

Bown and Pearson (2009) identified 12 species that have their highest occurrences at or near the PETM onset from Tanzania and around the globe. *Calciosolenia aperta* last occurs just above the P/E boundary in our sections. The last occurrence of *C. aperta* has been recorded from various other sections (Bybell and Self-Trail, 1995; Angori and Monechi, 1996; Monechi et al., 2000; Bown and Pearson, 2009). *Zygodiscus sheldoniae* last occurs around the P/E boundary in our section. However, *Zygodiscus sheldoniae*, a fairly recently described species, has only been identified from Tanzania (Bown, 2005), New Jersey (Gibbs et al., 2006), and Maryland (Self-Trial, 2011), and so its range is still uncertain. *Zygrhablithus bijugatus* is thought by Wei and Wise (1990) and Agnini et al. (2007) to have been controlled by productivity and water depth, thriving in deep-water oligotrophic conditions.

5. Early Eocene hiatus within Zone NP10

As previously discussed, the *T. contortus* Zone (NP10) is subdivided into three subzones based on the sequential appearances of *Tribrachiatus bramlettei* (NP10a), *Tribrachiatus digitalis* (NP10b), and *Tribrachiatus contortus* (NP10c). At the Gebel Matulla and Markha sections, Subzone NP10c is missing, suggesting a small hiatus at the NP10/NP11 contact (Figure 7). The two subzones NP10b and NP10c are missing in the El-Quss Abu Said section, and a bank of large foraminifers overlies the sediments of Subzone NP10b.

In the southern edge of El Guss Abu Said at the Farafra Oasis, a large nummulite, *N. luterbacheri*, forms a bank near the base of the Esna Formation. Calcareous nannofossils (Strougo and Faris, 2000) indicate that this bank most likely falls within Zone NP11. The absence of *T. contortus* in the shales underlying the nummulite bank could indicate a slight disconformity (NP10/NP11 boundary) at the base of the latter, as indicated by the absence of Subzone NP10c of Tantawy (1998).

The NP10c Subzone is absent in the Gebel Nukhul section, which may confirm that a minor hiatus occurs within the lower Eocene (Faris and Salem, 2007). In the El Qusaima area of northeast Sinai, Egypt, the calcareous nannofossil Subzone NP10c is absent and the Zone NP11 overlies unconformably NP10c (Ayyad et al., 2003). In the Thamad area of east central Sinai, Egypt, a short break is noted within Zone NP10 (subzones NP10b and NP10c are absent) where Subzone NP10a is overlain directly by Zone NP11 (Faris and Abu Shama, 2007). In North America a hiatus is also present in the lower Eocene sediments of the SDB core from the Salisbury Embayment of the mid-Atlantic Coastal Plain as evidenced by the absence of *Tribrachiatus digitalis* and *T. contortus* (Self-Trail et al., 2012). A correlative hiatus of shorter duration is also present in New Jersey (Aubry, 2000). At the Jabal El Rawdah section, due to the absence of *T. digitalis* and *T. contortus*, only subzone NP10a is present; the other subzones simply could not be defined (Faris et al., 2014). The wide distribution of the time gap across the NP10/NP11 boundary reflects a eustatic sea-level drop.

6. Summary

The main results can be summarized as follows: 1) The calcareous nannofossil biostratigraphy of the upper Paleocene–lower Eocene interval in the four sections studied, Gebel Matulla, Markha, Duwi, and El-Quss Abu Said, span three nannofossil zones, NP9, NP10, and NP11. 2) The PETM is marked by unusual calcareous nannofossil taxa (*Rhomboaster* spp., *Discoaster araneus*, and *D. anartios*), often referred to as the Calcareous Nannoplankton Excursion Taxa (CNET) or *Rhomboaster*–

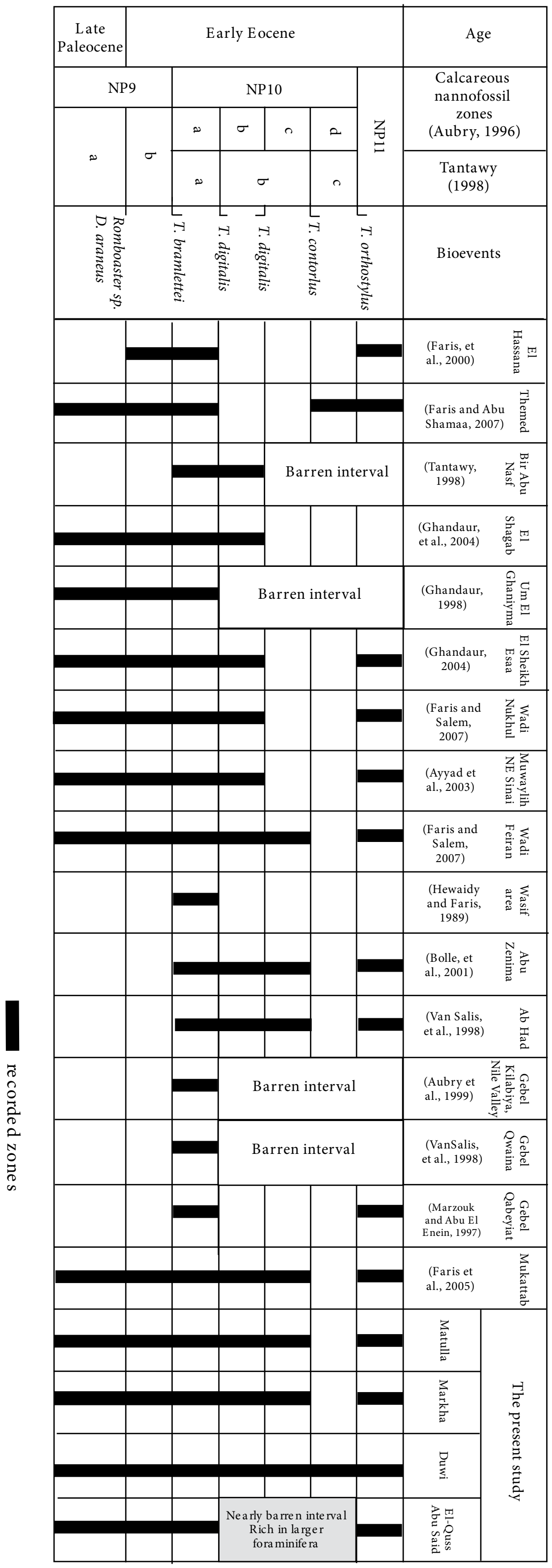


Figure 7. A regional hiatus within NP10/NP11 in the study sections and other sections in Egypt.

Discoaster (RD) assemblage. It is suggested that the *Rhomboaster–D. araneus* association shows strong provincialism, being geographically restricted to the Tethys Seaway, the North and South Atlantic Oceans, and the westernmost Indian Ocean (Aubry, 2001; Kahn and Aubry, 2004). 3) We recorded different species of the genus *Rhomboaster* (*R. intermedia*, *R. bitrifida*, and *R. spineus*) that evolved and radiated within the PETM, together with species of the genus *Tribrachiatus* (*T. bramelttei*, *T. digitalis*, and *T. contortus*). 4) *T. bramlettei*, the marker species of Zone NP10, occurs as two morphotypes (short and long arms). 5) *Zygrhablithus bijugatus* has its first occurrence in the upper part of Subzone NP9a in the four sections studied. It has low abundances in the upper Paleocene interval, but its abundance increased during the PETM. 6) Fasciculiths are highly diversified and abundant throughout the upper Paleocene interval. 7) *Fasciculithus alanii* only occurs within the Subzone NP9a and therefore seems to represent a reliable event for delineating the NP9a/NP9b boundary in our four sections. 8) The LO of *Discoaster mahmoudii*, however, is represented only by rare specimens in the upper NP9b (early Eocene), and its HO is within Subzone NP10a. This is a reliable and easily recognized event. 9) *Rhomboaster* and *Tribrachiatus* at the Paleocene–Eocene transition interval characterize very warm and oligotrophic conditions based on their co-occurrences with excursion taxa (*D. araneus*, *D. anartios*) plus *Sphenolithus* and *E. subpertusa*. 10) The calcareous nannofossil distribution indicates two subzones, NP10a and NP10b, in Gebels Matulla and Markha sections, and clearly suggests a stratigraphic gap, ranging from NP10c up to NP11 since the marker species for NP10c is missing. On the other hand, three subzones (NP10a, b, and c) are recorded in the Duwi section. At the El-Quss Abu Said section, only the NP10a subzone is present but overlain by an interval rich in larger foraminifera (nummulites, operculines) and barren of calcareous nannofossils subjacent to Zone NP11. 11) The excellent correlation of a short hiatus across large distances and different tectonic plates at the NP10/NP11 zonal boundary rules out a tectonic control, strongly supporting a eustatic origin of these unconformities.

Acknowledgment
Many thanks are extended to Prof Sherwood WW Wise Jr (Florida State University) for revisions, constructive comments, and discussions.

Appendix of the identified calcareous nannofossil taxa

1. *Braarudosphaera bigelowii* (Gran & Braarud, 1935) Deflandre (1947)
2. *Calciosolenia aperta* (Hay & Mohler, 1967) Bown (2005)
3. *Campylosphaera dela* (Bramlette & Sullivan, 1961) Hay & Mohler (1967)
4. *Campylosphaera eodela* Bukry & Percival (1971)
5. *Chiasmolithus bidens* (Bramlette & Sullivan, 1961) Hay & Mohler (1967)
6. *Chiasmolithus californicus* (Sullivan, 1964) Hay & Mohler (1967)
7. *Chiasmolithus consuetus* (Bramlette & Sullivan, 1961) Hay & Mohler (1967)
8. *Chiasmolithus eograndis* Perch-Nielsen (1971)
9. *Chiasmolithus solitus* (Bramlette & Sullivan, 1961) Locker, 1968
10. *Coccolithus bownii* Jiang &Wise (2007)
11. *Coccolithu*s *pelagicus* (Wallich, 1877) Schiller (1930)
12. *Coronocyclus brameltte*i (Haw & Towe, 1926) Bown, 2005
13. *Discoaster anartios* Bybell & Self-Trail (1995)
14. *Discoaster araneus* Bukry (1971)
15. *Discoaster backmanii* Agnini & Fornaciari (2008)
16. *Discoaster barbadiensis* Tan (1927)
17. *Discoaster binodosus* Martini (1958)
18. *Discoaster deflandrei* Bramlette & Riedel (1954)
19. *Discoaster diastypus* Bramlette & Sullivan (1961)
20. *Discoaster falcatus* Bramlette & Sullivan (1961)
21. *Discoaster lenticularis* Bramlette & Sullivan (1961)
22. *Discoaster mahmoudii* Perch-Nielsen (1981)
23. *Discoaster megastypus* (Bramlette & Sullivan, 1961)
24. *Discoaster modiostus* Bramlette & Sullivan (1961)
25. *Discoaster mohleri* Bukry & Percival (1971)
26. *Discoaster multiradiatus* Bramlette & Reidel (1954)
27. *Discoaster paelikei* Agnini & Fornaciari (2008)
28. *Discoaster splendidus* Martini (1960)
29. *Ellipsolithus distichus* (Bramlette & Sullivan, 1961) Sullivan (1964)
30. *Ellipsolithus macellus* (Bramlette & Sullivan, 1961)
31. *Ericsonia cava* (Hay & Mohler, 1967) Perch-Nielsen (1969)
32. *Ericsonia robusta* Bramlette & Sullivan, 1961) Edwards & Perch-Nielsen (1975)
33. *Ericsonia subpertusa* Hay & Mohler (1967)
34. *Ericsonia universa* (Wind &Wise, 1977).
35. *Fasciculithus* (Romein, 1979)
36. *Fasciculithus alanii* Perch-Nielsen (1971b)
37. *Fasciculithus bobii* Perch-Nielsen (1971b)
38. *Fasciculithus clinatus* Bukry (1971a)
39. *Fasciculithus involutus* Bramlette & Sullivan (1961)
40. *Fasciculithus richardii* Perch-Nielsen (1971b)
41. *Fasciculithus schaubii* Hay & Mohler (1967)
42. *Fasciculithus thomasii* Perch-Nielsen (1971b)
43. *Fasciculithus tympaniformis* Hay & Mohler in Hay et al. (1967)
44. *Lithoptychius bitectus* (Romein, 1979) Aubry (2011)
45. *Lophodolithus nascens* Bramlette & Sullivan (1961)
46. *Micrantholithus bramlettei* Deflandre *in* Deflandre & Fert (1954)
47. *Micrantholithus vesper* Deflandre (1950)
48. *Neochiastozygus chiastus* (Bramlette & Sullivan, 1961) Perch-Nielsen (1971)
49. *Neochiastozygus junctus* (Bramlette & Sullivan, 1961) Perch-Nielsen (1971)
50. *Neochiastozygus perfectus* Perch-Nielsen (1971)
51. *Neococcolithes protenus* (Bramlette & Sullivan, 1961) Black (1967)
52. *Placozygus sigmoides* (Bramlette & Sullivan, 1961)
53. *Pontosphaera exilis* (Bramlette & Sullivan, 1961) Romein (1979)
54. *Pontosphaera formosa* (Bukry & Bramlette, 1969) Romein (1979)
55. *Pontosphaera pectinata* (Bramlette & Sullivan, 1961) Sherwood (1974)
56. *Pontosphaera plana* (Bramlette & Sullivan, 1961) Haq (1971)
57. *Pontosphaera pulchera* (Deflandre *in* Deflandre & Pert, 1954) Romein (1979)
58. *Pontosphaera rimosa* (Bramlette & Sullivan, 1961) Roth & Thierstein (1972)
59. *Pontosphaera versa* (Bramlette & Sullivan, 1961) Sherwood (1974)
60. *Rhomboaster bitrifida* Romein (1979)
61. *Rhomboaster calcitrapa* Gartner (1971)
62. *Rhomboaster cuspis* Bramlette & Sullivan (1961)
63. *Rhomboaster intermedia* Romein (1979)
64. *Rhomboaster spineus* (Shank & Stradner, 1971) Perch-Nielsen (1984)
65. *Sphenolithus anarrhopus* Bukry & Bramlette (1969)
66. *Sphenolithus editus* Perch-Nielsen *in* Perch-Nielsen et al. (1978)
67. *Sphenolithus moriformis* (Bronnimann & Stradner, 1960) Bramlette & Wilcoxon (1967)
68. *Sphenolithus primus* Perch-Nielsen (19710)
69. *Sphenolithus radians* Deflandre *in* Grasse (1952)
70. *Toweius craticulus* Hay & Mohler (1967)
71. *Toweius eminens* (Bramlette & Sullivan, 1961)
72. *Toweius pertusus* (Sullivan, 1965) Romein (1979)
73. *Toweius tovae* Perch-Nielsen (1971b)
74. *Tribrachiatus bramlettei* (Bronnimann & Stradner, 1960) Proto Decima el al. (1975)
75. *Tribrachiatus contorlus* (Stradner, 1958) Bukry (1972)
76. *Tribrachiatus orthostylus* Sharnrai (1963)
77. *Zygodiscus adamas* Bramlette & Sullivan (1961)
78. *Zygodiscus herlynii* Sullivan (1964)
79. *Zygodiscus plectopons* Bramlette & Sullivan (1961)
80. *Zygolithus sheldaniae* Bown, 2005
81. *Zygrhablithus bijugatus* (Deflandre *in* Deflandre & Fert, 1954) Deflandre (1959)

References

Agnini C, Fornaciari E, Rio D, Tateo F, Backman J, Giusberti L (2007a). Responses of calcareous nannofossil assemblages, mineralogy and geochemistry to the environmental perturbations across the Paleocene/Eocene boundary in the Venetian Pre-Alps. Mar Micropaleontol 63: 19–38.

Agnini C, Fornaciari E, Raffi I, Rio D, Röhl U, Westerhold T (2007b). High resolution nannofossil biochronology of middle Paleocene to early Eocene at ODP Site 1262: implications for calcareous nannoplankton evolution. Mar Micropaleontol 64: 215–248.

Agnini C, Muttoni G, Kent DV, Rio D (2006). Eocene biostratigraphy and magnetic stratigraphy from Possagno, Italy: the calcareous nannofossil response to climate variability. Earth Planet Sci Lett 241: 815–830.

Angori E, Monechi S (1996). High-resolution calcareous nannofossil biostratigraphy across the Paleocene/Eocene boundary at Caravaca (Southern Spain). Israel J Earth Sci 44: 197–206.

Aubry MP (1996). Towards an upper Paleocene–lower Eocene high resolution stratigraphy. Israel J Earth Sci 44: 239–253.

Aubry MP (1998). Early Paleogene calcareous nannoplankton evolution: a tale of climatic amelioration. In: Aubry MP, Ouda K, editors. Late Paleocene-early Eocene Biotic and Climatic Events in the Marine and Terrestrial Records. Columbia University Press, New York, 158–201.

Aubry MP (2001). Provincialism in the photic zone during the LPTM. In: Ash A, Wing S (Eds.), Climate and Biota of the Early Paleogene. Intern. Meeting, Powell, Abst., p. 6.

Aubry MP, Cramer B, Miller KG, Wright J, Kent DV, Olsson RD (2000). Late Paleocene event chronology: unconformities not diachrony: Bulletin de la Société géologique de France 171: 367–378.

Aubry MP, Ouda K (2003). Introduction to the upper Paleocene–Lower Eocene of the Upper Nile Valley: Part I Stratigraphy. Micropaleontol 49: ii–iv.

Aubry MP, Ouda, K, Dupuis, C, Berggren WA, Van Couvering JA, the members of the Working Group on the Paleocene/Eocene Boundary (2007). The Global Standard Stratotype-section and Point (GSSP) for the base of the Eocene Series in the Dababiya section (Egypt). Episodes 30: 271–286.

Aubry MP, Requirand C, Cook J (2000). The *Rhomboaster–Tribrachiatus* lineage: a remarkable succession of events from 55.5 to 53.2 Ma. GFF 122: 15–18.

Aubry MP, Salem R (2012-2013). The Dababiya Quarry Core: Coccolith Biostratigraphy. Stratigraphy 9 (3–4): 241–259.

Ayyad SN, Faris M, El Nahass HA, Saad AA (2003). Planktonic foraminiferal and calcareous nannofossil biostratigraphy of the Upper Cretaceous-Lower Eocene successions in the northeast Sinai, Egypt. The Third International Conference, Assiut, Egypt 1: 649–683.

Backman J (1986). Late Paleocene to middle Eocene calcareous nannofossil biochronology from the Shatsky Rise, Walvis Ridge and Italy. Palaeogeogr Palaeoclimatol Palaeoecol 57: 43–59.

Bolle MP, Tantawy A, Pardo A, Adate T, Burns S, Kassab A (2000). Climatic and environmental changes documented in the Upper Paleocene to Lower Eocene of Egypt. Ecol Geol Helv 93: 33–51.

Bown PR (2005). Palaeogene calcareous nannofossils from the Kilwa and Lindi areas of coastal Tanzania (Tanzania Drilling Project 2003-4). J Nannoplankton Research 27: 21–95.

Bown P, Pearson P (2009). Calcareous plankton evolution and the Paleocene/Eocene thermal maximum event: new evidence from Tanzania. Mar Micropaleontol 71: 17–34.

Bralower TJ (2002). Evidence of surface water oligotrophy during the Paleocene–Eocene thermal maximum: nannofossil assemblage data from Ocean Drilling Program Site 690, Maud Rise, Weddel Sea. Paleoceanography 17: 1029–1042.

Bralower TJ (2005). Data report: calcareous nannofossil biostratigraphy of the Paleocene to early Oligocene interval at ODP Sites 1209, 1210, and 1211, Shatsky Rise, Pacific Ocean. In: Bralower TJ, Premoli Silva I, Malone M, editors. Proc. ODP, Sci Results 198.

Bralower TJ, Mutterlose J (1995). Calcareous nannofossil biostratigraphy of ODP Site 865, Allison Guyot, Central Pacific Ocean: a tropical Paleogene reference section. In: Winterer EL, Sager WW, Firth JV, et al., editors. Proceedings of the Ocean Drilling Program Scientific Results 143: 31–72.

Bramlette MN, Sullivan FR (1961). Coccolithophorids and related nannoplankton of the Early Tertiary in California. Micropaleont 7: 129–188.

Bybell IM, Self-Trail JM (1995). Evolutionary, biostratigraphic, and taxonomic study of calcareous nannofossils from a continuous Paleocene-Eocene boundary section in New Jersey. US Geological Survey Professional paper 1554: 1–114.

Dupuis C, Aubry MP, Steurbaut E, Berggren WA, Ouda K, Magioncalda R, Cramer BS, Kent DV, Speijer RP, Heilmann-Clausen C (2003). The Dababiya quarry section: lithostratigraphy, clay mineralogy, geochemistry and paleontology. Micropaleont 49: 41–59.

Faris M (1993). Calcareous nannofossil events at the Paleocene-Eocene boundary in Egypt. Bull Fac Sci Qena (Egypt) 1: 89–99.

Faris M, Abu Shama AM (2007). Nannofossil biostratigraphy of the Paleocene lower Eocene succession in the Thamad area, east central Sinai, Egypt. Micropaleont 53: 127–144.

Faris M, Abdelghany O, Zahran E (2014). Upper Maastrichtian to Lutetian nannofossil biostratigraphy, United Arab Emirates, west of the Northern Oman Mountains. J Afr Earth Sci 93: 42–56.

Faris M, Salem RF (2007). Paleocene-early Eocene calcareous nannofossil biostratigraphy in west central Sinai, Egypt. Proceeding of the 8th Conf. Geology of Sinai for Development, Ismailia, 1–14.

Galeotti S, Krishnan S, Pagani M, Lanci L, Gaudio A, Zachos JC, Monechi S, Morelli G, Lourens L (2010). Orbital chronology of Early Eocene hyperthermals from the Contessa Road section, central Italy. Earth Planet Sci Lett 290: 192–200.

Gibbs SJ, Bown PR, Seessa JA, Bralower TJ, Wilson PA (2006). Nannoplankton extinction and origination across the Paleocene-Eocene Thermal Maximum. Geology 34: 233–236.

Hay WW (1964). The use of the electron microscope in the study of fossils. Annu Rep Smithsonian Inst 409–415.

Kahn A, Aubry MP (2004). Provincialism associated with the Paleocene/Eocene Thermal Maximum: temporal constraint. Mar Micropaleontol 52: 117–132.

Khalil H, Al Sawy S (2014). Integrated biostratigraphy, stage boundaries and paleoecology of the Upper Cretaceous-Lower Paleogene successions in Kharga and Dakhla Oases, Western Desert, Egypt. J Afri Earth Sci 96: 220–242.

Khozyem H, Adatte T, Keller G, Tantawy AA, Spangenberg JE (2014). The Paleocene-Eocene GSSP at Dababiya, Egypt. Revisited Episodes 37: 78–86.

Khozyem H, Adatte T, Spangenberg JE, Tantawy AA, Keller G (2013). Palaeoenvironmental and climatic changes during the Palaeocene–Eocene Thermal Maximum (PETM) at the Wadi Nukhul Section, Sinai, Egypt. J Geological Society London 170: 341–352.

Martini E (1971). Standard Tertiary and Quaternary calcareous nannoplankton zonation. In: Farinacci A, editor. Proceedings of the II Planktonic Conference 2, Roma (1970): 739–785.

Monechi S, Angori E, Speijer RP (2000a). Upper Paleocene biostratigraphy in the Mediterranean region: zonal markers, diachronism, and preservational problems. GFF 122: 108–110.

Monechi S, Angori, E, von Salis K (2000b). Calcareous nannofossil turnover around the Paleocene/Eocene transition at Alamedilla (southern Spain). Bull. Soc. Géol. Fr. 171: 477–489.

Perch-Nielsen K (1985). Cenozoic calcareous nannofossils. In: Bolli HM, Saunders JB, Perch-Nielsen K, editors. Plankton Stratigraphy. Cambridge Univ Press, pp. 427–554.

Pospichal JJ, Wise SW (1990). Paleocene to middle Eocene calcareous nannofossil of ODP Sites 689 and 690, Maud Rise, Weddell Sea. In: Barker KP, Kennett JP, et al., editors. Proc ODP Sci Results 113: College Station, TX (Ocean Drilling Program), pp. 613–638.

Raffi I, Backman J, Pälike H (2005). Change in calcareous nannofossil assemblages across the Paleocene/Eocene transition from the paleo-equatorial Pacific Ocean. Palaeogeogr Palaeoclimatol Palaeoecol 226: 93–126.

Salis K Von, Ouda K, Saad El Din M, Tantawy AA, Bernasconi S (1998). Calcareous nannofossil, foraminifera and stable isotope studies from the P/E boundary section in Egypt. Strata, Actes du laboratoire de Geologie Sedimentaire et Paleontologie de l'Université Paul-Sabatier 1: 113–115.

Self-Trial JM (2011). Paleogene calcareous nannofossils of Southern Maryland, South Dover Bridge Core, USA. J Nannoplankton Res 32: 1–28.

Self-Trial JM, Powars DS, Watkins DK, Wandless GA (2012). Calcareous nannofossil assemblage changes across the Paleocene–Eocene Thermal Maximum: evidence from a shelf setting. Mar Micropaleontol 92–93: 61–80.

Strougo A, Faris M (2000). Additional data on the age of the *Nummulites luterbacheri* bank (southern edge of El Guss Abu Said, Farafra Oasis), based on calcareous nannofossils. M.E.R.C. Ain Shams Univ Earth Sci Ser 14: 229–238.

Tantawy AA (1998). Stratigraphical and paleoecological studies on some Paleocene-Eocene successions in Egypt. Unpub PhD Thesis Assiut Univ Egypt, 273 p.

Wei W, Wise SW Jr (1990). Biogeographic gradients of middle Eocene–Oligocene calcareous plankton in the South Atlantic Ocean. Palaeogeogr Palaeoclimatol Palaeoecol 79: 29–61.