Arab J Geosci (2016) 9:480
DOI 10.1007/s12517-016-2445-3

ORIGINAL PAPER

Calcareous nannofossil biostratigraphy of the marine Oligocene and Miocene succession in some wells in Northern Egypt

Mahmoud Faris[1] **· Hassan El Sheikh**[2] **· Fatma Shaker**[2]

Received: 6 July 2015 / Accepted: 28 March 2016
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Abstract Twelve calcareous nannofossil biozones of Late Oligocene-Late Miocene in Northern Egypt were defined and correlated with their corresponding biozones in Egypt and other parts of the world. These are arranged from the top to base as Zone NN12, Zone NN11, Zone NN10, Zone NN8, Zone NN7, Zone NN6 Zone NN5, NN4, Zone NN3, Zone NN2 Zone NP25 and Zone NP24. In the present study (Boughaz-1 Well), the Late Miocene unconformably overlies the Middle Miocene. This unconformity surface is recognized by the missing of calcareous nannofossil zones NN7 to NN9. While, in North Sinai (Malha-1 Well), the Early/Middle Miocene boundary cannot be recognized, where the Middle Miocene unconformably overlies the topmost Oligocene, and it is defined by the missing calcareous nannofossil zones NN1 to NN4.

Keywords Calcareous nannofossil · Oligocene · Miocene wells · Northern Egypt

Introduction

In comparison to the widespread distribution of Paleocene to Eocene rocks in the Levant and the Middle East, Oligocene strata are recorded from only a few outcrops of restricted extent. Within the Mediterranean coast and the Red Sea/Gulf of Suez regions, Oligocene exposures are patchy in occurrence. This is due to erosion, as a consequence of tectonically induced uplift, enhanced by a major mid-Oligocene global sea-level fall (Haq et al., 1988; Haq and Al-Qahtani, 2005).

The Miocene succession in Egypt represents about 12 % of the total land surface (Ball 1952). Lying unconformably on the older rocks, they extend from near Cairo westwards across the northern part of the Western Desert into Libya. They are forming a plateau rising gradually to south and reaching height over 200 m. Also, they occur in hills to the east of Cairo, as well as, along both sides of the Gulf of Suez and near the Red Sea coast in both Egypt and Sudan (El-Heiny 1979).

Several biostratigraphical studies have been done on this succession, (e.g. El Heiny and Martini 1981; Arafa 1982, 1991; El Heiny and Morsi 1992; El Sheikh 1995; Marzouk 1998; Sadek 2000, 2001; Mandur 2003; Marzouk and Soliman 2004; Abu Shama 2007; Faris et al. 2007, 2009; Soliman et al. 2012; Boukhary et al. 2012; Samir 2013; Hewaidy et al. 2014).

This study aims (1) to investigate the distribution of the calcareous nannofossils and establish biostratigraphic zonation for the subsurface Oligo-Miocene rocks in five wells (Boughaz-1, El-Temsah-2, San El-Hagar-1, Bardawil-1, and Malha-1) and (2) to discuss some Neogene Stage boundaries.

Location and material

A total of 138 subsurface ditch samples were collected from five subsurface wells in Northern Egypt, Boughaz-1 Well was drilled to a total depth of about 3540.9 m by Continental Delta Oil Company and located at (lat. 31° 09′ 24.6″ N, long. 32° 40′

✉ Fatma Shaker
fatma_elkammar@hotmail.com;
FATMA.ELDESOUKY@fsc.bu.edu.eg

[1] Department of Geology, Faculty of Science, Tanta University, Tanta, Egypt

[2] Department of Geology, Faculty of Science, Benha University, Benha 13518, Egypt

Published online: 26 May 2016

47.55″ E), El-Temsah-2 Well was drilled to a total depth of about 4689 m by Mobil exploration Egypt Incorporated Company at location (lat. 31° 47′ 7.38″ N, long. 32° 10′ 26.68″ E), San El-Hagar-1 Well was drilled to a total depth of about 3772 m by Continental Delta Oil Company with location of (lat. 30° 29′ 13″ N, long. 31° 50′ 53″ E), Bardawil-1 Well was drilled to a total depth of about 4490 m by Egyptian Petroleum Company (E.G.P.C) and located (lat. 31° 08′ 14″ N, long. 33° 07′ 35″ E) and Malha-1 Well was drilled to a total depth of about 2198 m by (E.G.P.C) at location (lat. 30° 59′ 12″ N, long. 33° 20′ 32″ E) (Fig. 1).

Methodology

Smear slides of each sample were prepared. Small pieces of the ditch samples were taken for nannofossil investigations according to the commonly technique suggested by Bramlette and Sullivan (1961), Hay (1964) and Perch-Nielsen (1985). The smear slides were examined using polarizing microscope at ×1000 magnification in cross polarized light.

Semi-quantitative analysis of the calcareous nannofossils was carried out on this study. Relative species abundance of calcareous nannofossils was estimated following the criteria used by some authors as Rio et al. (1990) and Fornaciari et al. (1996) as the following: *A* = abundant (>10 specimens/field of view), *C* = common (1–10 specimens/field of view), *F* = few (1 specimen/1–10 fields of view) and *R* = rare (1 specimen/ >10 fields of view).

Lithostratigraphy

The Oligo-Miocene sequence in this study was represented by five rock units arranged for the top to base as follows: Qawasim, Sidi Salem, Kareem, Rudeis and Qantara formations. The litho- and biostratigraphy of these rock units in the five wells are shown in (Figs. 2, 3, 4, 5 and 6).

Qawasim formation

The Qawasim Formation was first introduced by Rizzini et al. (1978). The type section is in the Qawasim-1 Well (lat. 31° 21′ N and long. 30° 51′ E), Nile Delta area (depth intervals between 2800 to 3765 m). It consists essentially of sand/shale section together with conglomerate (Zaghloul et al. 1977b). This formation conformably overlies the Sidi Salem and the Kareem formations in the El-Temsah-2 and San El-Hagar wells, respectively. It is not studied in the Boughaz-1, Bardawil-1 and Malha-1 wells.

Sidi Salem formation

This formation was introduced by the Stratigraphic Subcommittee of the NCGS (1974). The type section was drilled in the Sidi Salem-1 Well (lat. 31° 20′ N and long. 30° 43′ E), South of Lake Burullus.

The Sidi Salem Formation attains thicknesses of about 475, 400, 570 and 50 m in the Boughaz-1, El-Temsah-2, Bardawil-1 and Malha-1 wells, respectively. It unconformably overlies the Rudeis Formation and conformably underlies the Qawasim Formation in the Boughaz-1 Well. In the El-Temsah-2 Well, this formation is conformably overlain and underlain by the Qawasim and Qantara formations, respectively. While in the Malha-1 Well, it is unconformably underlain by the Qantara Formation.

Kareem formation

The Kareem Formation was first introduced by Ghorab et al. (1964) in its type locality at Gharib North-2 Well, Eastern Desert, from depth intervals 1310 to 1571 m (lat. 25° 25′ N and long. 32° 54′ E). This formation builds up the youngest rock unit of the Gharandal Group. In the type section, the Kareem Formation attains about 260 m thick and composed of evaporite in its lower part and becomes highly calcareous shale grading into marl in its upper part.

In the present study, the Kareem Formation is represented only in the San El-Hagar-1 Well, measures about 100 m thick and conformably overlies the Rudeis Formation.

Rudeis formation

The Rudeis Formation was originally described by Ghorab et al. (1964). The type section of this formation corresponds to the interval 1840–2620 m, in the Rudeis-2 Well in the West Central Sinai (lat. 28° 53′ N and long. 33° 10′ E). In the type section, the Rudeis Formation attains a thickness of 780 m and is composed of sandy shales and calcareous shales with hard sandstone beds and minor limestone.

In the present study, the Rudeis Formation attains a thickness of about 475 m in the Boughaz-1 Well and in the San El-Hagar Well; this formation measures about 110 m thick. In the Boughaz-1 Well, the Rudeis Formation unconformably underlies the Sidi Salem Formation while it conformably overlies the Qantara Formation. On the other hand, this formation in the San El-Hagar-1 Well conformably underlies and overlies the Kareem and Qantara formations, respectively.

Qantara formation

The type section is in Qantara-1 Well (lat. 31° 02′ N and long. 32° 14′ E), northeastern side of the Nile Delta area (from depth 2577–3110 m). The Qantara Formation was introduced by the

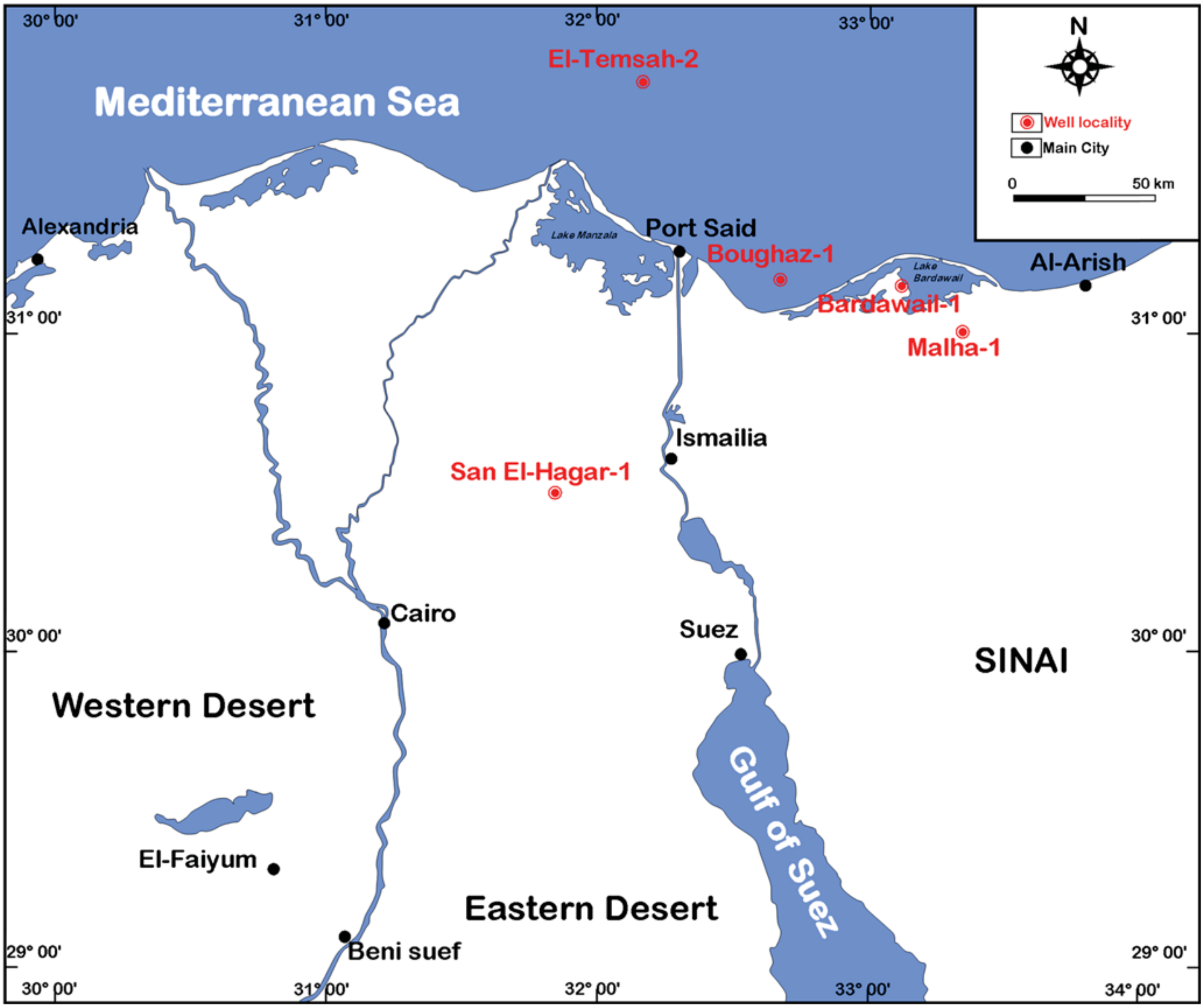


Fig. 1 Location map of the studied wells

International Egyptian Oil Company (IEOC, internal report). In the type section, this formation consists of light grey to whitish marls, with sandstone intercalation (El Heiny and Morsi 1992).

In the studied wells, the Qantara Formation measures about 828, 664, 680 and 50 m thick in the Boughaz-1, El-Temsah-2, San El-Hagar-1 and Malha-1 wells, respectively. In the Boughaz-1 Well, this formation conformably underlies the Rudeis Formation and unconformably overlies the Late Cretaceous sediments. The Qantara Formation conformably underlies the Sidi Salem Formation and the Rudeis Formation in the El-Temsah-2 Well and the San El-Hagar-1 Well, respectively. In the Malha-1 Well, the Qantara Formation unconformably underlies and overlies the Sidi Salem Formation and the Late Cretaceous formations, respectively.

Results and discussion

Nannofossil biostratigraphy

In the present study, the zonal schemes of Martini (1971) and Okada and Bukry (1980) have been followed. Other bioevents were used to improve nannofossil biostratigraphy. The biostratigraphic interpretations are based mainly on the lowest occurrence (LO) and highest occurrence (HO) of the marker species. In the subsurface wells, examinations of samples are usually downward due to contamination by caving, so, the first appearance (HO) of taxon downward was used for the determination of zonal boundaries. The ages, nannofossil zonal scheme, nannofossil relative abundance (ranged from common to very rare) and preservation (ranged from good to moderate) in the studied

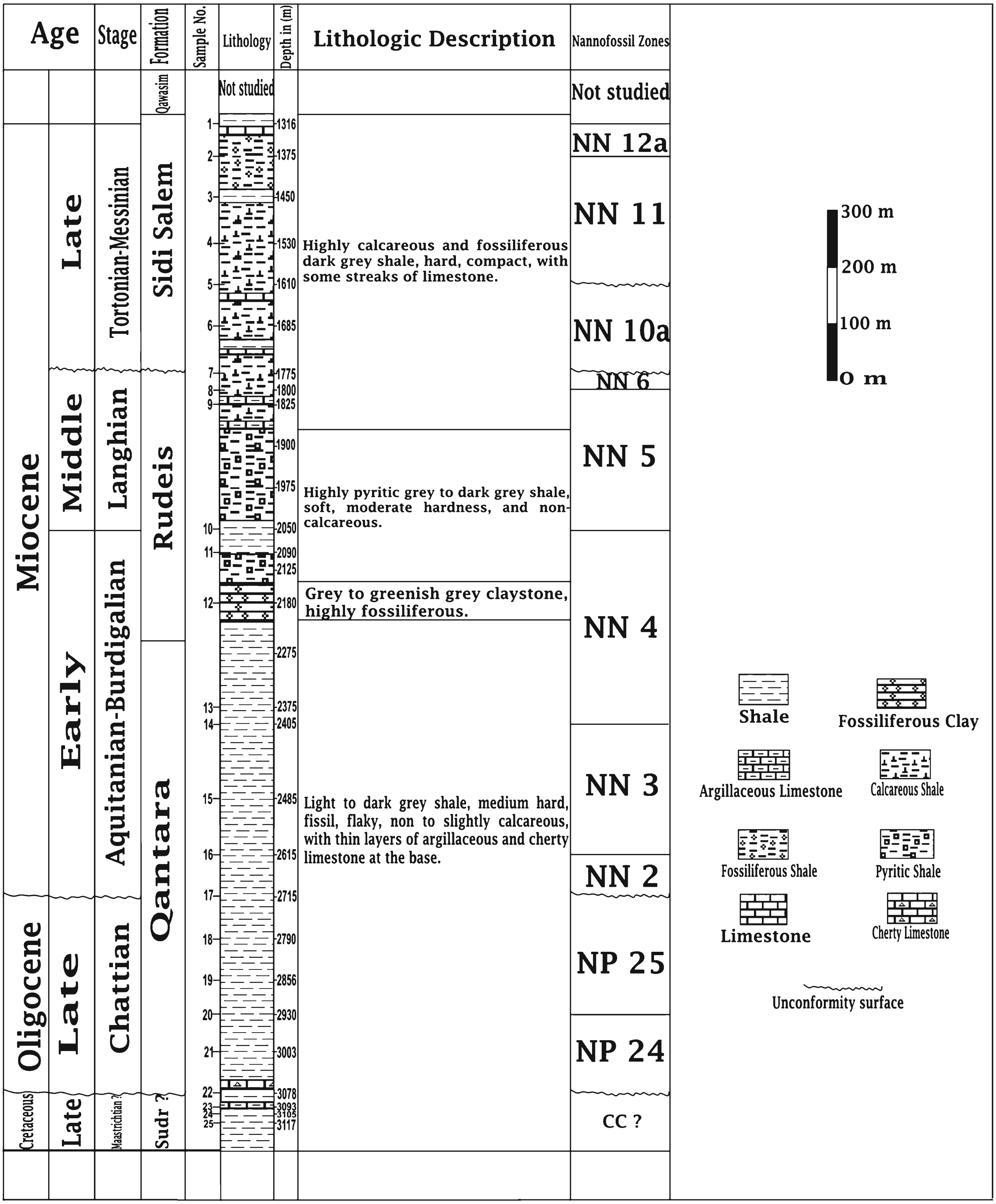


Fig. 2 Litho- and biostratigraphic units of the Boughaz-1 Well

wells are shown in stratigraphic distribution charts, (Figs. 7, 8, 9, 10 and 11). Unfortunately, some Cretaceous reworked taxa were recorded in the Boughaz-1 and Malha-1 wells (*Arkhangelskiella cymbiformis*, *Lucianorhabdus cayeuxii*, *Micula decussara*, *Watznaueria barnesae*, *Kamptnerius magnificus*, *Eiffellithus gorkae*,

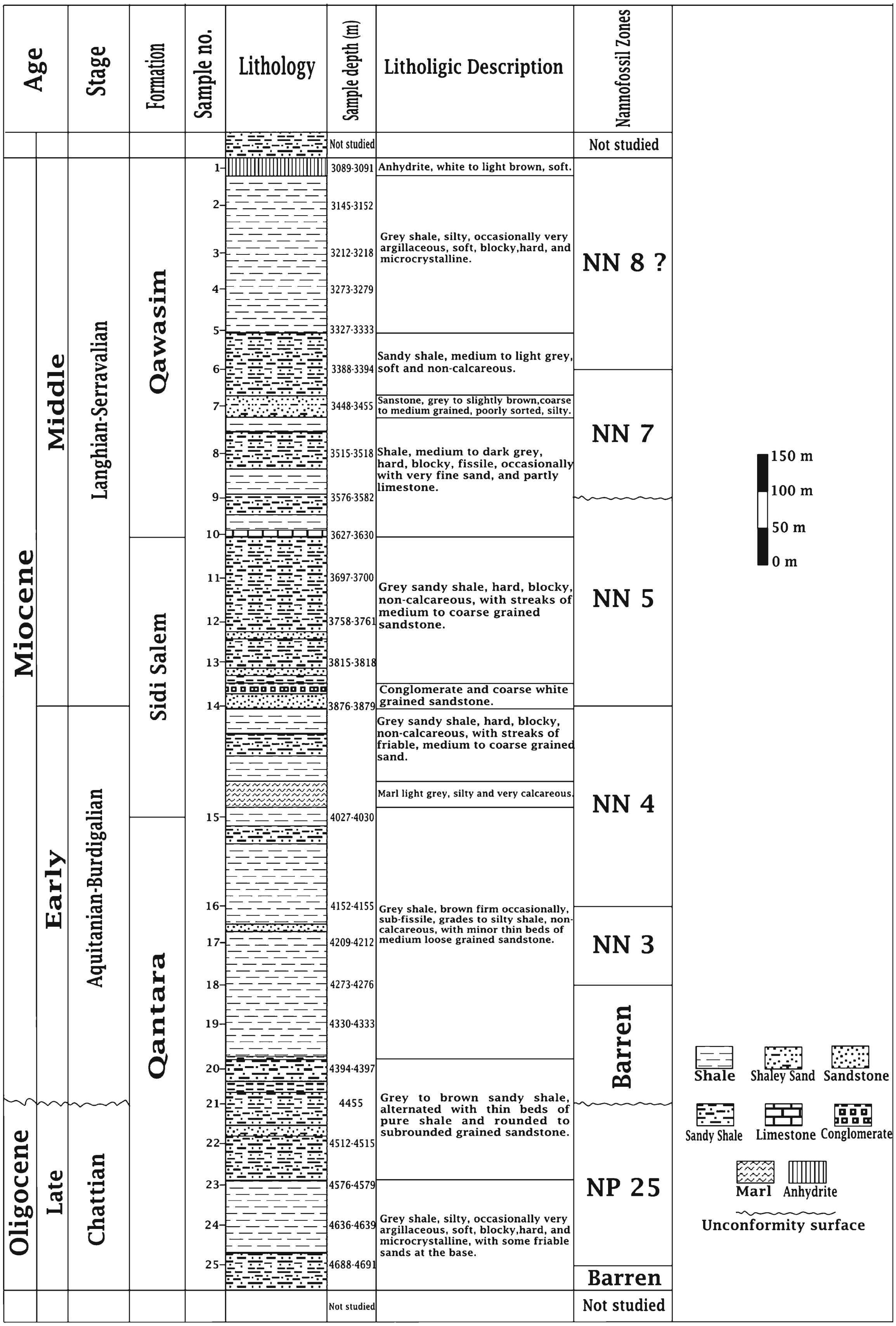


Fig. 3 Litho- and biostratigraphic units of the El-Temsah-2 Well

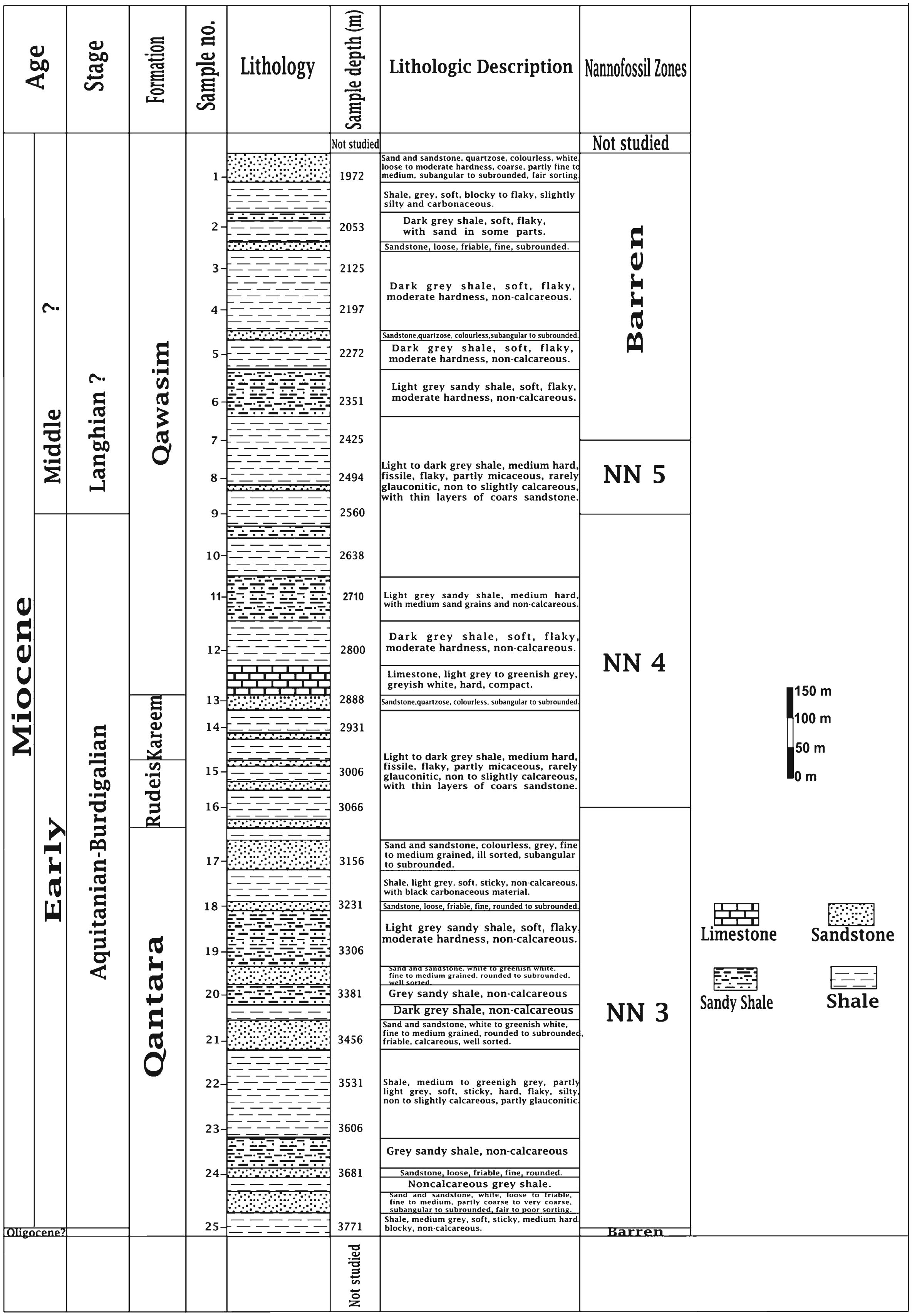


Fig. 4 Litho- and biostratigraphic units of the San El-Hagar-1 Well

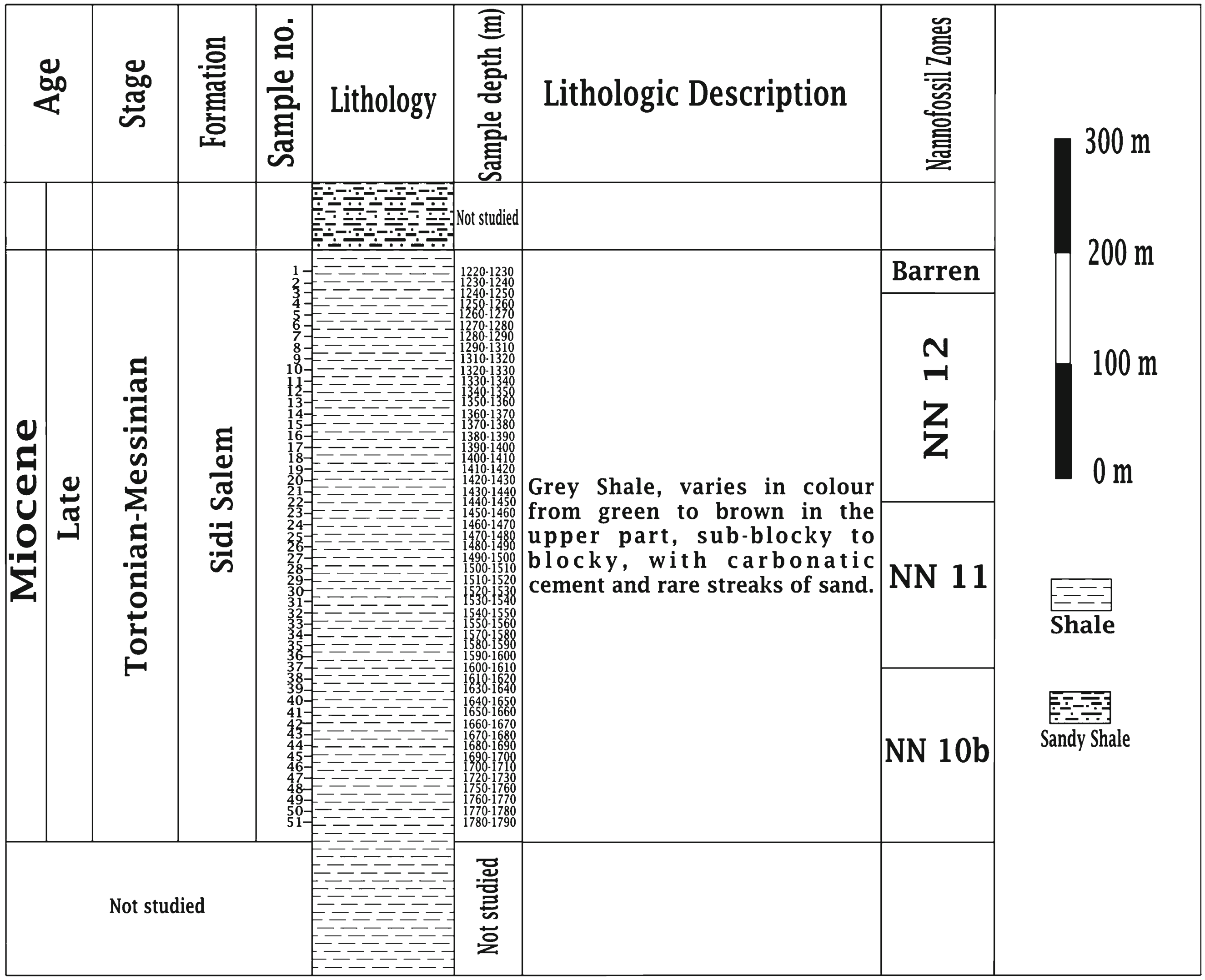


Fig. 5 Litho- and biostratigraphic units of the Bardawil-1 Well

etc.) (Figs. 7 and 11). Some representative nannofossil taxa are illustrated in Plates 1, 2, 3 and 4.

Amaurolithus tricorniculatus zone (NN12)

This zone is defined as the interval from the HO of *Discoaster quinqueramus* to the LO of *Ceratolithus rugosus* and/or the HO of *Ceratolithus acutus*.

In this study, the *A. tricorniculatus* Zone (NN12) is well recorded in the Bardawil-1 Well, and its lower part (NN12a) Subzone was defined in the Boughaz-1 Well. In the Bardawil-1 Well, it attains a thickness of about 200 m; the top of this zone was recorded at depth 1240 m whereas the base was at 1440 m. The NN12 Zone in this well occupies the upper part of Sidi Salem Formation. In the Boughaz-1 Well, the top of *Triquetrorhabdulus rugosus* Subzone (NN12a) was recorded at depth 1316 m and its base at depth 1375 m, (59 m thick), and it lies at the top of Sidi Salem Formation.

In the Bardawil-1 Well, the top of this zone was recognized at the lowest occurrence *of Ceratolithus rugosus* and the base was identified at the highest occurrence of *Discoaster quinqueramus.* While in the Boughaz-1 well, according to Martini (1971), the base of this zone was defined at the HO of *D. quinqueramus*, the top cannot be determined due to the lack of sufficient samples. The *Triquetrorhabdulus rugosus* Subzone (NN12a) of the Late Miocene is defined as the interval from the HO of *Discoaster quinqueramus* to the LO of *Ceratolithus acutus* (Okada and Bukry 1980).

So, in the Boughaz-1 well, only the *Triquetrorhabdulus rugosus* Subzone (NN12a) was defined and includes the interval from the HO of *Discoaster quinqueramus* to the HO of *Discoaster intercalaris*.

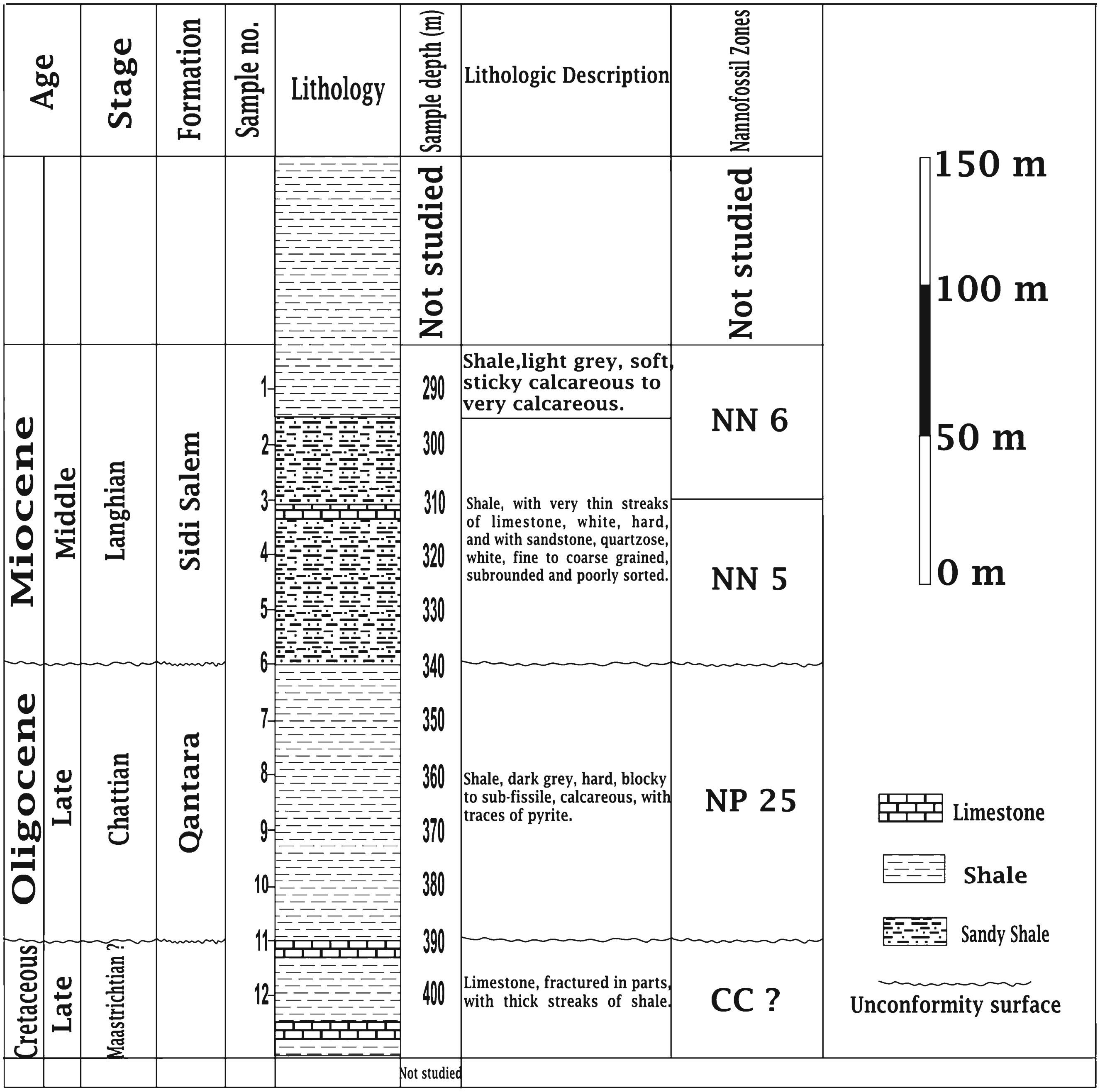


Fig. 6 Litho- and biostratigraphic units of the Malha-1 Well

Ceratolithus rugosus is rare in many basins worldwide, and its lowest occurrence can hardly be recognized due to the absence of core and side-wall samples (Huang 1997). For this reason, the highest occurrence of *Ceratolithus acutus* which defines the top of the Subzone CN10b by Bukry (1975) was adopted to mark the top of the Zone NN12 for the cutting samples as suggested by Varol (1983) and Womardt et al. (1992). The lowest occurrence of *Ceratolithus acutus* defines the boundary between the *Triquetrorhabdulus rugosus* Subzone (CN10a) and the overlying *C. acutus* Subzone (CN10b) of Bukry (1973) who noted that the nannofossils Subzone CN10a has a very short duration.

The *Amaurolithus tricorniculatus* Zone (NN12) or its subzones were correlated with that recorded by some other authors (e.g. Berggren et al. 1985; Raffi and Flores 1995; Gartner and Shyu 1996; Okada 2000; Abu Shama 2007; Faris et al. 2007; Fadiya and Salami 2012).

The most common assemblages of this zone are *Amaurolithus delicates*, *A. tricorniculatus*, *Braarudosphaera bigelowii*, *Coccolithus pelagicus*, *Reticulofenestra pseudoumbilicus*, *R. minuta*, *R. minutula*,

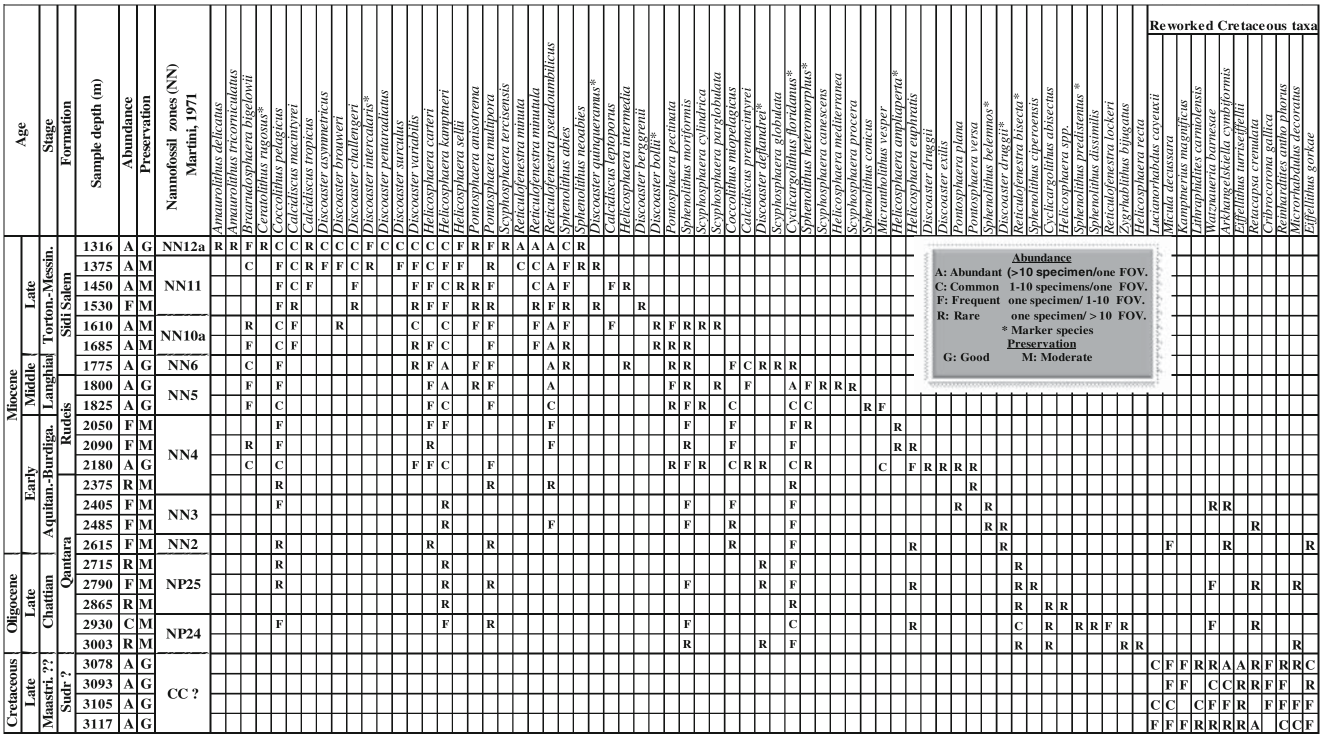


Fig. 7 Stratigraphic distribution chart of the recorded calcareous nannofossil species of the Boughaz-1 Well

Calcidiscus leptoporus, *C. macintyrei*, *C. tropicus*, *Discoaster brouweri*, *D. intercalaris*, *D. surculus*, *D. asymmetricus*, *D. challenger*, *D. pentaradiatus*, *D. variabilis*, *Helicosphaera carteri*, *H. sellii*, *Pontosphaera anisotrema*, *P. multipora*, *Scyphosphaera tercisensis*, *Sphenolithus abies* and *Sph. Neoabies*, in addition to the presence of *Ceratolithus rugosus.*

Discoaster quinqueramus zone (NN11)

It is defined as the interval from the LO to the HO of *D. quinqueramus* and the LO of *D. berggrenii* and/or the LO of *D. surculus* to the HO of *D. quinqueramus*.

This zone was recorded in the Boughaz-1 and Bardawil-1 wells, representing the middle part of Sidi Salem Formation. In the Boughaz-1 Well, this zone attains a thickness of about 235 m, from depth intervals 1375 m (top) to 1610 m (base). In the Bardawil-1 Well, it measures a thickness of about 160 m, from depth intervals 1440 m (top) to 1600 m (base). In both the Boughaz-1 and Bardawil-1 wells, the top and the base of the Zone NN11 were defined by the HO and the LO of *D. quinqueramus*, respectively.

Okada and Bukry (1980) subdivided the *Discoaster quinqueramus* Zone (CN9) into a lower *D. berggrenii* Subzone (CN9a) and an upper *Amaurolithus primus* Subzone (CN9b) according to the lowest occurrence of *A. primus* (the first horseshoe shaped calcareous nannofossil in the Neogene). Also, the LO of *Amaurolithus delicatus* and the HO of *Reticulofenestra rotaria* are significant in determination of Zone NN11. The LO of *A. delicatus* was proposed by Martini and Müller (1986) and it is equivalent to the LO of *A. primus* proposed by Bukry (1973). The two LOs (*A. primus* and *A. delicates*) were used for subdividing the Zone NN11 into the lower NN11a and upper NN11b subzones (Huang 1997). The LO of *R. rotaria* was first used by Theodoridis (1984) to define the base of the total range zone of *R. rotaria* within the Zone NN11. The lowest common occurrence (LCO) of *R. rotaria* has been detected above the LO of *A. primus* (Flores et al. 1992; Tazzi 1996).

In the Boughaz-1 and Bardawil-1 wells, *Discoaster quinqueramus* was grouped with *D. berggrenii*, but typical specimens of the *D. berggrenii* become extinct before the highest occurrence of *D. quinqueramus* as noted by Bukry (1973) in some oceanic areas and by Faris et al. (2007) in Northeast Nile Delta, Egypt. Also, the top and the base of the Zone NN11 were defined by the HO and the LO of *Discoaster quinqueramus*, respectively by El Sheikh (1995), Abu Shama (2007) and by Fadiya and Salami (2012).

In this study, both *Amaurolithus delicatus* and *A. primus* cannot be recorded in any sample. So, the LO and HO of *D. quinqueramus* is used herein to define the Zone NN11.

The nannofossil assemblages of *Discoaster quinqueramus* Zone (NN11) include *Braarudosphaera bigelowii*, *Coccolithus pelagicus*, *Reticulofenestra pseudoumbilicus*,

Age		Stage	Formation	Sample depth (m)	Abundance	Preservation	Nannofossil zones (NN) Martini, 1971	*Reticulofenestra pseudoumbilicus*	*Reticulofenestra minutula*	*Helicosphaera kamptneri*	*Coccolithus pelagicus*	*Helicosphaera sellii*	*Sphenolithus abies*	*Sphenolithus ne oabies*	*Pontosphaera multipora*	*Pontosphaera anisotrema*	*Calcidiscus leptoporus*	*Helicosphaera carteri*	*Calcidiscus macintyrei*	*Coccolithus miopelagicus*	*Calcidiscus tropicus*	*Sphenolithus moriformis*	*Pontosphaera plana*	*Sphenolithus heteromorphus**	*Cyclicargolithus floridanus*	*Discoaster variabilis*	*Discoaster deflandrei*	*Discoaster druggii*	*Helicosphaera ampliaperta**	*Sphenolithus belemnos**	*Helicosphaera euphratis*	*Sphenolithus conicus*	*Reticulofenestra bisecta**
Miocene	Middle	Langhian-Serravalian	Qawasim	3089-3090	R	M	NN8?	R	R	R	R	R	F	F	R	R	R	F															
				3145-3152	F	M		R	R	R	R	R	F	R	R	R																	
				3212-3219	C	M		C	F	F		F			R		R	F															
				3273-3279	R	M		R	R	R	R				R																		
				3327-3333	VR	M		R			R		R																				
				3388-3394	C	M	NN7	C	R	F	F		R		R	R		F	F	F	R												
				3448-3455	VR	M		R	R		R																						
				3515-3518	C	M		C		F	F				R			F	R	F		R	R										
				3576-3582	R	M	NN5			R					R			R		R				R									
			Sidi Salem	3627-3630	R	M		R		R						R		R		R				R									
				3697-3700	R	M		R		R					R			R		R		R											
				3758-3761	VR	M		R			R							R		R				R	R								
				3815-3818	R	M		R			R							R		R				R	R								
	Early	Aquitan.-Burdiga.		3876-3879	R	M	NN4				R				R							R		R		R			R				
			Qantara	4027-4030	F	M		F			R				R					R		F			F	R	R	R	F				
				4152-4155	F	M	NN3				R									R		R		R	F					R	R	R	
				4209-4212	R	M		R			R				R					F			R		R				R	R			
				4273-4276	B	-	Barren																										
				4330-4333	B	-																											
				4394-4397	B	-																											
Oligocene	Late	Chattian		4455	R	M	NP25	R			R				R										R								R
				4512-4515	R	M		R			VR											R											
				4576-4579	R	M					VR				R																		
				4636-4639	R	M		R			R											R											R
				4688-4691	B	-	Barren																										

Fig. 8 Stratigraphic distribution chart of the recorded calcareous nannofossil species of the El-Temsah-2 Well

R. minuta, *R. minutula*, *Calcidiscus leptoporus*, *C. macintyrei*, *C. tropicus*, *Discoaster brouweri*., *D. intercalaris*, *D. surculus*, *D. asymmetricus*, *D. challengeri*, *D. pentaradiatus*, *D. variabilis*, *D. berggrenii*, *Helicosphaera carteri*, *H. intermedia*, *H. sellii*, *Pontosphaera anisotrema*, *P. multipora*, *P. pectinata*, *Scyphosphaera tercisensis* Lezaud, *Sphenolithus abies* and *Sph. neoabies*, in addition to the marker species *Discoaster quinqueramus*.

Discoaster calcaris zone (NN10)

This zone is defined as the interval from the HO of *Discoaster hamatus* to the LO of *Discoaster quinqueramus*, or the LO of *Discoaster berggrenii*, or the LO of *Discoaster surculus*.

In the present study, this zone has been recorded in the Bardawil-1 and Boughaz-1wells. The Zone NN10 was recorded in lower part of Sidi Salem Formation in both two wells. The Zone NN10 can be divided into two subzones: NN10a and NN10b.The uppermost of *Discoaster calcaris* Zone (=Subzone NN10b) was recorded in the Bardawil-1 Well (depth 1600 to1790 m, about 190 m thick), while in the Boughaz-1 Well, the top of Subzone NN10a was defined (depth 1610 m), and it unconformably underlies the Zone NN11 due to the absence of the Subzone NN10b and it unconformably overlies the Zone NN6 due to the absence of zones NN9, NN8 and NN7. The Subzone NN10a in Boughaz-1 Well has 165 m thick.

In the Bardawil-1 Well, the top of *Discoaster calcaris* Zone NN10 (NN10b) was defined by the LOs of *Discoaster quinqueramus*, *D. berggrenii* and *D. surculus*. Whereas the base of Zone NN10 (NN10a) in this well cannot be detected due to the absence of *D. hamatus*. In the Boughaz-1 Well, the highest occurrence of *D. bollii* occurs near the top of Zone NN10, just below the lowest occurrence of *D. quinqueramus* (depth 1610 m), which defines the top of Zone NN10 in the Boughazi1 Well. So, there is a small hiatus between this Subzone NN10a and the Zone NN11, represented by the

Age		Stage	Formation	Sample depth (m)	Abundance	Preservation	Nannofossil zones (NN) Martini, 1971	*Cyclicargolithus floridanus*	*Coronocyclus nitescens*	*Sphenolithus heteromorphus**	*Reticulofenestra pseudoumbilicus*	*Reticulofenestra minutula*	*Helicosphaera kamptneri*	*Sphenolithus moriformis*	*Helicosphaera mediterranea*	*Pontosphaera multipora*	*Helicosphaera euphratus*	*Coccolithus miopelagicus*	*Sphenolithus conicus*	*Coccolithus pelagicus*	*Helicosphaera carteri*	*Braarudosphaera bigelowii*	*Discoaster druggii*	*Reticulofenestra lockeri*	*Thoracosphaera operculata*	*Discoaster variabilis*	*Coronocyclus nitiscens*	*Helicosphaera ampliaperta**	*Helicosphaera scissura*	*Sphenolithus belemnos**	*Cyclicargolithus abisectus*
Miocene	Middle	Langhian ?	Qwasim	1972	B	-	Barren																								
				2053	B	-																									
				2125	B	-																									
				2179	B	-																									
				2272	B	-																									
				2351	B	-																									
				2425	C	M	NN5	C	R	C	C	F	F	R	R	R	R	C	R	F	R	R									
				2494	C	M		C		C	C		F	F	R		R	F	R	F			R	R	R	R					
	Early	Aquitanian-Burdigalian		2560	A	G	NN4	C		C	C		F	F	R		R	F	R	F							R	F	R		
				2638	C	M		C		R	C		F			R		F		F				R				C	R		
				2710	C	M		C	R		C		F	R		R		C	R				R					F	R		
				2800	C	M		C			C		F	F		R	R	F						R	R			F	F		
			Kareem	2888	R	M		F		R										R											
				2931	R	M		R												R											
			Rudeis	3006	R	M		R												R											
				3066	B	-																									
			Qantara	3156	B	-																									
				3231	C	M		C			F			F				F		C			R	R							
				3306	F	M	NN3	F												R								R		R	
				3381	R	M		R												R											
				3465	C	M		C										C		F								R			
				3531	C	M		C			R		R	R						F	R			R							
				3606	F	M		F					R	R						R					R						
				3681	C	M		C			R			R			R			C											R
Oligocene?				3771	B	-	Barren																								

Fig. 9 Stratigraphic distribution chart of the recorded calcareous nannofossil species of the San El-Hagar-1 Well

absence of the Subzone NN10b. In the Boughaz-1 Well, the base of the Subzone NN10a cannot be determined due to the presence of a big hiatus (missing of zones NN9, NN8 and NN7).

Bukry (1973) subdivided the *Discoaster calcaris* Zone (CN8) (=NN10) into a lower *Discoaster bellus* Subzone (CN8a) and an upper *Discoaster neorectus* Subzone (CN8b) by the LO of *D. neorectus* and/or the LO of *Discoaster loeblichii*. Rio et al. (1990) noted a few specimens of typical *D. neorectus* from western equatorial Indian Ocean (Leg 115) and recorded *D. loeblichii* as sporadic species only occurred at higher stratigraphic level; therefore, they could not subdivide this zone as Bukry (1973).

The highest occurrence *Discoaster loeblichii* is used by Bukry (1973) to define the top of Subzone CN8b. The co-occurrences of *D. loeblichii* and of *D. berggrenii* were previously noted by Proto-Decima et al. (1978), Mazzei et al. (1979) and Parker et al. (1985) in the Atlantic Ocean. The range of *D. neorectus* restricted to CN8b of Bukry (1973). The top of Zone NN10 is defined by the lowest occurrence of *Discoaster quinqueramus*, and the top of the Zone CN8 (equivalent to top of the Zone NN10) is defined by the lowest occurrence of *Discoaster berggrenii*. Therefore, the highest occurrence of *Discoaster neohamatus* is a bioevent that occurs slightly below the lowest occurrence of *D. quinqueramus* and is used as the marker for defining the top of NN10 (Varol 1983). Another useful characteristic of this zone is the apparent decrease of *Reticulofenestra* over 7 μm in size and abrupt increase of *Reticulofenestra* less than 5 μm. Faris et al. (2007) determined the top and base of Zone NN10 in some wells at Northeast Nile Delta area.

The characteristic nannofossils of this zone include *Braarudosphaera bigelowii*, *Coccolithus pelagicus*, *Reticulofenestra pseudoumbilicus*, *R. minuta*, *R. minutula*, *Calcidiscus leptoporus*, *C. macintyrei*, *Discoaster brouweri* Tan emend., *D. surculus*, *D. bollii*, *D. variabilis*, *Helicosphaera carteri*/*H. kamptneri*, *Pontosphaera anisotrema*, *P. multipora*, *P. pectinata*, *Sphenolithus abies* and *Sph. moriformis*.

Catinaster coalitus zone (NN8)

The *Catinaster coalitus* Zone (NN8) is defined by the interval from the LO of *Catinaster coalitus* to the LO of *Discoaster hamatus*.

The base of *Catinaster coalitus* Zone (NN8) was recorded only in the El Temsah-2 Well at depth 3388 m. It occupies the upper part of Qawasim Formation. The thickness as well as top of this zone herein cannot be determined due to the absence of *Discoaster hamatus*.

Age		Stage	Formation	Sample depth (m)	Abundance	Preservation	Nannofossil zones (NN) Martini, 1971	*Amaurolithus delicatus*	*Amaurolithus tricorniculatus*	*Braarudosphaera bigelowii*	*Ceratolithus rugosus**	*Coccolithus pelagicus*	*Calcidiscus macintyrei*	*Calcidiscus tropicus*	*Discoaster asymmetricus*	*Discoaster brouweri*	*Discoaster challengeri*	*Discoaster pentaradiatus*	*Discoaster surculus*	*Discoaster variabilis*	*Helicosphaera carteri*	*Helicosphaera kamptneri*	*Helicosphaera sellii*	*Pontosphaera anisotrema*	*Pontosphaera multipora*	*Scyphosphaera tercisensis*	*Reticulofenestra minuta*	*Reticulofenestra minutula*	*Reticulofenestra pseudoumbilicus*	*Sphenolithus abies*	*Sphenolithus neoabies*	*Discoaster quinqueramus**	*Calcidiscus leptoporus*	*Helicosphaera intermedia*	*Discoaster berggrenii*	*Pontosphaera pectinata*	*Sphenolithus moriformis*	*Scyphosphaera cylindrica*	*Scyphosphaera parglobulata*
Miocene	Late	Tortonian-Messinian	Sidi Salem	1220-1230	B	-	Barren																																
				1230-1240	B	-																																			
				1240-1250	F	M	NN12	R	R	C	R	R	C	R	C	R	C	C	R	R	C	C	R	R	F	R	C	C	F	C	R								
				1250-1260	F	M		R	R	R		VR	F	R	R		R			R		R	R	F	R		F	F	R	F	R								
				1260-1270	C	M		R	R	R		F	F	F	C	R	R		R	F	F	F		R	R	F	R	F	R	R									
				1270-1280	B	-																																	
				1280-1290	B	-																																	
				1290-1310	R	M		R	R	R	VR	R	R	R	R	R		R	R	R	R	R		R	R	R	R	R	R	R	R								
				1310-1320	R	M		R	R	R		R	F		R		R		R		R	R	R	VR	R	F	F	R	VR	R	R								
				1320-1330	B	-																																	
				1330-1340	B	-																																	
				1340-1350	R	M			R	F	VR	F	R	R			R			R	R	R		VR	R		R	R	R		R								
				1350-1360	R	M		R		R		R		R					R		R	R			R		R			R	R								
				1360-1370	F	M		R		R		R	R		R	R		R		R		F	R	R		R	R	R		R									
				1370-1380	B	-																																	
				1380-1390	F	M				R		R		R	R			R		R		F		R	R		R	R	R	R	R								
				1390-1400	R	M		R		R		R		R					R		R	R		R			R			R									
				1400-1410	R	M			R			R	R			R					R	R		R			R	R			R								
				1410-1420	R	M				R	VR	R									R	R		R			R	R											
				1420-1430	C	G		F	F			R			R	R	R	R		R	F	F	R	F	R	R	R	R	F	R	R								
				1430-1440	R	M		R		R	VR	R		R					R			R			R		R			R	R								
				1440-1450	R	M	NN11			R		F	R	R	F	F	R		F	F	R	F	F		R		R	R	R	F	R	R	R	R					
				1450-1460	R	M						F	R	F			F			F	F	R	R	R	F			R	R	F			F	R					
				1460-1470	F	M						F	R				R			R	F	F		R	R		R	R	F	R		R			R				
				1470-1480	R	M				R		R		R							R			R	R			R											
				1480-1490	R	M				R			R							R		R			R		R	R		R	R			R					
				1490-1500	R	M							R							R		R	R					R	R										
				1500-1510	R	M						R								R		R		R			R	R		R									
				1510-1520	F	M				F			R				R		R	R	R			R				R	R	R			R						
				1520-1530	C	G				F		R	R	R	R	R	R	R		R		F	R		F	R	R	R	R	R	R	R		R	R	R			
				1530-1540	R	M				R		R	R							R				R	R			R											
				1540-1550	R	M						R		R						R	R						R	R	R	R									
				1550-1560	R	M							R							R	R	F			R			R	R										
				1570-1580	R	M				R		R								R	R	R		R	R			R	R										
				1580-1590	F	M						R	R			R	R		R	R		R	R				R	R		R			R	R					
				1590-1600	R	M				R		R		R					R	R		R			R			R	R	R	R	R			R				
				1600-1610	R	M	NN10			R		R	F			R		R		R		R		F	R			F	R	F			R			F	R	R	R
				1610-1620	R	M				R		R	R							R	F	R			F			R	R	R						R	R		
				1630-1640	R	M						R								R		R								R						R		R	
				1640-1650	R	M							R	R		R		R				R			R					R						R	R		R
				1650-1660	R	M						R								R		R								R						R		R	
				1660-1670	R	M						R								R		R						R										R	
				1670-1680	R	M														R	R	R					R							R			R		
				1680-1690	B	-																																	
				1690-1700	B	-																																	
				1700-1710	F	M				R		R	R					R	R			R			F			R			R					R			R
				1720-1730	F	M				R		R	R				R			R			R					R	R							R	R		
				1750-1760	R	M						R									R	R							R										
				1760-1770	R	M						R									R	R			R											R		R	
				1770-1780	R	M						R										R						R		R									
				1780-1790	F	M				R		R	R			R				R	R	R		VR	R			R	F	R	R					R	R	R	R

Fig. 10 Stratigraphic distribution chart of the recorded calcareous nannofossil species of the Bardawil-1 Well

																																Reworked Cretaceous taxa											
Age		Stage	Formation	Sample depth (m)	Abundance	Preservation	Nannofossil zones (NN) Martini, 1971	*Braarudosphaera bigelowii*	*Coccolithus pelagicus*	*Calcidiscus macintyrei*	*Calcidiscus tropicus*	*Helicosphaera carteri*	*Helicosphaera kamptneri*	*Pontosphaera anisotrema*	*Pontosphaera multipora*	*Reticulofenestra minuta*	*Reticulofenestra pseudoumbilicus*	*Sphenolithus abies*	*Calcidiscus leptoporus*	*Helicosphaera intermedia*	*Pontosphaera pectinata*	*Sphenolithus moriformis*	*Coccolithus miopelagicus*	*Calcidiscus premacintyrei*	*Scyphosphaera globulata*	*Cyclicargolithus floridanus**	*Triquetrorhabdulus rugosus*	*Sphenolithus heteromorphus**	*Zygrhablithus bijugatus*	*Reticulofenestra bisecta**	*Lucianorhabdus cayeuxii*	*Micula decussara*	*Kamptnerius magnificus*	*Lithraphidites carniolensis*	*Watznaueria barnesae*	*Arkhangelskiella cymbiformis*	*Eiffellithus turriseiffellii*	*Retacapsa crenulata*	*Cribrocorona gallica*	*Reinhardtites anthophorus*	*Microrhabdulus decoratus*	*Eiffellithus gorkae*
Miocene	Middle	Langhian	Sidi Salem	290	F	M	NN6	F	F	R	R	R	C	R	F	R	R	R	R		R		F	F	R	R	R															
				300	F	M		R	F	R	R		F	R	F	R				R		R	F			R																
			Qantara	310	C	M	NN5	C	C			F	R		F								C					R								R						
				320	F	M		R	R				R													R																
				330	A	M		R	F			R	R		R								F					R										R				
Oligocene	Late	Chattian		340	F	M	NP25	R	R						R														R	F												
				350	F	M		F	F				R		R															F										R		
				360	F	M		R	R				F																		F											
				370	F	M		F	R																					R					F							
				380	F	M		R																						R					R							
Cret.	Late	Maas	?	390	F	M	CC ?																								F	R	R		F	R		F		F	F	F
				400	A	G																									A	R	F	R	A	F	R	A	A	A	F	F

Fig. 11 Stratigraphic distribution chart of the recorded calcareous nannofossil species of the Malha-1 Well. (Note: all lithologic descriptions and symbols for (Figs. 7–11) are presented in (Figs. 2–6) respectively)

In the El-Temsah-2 Well, the base of this zone has been defined roughly by the HO of *Coccolithus miopelagicus* due to the absence of *Catinaster coalitus*. The top of Zone NN8 also cannot be determined in the present study as a result of the absence of the Zone NN9. *Discoaster exilis* and *Coccolithus miopelagicus* usually disappear near the top of Zone NN8 (Perch-Nielsen 1985; Rio et al. 1990).

The LO of *Discoaster pseudovariabilis* also approximates the LO of *Catinaster coalitus* (Perch-Nielsen 1985). Rio et al. (1990) recorded that *Discoaster brouweri* and *D. calcaris* are common in this inteval and *D. pseudovariabilis* is rare. On the other hand, the HO of *C. miopelagicus* is used to approximate the base of the Zone NN8 in the absence of *C. coalitus* (Raffi and Flores 1995; Marino and Flores 2002; McGonigal and Wei 2003). The top of NN8 fits the original definition of the same zone by Martini (1971) in some wells of the Northeast Nile Delta as the Ras El Barr-1 Well (Faris et al. (2007). Whereas, the HO of *Discoaster exilis* is used to approximate the top of the Zone NN8 (Perch-Nielsen 1985; Rio et al. 1990).

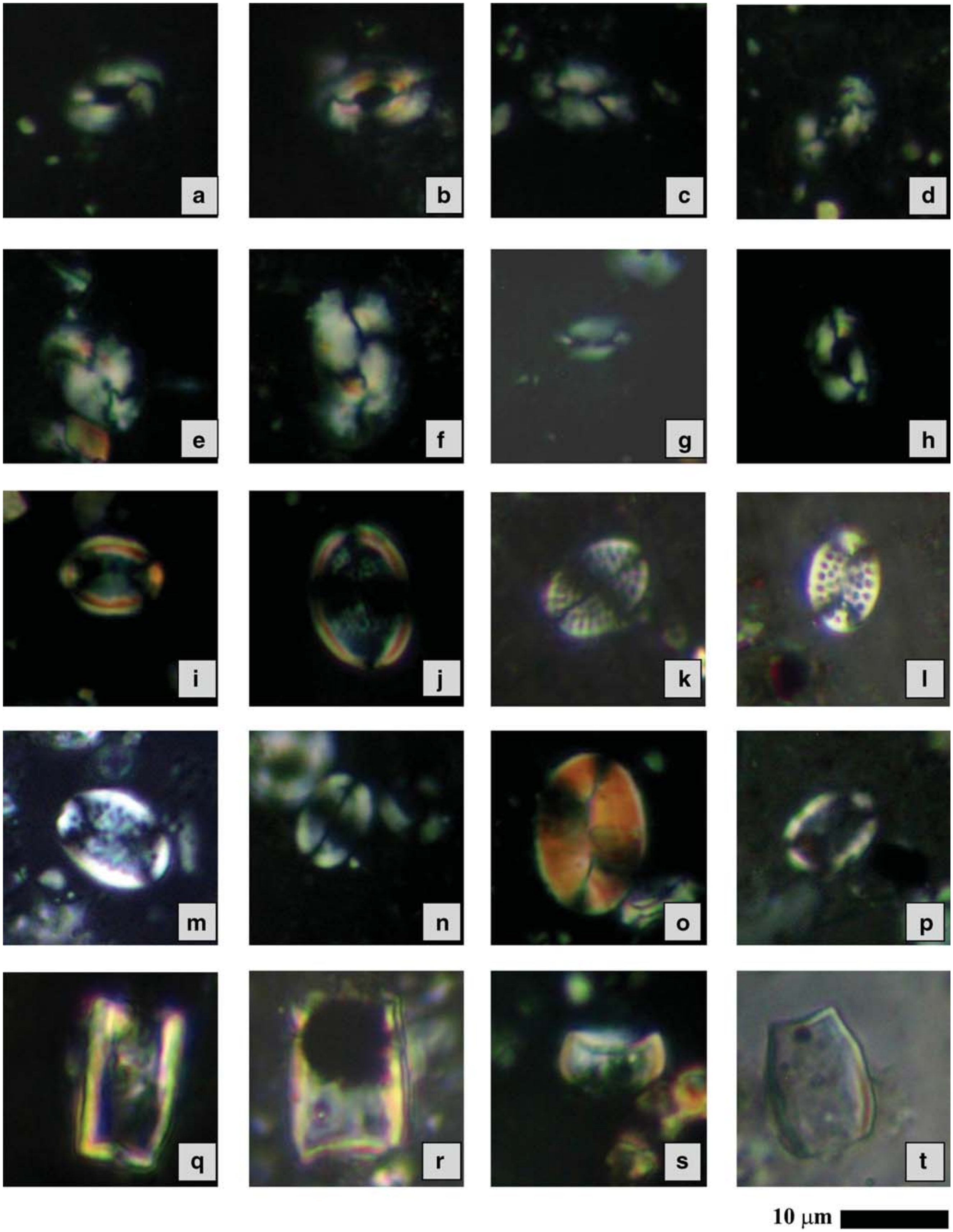
The most common assemblages of this zone include *Reticulofenestra pseudoumbilicus*, *R. minutula*, *Calcidiscus macintyrei*, *Helicosphaera carteri*/*H. kamptneri*, *Pontosphaera anisotrema*, *P. multipora* and *Sphenolithus abies*.

Discoaster kugleri zone (NN7)

This zone includes the Interval from the LO of *Discoaster kugleri* and/or the HO of *Cyclicargolithus floridanus* to the LO of *Catinaster coalitus*.

The top of the Zone NN7 can be recognized in only one well (El-Temsah-2) of the present five studied wells. It lies at depth 3388 m, while its base cannot be recognized due to the absence of the Zone NN6. The thickness of the *Discoaster kugleri* Zone (NN7) in the El-Temsah-2 Well extends to the top of the Zone NN5, from depth 3388 to 3576 m (188 m thick.), in the lower part of Qawasim Formation. In the present study, the top of this zone can be roughly defined by the HO *Coccolithus miopelagicus* as Marino and Flores (2002) due to the absence of the marker species *Catinaster coalitus*. On the other hand, the base of this zone cannot be defined due to the presence of unconformity surface between the Zone NN7 and the Zone NN5, recorded by the absence of the Zone NN6. So, in the El-Temsah-2 Well, the Zone NN7 unconformably overlies the Zone NN5.

Discoaster deflandrei becomes very rare and disappears near the top of the Zone NN7 (Perch-Nielsen 1985). According to Ellis (1981) and Perch-Nielsen (1985), *Discoaster kugleri* disappears near the top of Zone NN7. The highest occurrence of *D. kugleri*, an auxiliary bioevent proposed by Bukry (1973), was used to mark the top of the NN7 Zone. Theodoridis (1984) mentioned that the highest occurrence of *Helicosphaera walbersdorfensis* occurs close to the lowest occurrence of *Catinaster coalitus*. The highest occurrence of *H. walbersdorfensis* is correlated with the top of NN7 Zone (Fornaciari et al. 1996; Siesser and de Kaenel 1999). Marino and Flores (2002) used the highest occurrence of *Coccolithus miopelagicus* to roughly approximate the NN7/NN8 boundary. Faris et al. (2007) used the highest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◀ **Plate 1** **a**, **b** *Helicosphaera ampliaperta* Bramlette and Wilcoxon (1967). **a** San El-Hagar-1 Well, Sample depth 2638 m, Qawasim Formation, *Helicosphaera ampliaperta* Zone (NN4). **b** Boughaz-1 Well, Sample depth 2090 m, Rudeis Formation, *Helicosphaera ampliaperta* Zone (NN4). **c** *Helicosphaera kamptneri*/*Helicosphaera carteri* (Wallich, 1877) Kamptner, 1954, Boughaz-1 Well, Sample depth 1375 m, Sidi Salem Formation, *Discoaster quinqueramus* Zone (NN11). **d** *Helicosphaera euphratis*, Haq (1966), Boughaz-1 Well, Sample depth 2930 m, Qantara Formation, *Sphenolithus distentus* Zone (NP24). **e**, **f** *Helicosphaera carteri*/*Helicosphaera kamptneri*, Hay and Mohler in Hay et al. (1967), Boughaz-1 Well, Sample depth 1375 m, Sidi Salem Formation, *Discoaster quinqueramus* Zone (NN11). **g** *Helicosphaera sellii*, (Bukry and Bramlette, 1969) Jafar and Martini, 1975, Boughaz-1 Well, Sample depth 1316 m, Sidi Salem Formation, *Amaurolithus tricorniculatus* Zone (NN12). **h** *Helicosphaera scissura*, Miller (1981), San El-Hagar-1 Well, Sample depth 2800 m, Qawasim Formation, *Helicosphaera ampliaperta* Zone (NN4). **i**, **j** *Pontosphaera anisotrema*, (Kamptner, 1956) Backman, 1980. **i** El-Temsah-2 Well, Sample depth 3394 m, Qawasim Formation, *Discoaster kugleri* Zone (NN7). **j** Boughaz-1 Well, Sample depth 1450 m, Sidi Salem Formation, *Discoaster quinqueramus* Zone (NN11). **k**, **l** *Pontosphaera multipora*, (Kamptner, 1948) Roth, 1970, **k** Boughaz-1 Well, Sample depth 1530 m, Sidi Salem Formation, *Discoaster quinqueramus* Zone (NN11). **l** Boughaz-1 Well, Sample depth 1685 m, Sidi Salem Formation, *Discoaster calcaris* Zone (NN10). **m** *Pontosphaera pectinata*, (Bramlette and Sullivan) Sherwood, 1974, Boughaz-1 Well, Sample depth 1610 m, Sidi Salem Formation, *Discoaster calcaris* Zone (NN10). **n**, **o** *Pontosphaera plana*, (Bramlette and Sullivan, 1961) Haq, 1971, Boughaz-1 Well, Sample depth 2180 m, Rudeis Formation, *Helicosphaera ampliaperta* Zone (NN4). **p** *Pontosphaera versa*, (Bramlette & Sullivan, 1961) Sherwood (1974), Boughaz-1 Well, Sample depth 2180 m, Rudeis Formation, *Helicosphaera ampliaperta* Zone (NN4). **q** *Scyphosphaera cylindrica*, Kamptner (1955), Boughaz-1 Well, Sample depth 1610 m, Sidi Salem Formation, *Discoaster calcaris* Zone (NN10). **r** *Scyphosphaera tercisensis*, Lezaud (1968), Boughaz-1 Well, Sample depth 1316 m, Sidi Salem Formation, *Amaurolithus tricorniculatus* Zone (NN12). **s** *Scyphosphaera parglobulata*, Bukry & Percival (1971), Boughaz-1 Well, Sample depth 1610 m, Sidi Salem Formation, *Discoaster calcaris* Zone (NN10). **t** *Scyphosphaera procera*, Kamptner (1955), Boughaz-1 Well, Sample depth 1800 m, Rudeis Formation, *Sphenolithus heteromorphus* Zone (NN5)

occurrence of *Helicosphaera walbersdorfensis* at Bougaz E-1 Well, to roughly approximate the NN7/NN8 boundary.

This zone includes *Reticulofenestra pseudoumbilicus*, *R. minutula*, *Calcidiscus macintyrei*, *C. tropicus*, *Coccolithus miopelagicus*, *Helicosphaera carteri*/*H. kamptneri*, *Pontosphaera anisotrema*, *P. multipora*, *P. plana*, *Sphenolithus moriformis* and *Sphenolithus abies*.

Discoaster exilis zone (NN6)

This zone is defined as the interval from the HO of *Sphenolithus heteromorphus* to the LO of *Discoaster kugleri* and/or the HO of *Cyclicargolithus floridanus*.

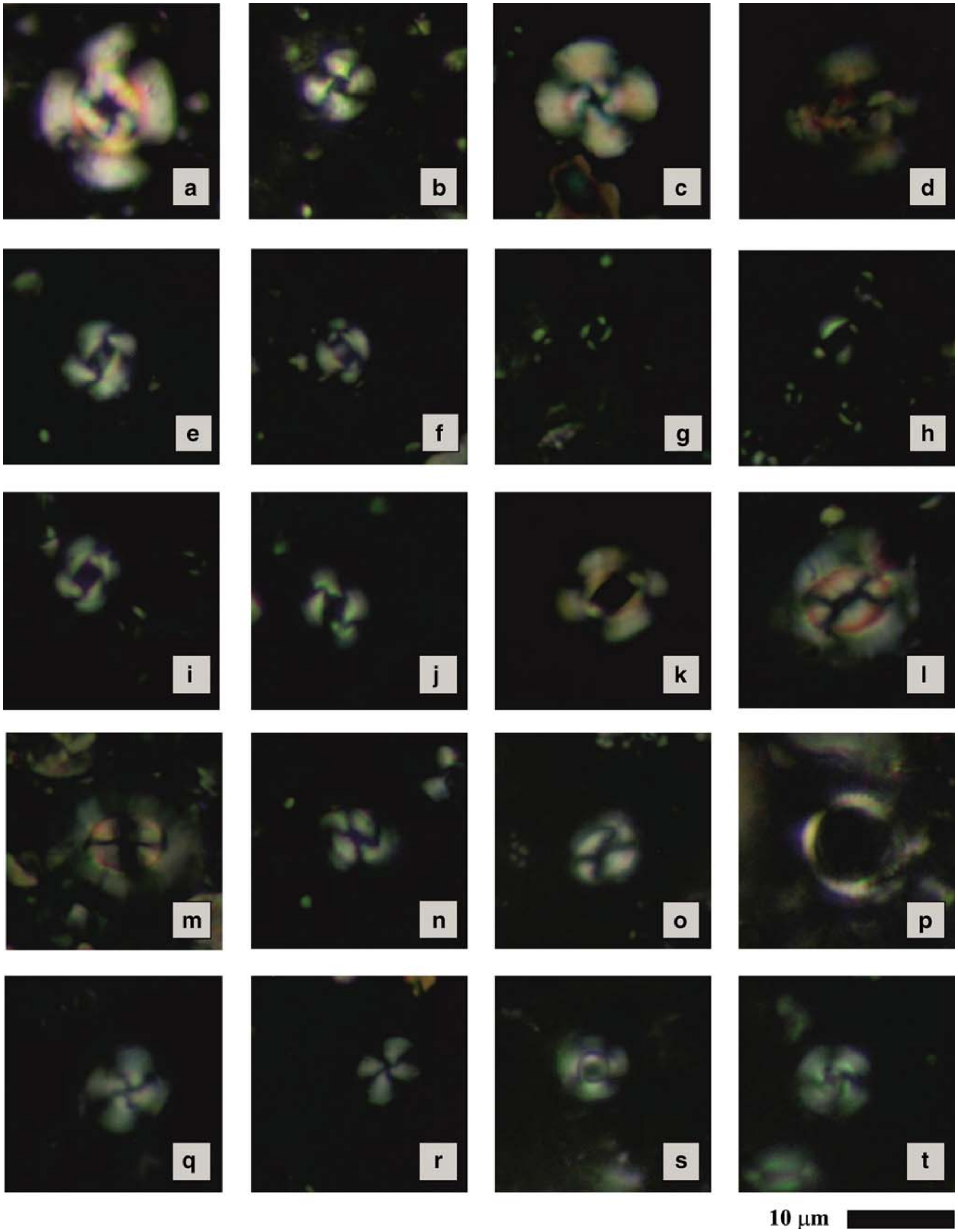
The Zone NN6 has been recorded in the Boughaz-1 and Malha-1 wells. In the Boughaz-1 Well, the highest occurrence of *Cyclicargolithus floridanus* occurs at depth 1775 m, within the topmost part of Rudeis Formation and defines the top of this zone. While, the base of the Zone NN6 occurs at depth 1800 m within the uppermost part of Rudeis Formation. It attains a thickness of about only 25 m due to the presence of a big hiatus between this zone and the Subzone NN10a. So that, may be the upper part of this zone has been eroded. In the Malha-1 Well, the top of this zone can be placed at depth 290 m and its base at depth 310 m (20 m thick), within the Sidi Salem Formation.

The marker species *Discoaster kugleri* of the top of the Zone NN6 Martini (1971) was not recorded in both the Boughaz-1 and Malha-1 wells. The HO of this species was considered as poor event by many authors. So, an alternative criteria have been proposed to define the top boundary of Zone NN6 as the HO of *Cyclicargolithus floridanus* was taken as a secondary marker for the base of CN5b Subzone (Bukry 1973). Ellis (1981) suggested that as a substitute event of the lowest occurrence of *Discoaster bollii*. Gartner and Chow (1985) suggested that the highest occurrence of *Coronocyclus nitescens* may be useful in subdividing the interval above the HO of *Sphenolithus heteromorphus* and below the LO of *Catinaster coalitus*. Marino and Flores (2002) used the lowest occurrence of *Calcidiscus macintyrei* to roughly approximate the top of the *Discoaster exilis* (NN6) Zone. They mentioned that the HO of *Calcidiscus premacintyrei* comes together with the LO of *Calcidiscus macintyrei*, considering that the two bioevents are dated at 12.65 and 12.34 Ma (Shackleton et al. 1995), respectively, suggesting the presence of a short hiatus.

In the present study, the HO of *Cyclicargolithus floridanus* was used as a secondary marker to determine the top of the Zone NN6 in both the Boughaz-1 and Malha-1 wells. The base of the *Discoaster exilis* (NN6 Zone) in our study has been defined by the HO of *Sphenolithus heteromorphus* in the both two wells Boughaz-1 and Malha-1.

A short-spaced extinction between *Sphenolithus heteromorphus* and *Cyclicargolithus floridanus* is recorded in the Equatorial Pacific and Equatorial Atlantic Oceans (Olafsson 1989). Parker et al. (1985) observed in the mid-latitude of North Atlantic Ocean (DSDP Site 563) that the highest occurrence of *Cyclicargolithus floridanus* occurs well below the lowest occurrence of *Discoaster kugleri*. The highest common occurrence of *Calcidiscus premacintyrei* and lowest occurrence of the large form *C. macintyrei* have been observed in the Mediterranean sections by Fornaciari et al. (1996) and oceanic areas Raffi et al. (1995) which occur within NN6 Zone and correlate with MNN6-MNN7 pars of Fornaciari et al. (1996). Also, many other authors used the highest occurrence of *Cyclicargolithus floridanus* to define the top of the Zone NN6 (Faris et al. 2007, 2009; Abu Shama 2007).

Okada and Bukry (1980) used this species (*Cy. floridanus*) as a marker for the top of the CN5a Subzone. There are some nannofossil specialists in marking the top of the NN6 Zone by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10 μm

◀ **Plate 2** **a** *Cyclicargolithus abisectus*, (Müller, 1970) Wise (1973), Boughaz-1 Well, Sample depth 1825 m, Rudeis Formation, *Sphenolithus heteromorphus* Zone (NN5). **b**, **c** *Cyclicargolithus floridanus*, (Roth & Hay in Hay et al. 1967) Bukry (1971a), San El-Hagar-1 Well, Sample depth 2494 m, Qawasim Formation, *Sphenolithus heteromorphus* Zone (NN5). **d** *Reticulofenestra bisecta*, (Hay et al. 1966) Bukry and Percival, 1971, Boughaz-1 Well, Sample depth 2930 m, Qantara Formation, *Sphenolithus distentus* Zone (NP24). **e**, **f** *Reticulofenestra lockeri*, Müller (1970), Boughaz-1 Well, Sample depth 2930 m, Qantara Formation, *Sphenolithus distentus* Zone (NP24). **g**, **h** *Reticulofenestra minuta*, Roth (1970), Boughaz-1 Well, Sample depth 1316 m, Sidi Salem Formation, *Amaurolithus tricorniculatus* Zone (NN12). **i**–**k** *Reticulofenestra pseudoumbilicus*, (Gartner, 1967) Gartner, 1969, **i**, **j** Boughaz-1 Well, Sample depth 1316 m, Sidi Salem Formation, *Amaurolithus tricorniculatus* Zone (NN12). **k** San El-Hagar-1 Well, Sample depth 2425 m, Qawasim Formation, *Sphenolithus heteromorphus* Zone (NN5). **l**, **m** *Coccolithus miopelagicus*, (Bukry, 1971) Wise, 1973, Boughaz-1 Well, Sample depth 2180 m, Rudeis Formation, *Helicosphaera ampliaperta* Zone (NN4). **n**, **o** *Coccolithus pelagicus*, (Wallich, 1877) Schiller, 1930. **n** Boughaz-1 Well, Sample depth 1316 m, Sidi Salem Formation, *Amaurolithus tricorniculatus* Zone (NN12). **o** San El-Hagar-1 Well, Sample depth 2425 m, Qawasim Formation, *Sphenolithus heteromorphus* Zone (NN5). **p** *Coronocyclus nitescens*, (Kamptner, 1963) Bramlette and Wilcoxon, 1967, San El-Hagar-1 Well, Sample depth 2560 m, Qawasim Formation, *Helicosphaera ampliaperta* Zone (NN4). **q**, **r** *Calcidiscus leptoporus*, (Murray and Blackman, 1895) Loeblich and Tappan, 1978, Boughaz-1 Well, Sample depth 1450 m, Sidi Salem Formation, *Discoaster quinqueramus* Zone (NN11). **s**, **t** *Calcidiscus macintyrei*, (Bukry and Bramlette, 1966) Loeblich and Tappan, 1978, Boughaz-1 Well, Sample depth 1316 m, Sidi Salem Formation, *Amaurolithus tricorniculatus* Zone (NN12)

Cy. floridanus (e.g. Varol 1983; Huang and Huang 1984; Huang 1997; Tanaka and Takahashi 1998; Odin et al. 2001; McGonigal and Wei 2003; Pospichal 2003).

The characteristic nannofossils of this zone include *Reticulofenestra pseudoumbilicus*, *R. minutula*, *Coccolithus miopelagicus*, *Cyclicargolithus floridanus*, *Helicosphaera carteri*/*H. kamptneri*, *Pontosphaera anisotrema*, *P. multipora*, *Sphenolithus moriformis* and *Sphenolithus abies*. The highest occurrence of *Calcidiscus premacintyrei* and the lowest rare occurrence of *Calcidiscus macintyrei* occur within the NN6 Zone.

Sphenolithus heteromorphus zone (NN5)

Sphenolithus heteromorphus Zone (NN5) is defined by the interval from the HO of *Helicosphaera ampliaperta* to the HO of *Sphenolithus heteromorphus*.

This zone was recorded in four wells in the present study (Boughaz-1, El-Temsah-2, San El-Hagar-1, Malha-1). In the Boughaz-1 Well, this zone reaches a thickness of about 250 m from depth 1800 m (top) to 2050 m (base) within the upper part of Rudeis Formation. The base of this zone was also well recognized in both the El-Temsah-2 and San El-Hagar-1 wells at depths 3876 and 2560 m, respectively. In the El-Temsah-2 Well, the top of this zone cannot be defined due to the presence of unconformity surface represented by the absence of NN6 Zone. In this well, the Zone NN5 lies within the lowermost part of Qawasim Formation and within the upper part of Sidi Salem Formation. Whereas in the San El-Hagar Well, the top of the Zone NN5 can be placed roughly below the present barren zone at the HO of *Sphenolithus heteromorphus* at depth 2425 m within the Qawasim Formation. This zone attains a thickness of about 135 m below the barren horizon. In the Malha-1 Well, the *S. heteromorphus* Zone (NN5) attains a thickness of about 30 m. Its top was recorded at depth 310 m and its base at depth 340 m within the upper part of Sidi Salem Formation.

In this study, the HO of *Helicosphaera ampliaperta* and HO of *Sphenolithus heteromorphus* have been used to define the base and the top of the Zone NN5, respectively, in the Boughaz-1 Well. The marker species *Helicosphaera ampliaperta* has been used to determine the base of this zone in the El-Temsah-2 and the San El-Hagar-1 wells. In the El-Temsah-2 Well, the Zone NN5 underlies unconformably the Zone NN7, so that the top of (NN5) Zone in this Well cannot be recorded. While in the San El-Hagar-1 Well, the top of this zone can be placed below the present barren horizon at the HO of the marker species *Sphenolithus heteromorphus.* Whereas in the Malha-1 Well, the top of the (NN5) Zone can be placed by the HO of *Sphenolithus heteromorphus* and *Helicosphaera ampliaperta* cannot be identified and the Zone NN5 unconformably overlies the Latest Oligocene NP25 Zone. Consequently, the base of NN5 can be roughly drawn by the HO of *Helicosphaera recta*.

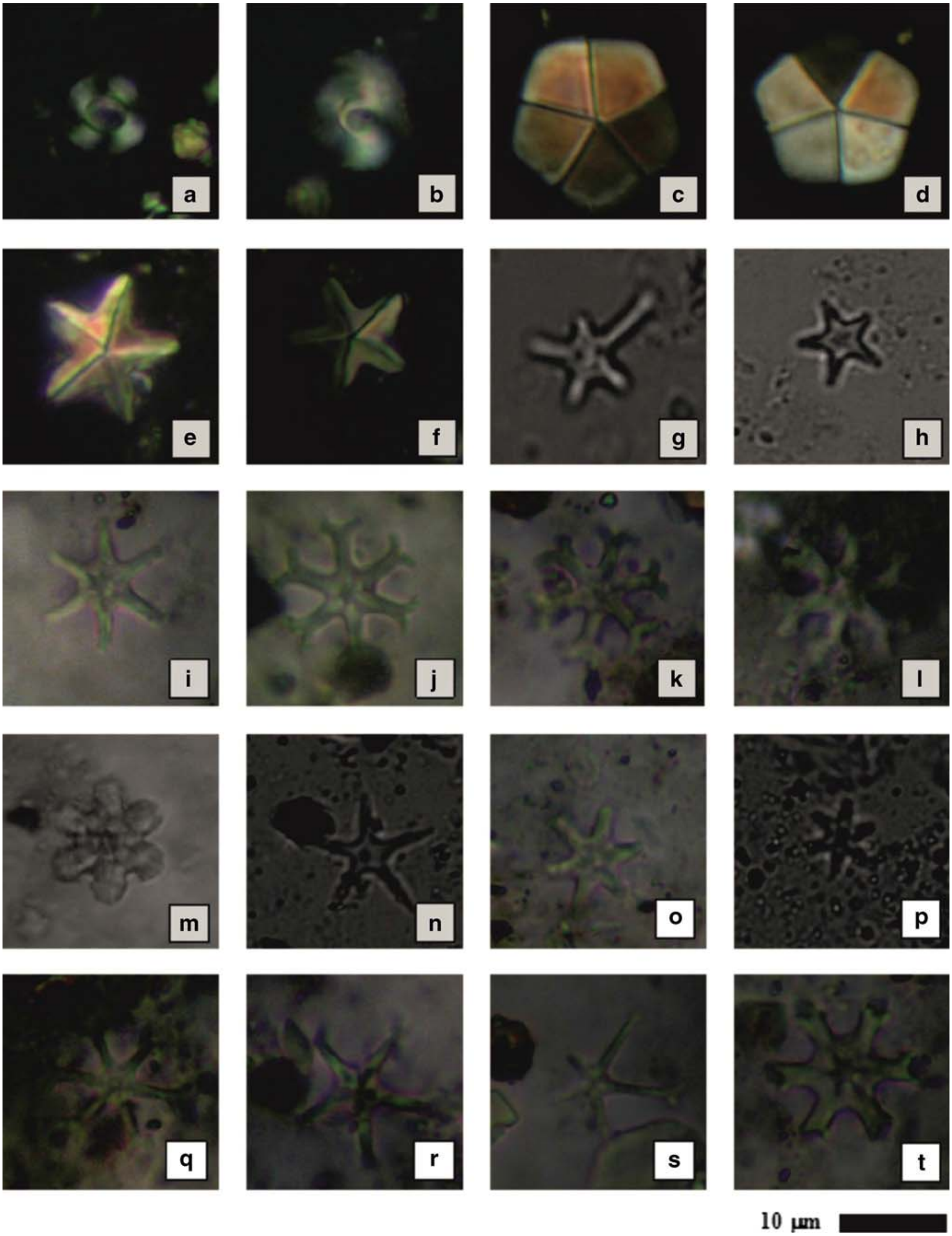
The top of the Zone NN5 is defined by the highest occurrence of *Sphenolithus heteromorphus*; it is the most easily determined bioevent in the Mediterranean areas (e.g. Fornaciari et al. 1996; Huang 1997; Tanaka and Takahashi 1998; Odin et al. 2001; McGonigal and Wei 2003; Pospichal; 2003) and in the Gulf of Suez and the Nile Delta area (e.g. Arafa 1982; Evans 1988; Marzouk 1998; Sadek 2001; Mandur 2003; Abu Shama 2007; Faris et al. 2007, 2009; Soliman et al. 2012).

Bukry (1973) mentioned that the lowest occurrence of *Sphenolithus abies* occurs within the *Sphenolithus heteromorphus* Zone (NN5), while some authors only reported the first occurrence of *S. abies* from the Late Miocene. This may be due to different species concepts and/or regional variations of distribution of this species (Perch-Nielsen 1985).

The nannofossil assemblage recorded in this interval includes *Helicosphaera carteri*/*H. kamptneri*, *Reticulofenestra pseudoumbilicus*, *Coccolithus miopelagicus*, *Cyclicargolithus floridanus*, *Discoaster druggii*, *Sphenolithus moriformis*, *Micrantholithus vesper* and *Braarudosphaera bigelowii*, in addition to the marker species *Sphenolithus heteromorphus.*

Helicosphaera ampliaperta zone (NN4)

This zone is defined as the interval from the HO of *Sphenolithus belemnos* to the HO of *Helicosphaera ampliaperta*.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10 µm

◀ **Plate 3** **a** *Calcidiscus premacintyrei*, Theodoridis (1984), Boughaz-1 Well, Sample depth 1775 m, Rudeis Formation, *Discoaster exilis* Zone (NN6). **b** *Calcidiscus tropicus*, (Kamptner, 1954) Varol, 1989, Boughaz-1 Well, Sample depth 1450 m, Sidi Salem Formation, *Discoaster quinqueramus* Zone (NN11). **c**, **d** *Braarodosphaera bigelowii*, (Gran and Braarud, 1935) Deflandre, 1947. **c** Boughaz-1 Well, Sample depth 1316 m, Sidi Salem Formation, *Amaurolithus tricorniculatus* Zone (NN12). **d** Boughaz-1 Well, Sample depth 1375 m, Sidi Salem Formation, *Discoaster quinqueramus* Zone (NN11). **e**, **f** *Micrantholithus vesper*, Deflandre (1950), Boughaz-1 Well, Sample depth 2180 m, Rudeis Formation, *Helicosphaera ampliaperta* Zone (NN4). **g** *Discoaster asymmetricus*, Gartner (1969), Boughaz-1 Well, Sample depth 1316 m, Sidi Salem Formation, *Amaurolithus tricorniculatus* Zone (NN12). **h** *Discoaster berggrenii*, Bukry (1971), Boughaz-1 Well, Sample depth 1530 m, Sidi Salem Formation, *Discoaster quinqueramus* Zone (NN11). **i** *Discoaster brouweri*, (Tan, 1927) Bramlette and Riedel, 1954, Boughaz-1 Well, Sample depth 1316 m, Sidi Salem Formation, *Amaurolithus tricorniculatus* Zone (NN12). **j**, **k** *Discoaster challengeri*, Bramlette and Riedel (1954), Boughaz-1 Well, Sample depth 1316 m, Sidi Salem Formation, *Amaurolithus tricorniculatus* Zone (NN12). **l** *Discoaster deflandrei*, Bramlette and Riedel (1954), Boughaz-1 Well, Sample depth 2180 m, Rudeis Formation, *Helicosphaera ampliaperta* Zone (NN4). **m** *Discoaster druggii*, Bramlette and Wilcoxon (1967), Boughaz-1 Well, Sample depth 2615 m, Qantara Formation, *Discoaster druggii* Zone (NN2). **n** *Discoaster quinqueramus*, Gartner (1969), Boughaz-1 Well, Sample depth 1375 m, Sidi Salem Formation, *Discoaster quinqueramus* Zone (NN11). **o**, **p** *Discoaster intercalaris*, Bukry (197 l), Boughaz-1 Well, Sample depth 1316 m, Sidi Salem Formation, *Amaurolithus tricorniculatus* Zone (NN12). **q** *Discoaster exilis*, Martini and Bramlette (1963), Boughaz-1 Well, Sample depth 2180 m, Rudeis Formation, *Helicosphaera ampliaperta* Zone (NN4). **r**, **s** *Discoaster pentaradiatus*, (Tan, 1927) Bramlette and Riedel, 1954, Boughaz-1 Well, Sample depth 1316 m, Sidi Salem Formation, *Amaurolithus tricorniculatus* Zone (NN12). **t** *Discoaster surculus*, Martini and Bramlette (1963), Boughaz-1 Well, Sample depth 1316 m, Sidi Salem Formation, *Amaurolithus tricorniculatus* Zone (NN12)

In the present study, the *Helicosphaera ampliaperta* Zone (NN4) was recorded in the three wells of the Nile Delta (Boughaz-1, El-Temsah-2 and San El-Hagar-1 Wells). In the Boughaz-1 Well, this zone attains a thickness of about 355 m from depth 2050 m (top) to 2405 m (base) within the lower part and the uppermost part of Rudeis and Qantara formations, respectively. In the El-Temsah-2 Well, the Zone NN4 attains 276 m thick from depth 3876 m (top) to depth 4152 m (base) within the lower part and the uppermost part of Sidi Salem and Qantara formations, respectively. In the San El-Hagar-1 Well, this zone has a thickness of about 506 m from depth 2560 m (top) to depth 3306 m (base) including the lower part of Qawasim Formation, Kareem Formation and the most of Rudeis Formation.

In some areas of South Atlantic and the Pacific, *Helicosphaera ampliaperta* is very rare or absent and thus NN4 and NN5 cannot be distinguished (Martini 1976). In some instance, the lowest occurrence of *Discoaster exilis* can be used to approximate the NN4/NN5 boundary (Martini and Worsley 1971; Müller 1974). Ellis (1981) considered this event as difficult to affirm because overgrowth on discoasterids makes the distinction between *Discoaster exilis* and *D. variabilis* difficult. Bukry (1973) proposed that the end of *Discoaster deflandrei* acme, as an alternative event, can be taken to define the NN4/NN5 boundary. Parker et al. (1985) noted that the use of *D. deflandrei* acme to define a zonal boundary (NN4/NN5) is not generally desirable, because such an event may vary from place to place for a variety of reasons.

Jiang and Gartner (1984) in the Walvis Ridge and Parker et al. (1985) in the mid-latitude North Atlantic used the lowest occurrence of long-armed discoasterids (*Discoaster variabilis* group) to distinguish zones CN3 and CN4. Soliman et al. (2012) considered that the LO of *Sphenolithus heteromorphus* is close to the HO of *Sphenolithus belemnos* ad can be used as an additional marker for the base of the Zone NN4 as the same case in Hewaidy et al. (2014). The top of NN4 Zone was defined by the highest occurrence of *Helicosphaera ampliaperta* at many places by different authors as the western equatorial Indian Ocean and equatorial Atlantic Ocean Fornaciari et al. (1990), Pearl River Mouth Basin, south China Sea Huang (1997), Ras Budran area, Gulf of Suez, Egypt Marzouk (1998), Northwestern Sinai, Egypt Abu Shama (2007), Northeast Nile Delta, Egypt Faris et al. (2007), and Gulf of Suez area, Egypt Faris et al. (2009), Boukhary et al. (2012) and in other Mediterranean zonation (Slezak et al. 1995; Fornaciari and Rio 1996).

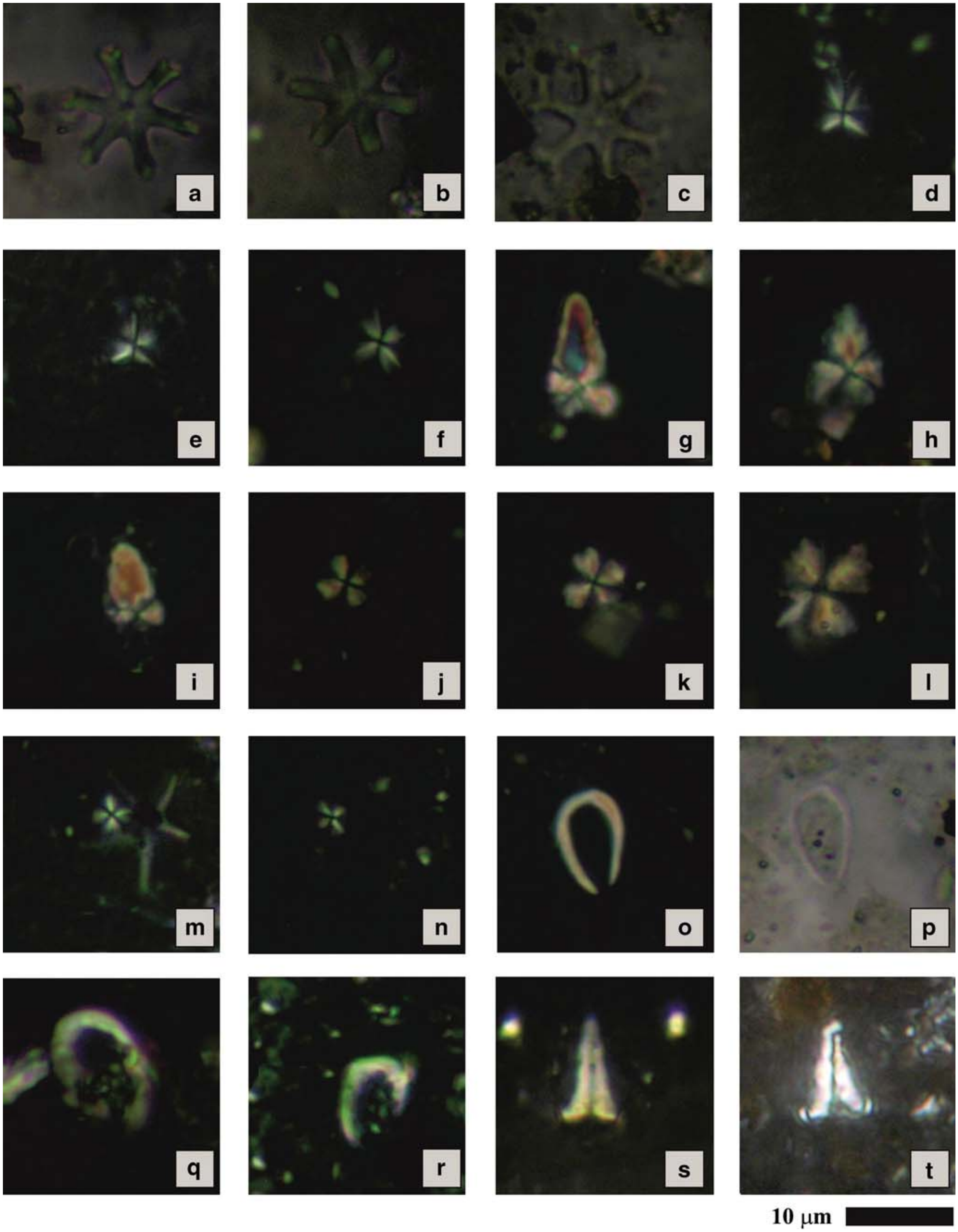
In the present study, the *Helicosphaera ampliaperta* Zone (NN4) has been defined as the original definition of the same zone by (Martini 1971) in all three wells of the Nile Delta. This zone is easy to recognize since the interval is bounded by the HO of *Helicosphaera ampliaperta* (top) and the HO of *Sphenolithus belemnos* (base).

This zone includes *Helicosphaera carteri*/*H. kamptneri*, *H. ampliaperta*, *Reticulofenestra pseudoumbilicus*, *Coccolithus pelagicus*, *Cyclicargolithus floridanus*, *Discoaster druggii*, *Discoaster variabilis*, *Sphenolithus moriformis*, *Micrantholithus vesper* and *Braarudosphaera bigelowii*. This zone is characterized by the co-occurrence of *Sphenolithus heteromorphus* and *Helicosphaera ampliaperta*.

Sphenolithus belemnos zone (NN3)

Sphenolithus belemnos Zone (NN3) is defined as the interval from the HO of *Triquetrorhabdulus carinatus* to the HO of *Sphenolithus belemnos*.

This zone was recorded in three studied wells. In the Boughaz-1 Well, this zone attains a thickness of about 210 m, in the upper part of Qantara Formation. The highest occurrence of *Sphenolithus belemnos* occurs at depth 2405 m and defines the top of this zone. The lowest occurrence of *S. belemnos* occurs at depth 2615 m and defines the base of this zone. In the El-Temsah-2 Well, this zone was represented by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◀ **Plate 4** **a**, **b** *Discoaster surculus*, Martini and Bramlette (1963), Boughaz-1 Well, Sample depth 1375 m, Sidi Salem Formation, *Discoaster quinqueramus* Zone (NN11). **c** *Discoaster variabilis*, Martini and Bramlette (1963), Boughaz-1 Well, Sample depth 1316 m, Sidi Salem Formation, *Amaurolithus tricorniculatus* Zone (NN12). **d**–**f** *Sphenolithus abies*, Deflandre in Deflandre and Fert (1954), Boughaz-1 Well, Sample depth 1316 m, Sidi Salem Formation, *Amaurolithus tricorniculatus* Zone (NN12). **g**–**i** *Sphenolithus heterormorphus*, Deflandre (1953), San El-Hagar-1 Well, Sample depth 2425 m, Qawasim Formation, *Sphenolithus heteromorphus* Zone (NN5). **j**–**l** *Sphenolithus moriformis*, (Brönnimann and Stradner, 1960) Bramlette and Wilcoxon, 1967, San El-Hagar-1 Well, Sample depth 2494 m, Qawasim Formation, *Sphenolithus heteromorphus* Zone (NN5). **m**, **n** *Sphenolithus neoabies*, Bukry & Bramlette (1969a), Boughaz-1 Well, Sample depth 1316 m, Sidi Salem Formation, *Amaurolithus tricorniculatus* Zone (NN12). **o**, **p** *Amaurolithus delicatus*, Gartner and Bukry (1975), Boughaz-1 Well, Sample depth 1316 m, Sidi Salem Formation, *Amaurolithus tricorniculatus* Zone (NN12). **q**, **r** *Ceratolithus rugosus*, Bukry and Bramlette (1968), Boughaz-1 Well, Sample depth 1316 m, Sidi Salem Formation, *Amaurolithus tricorniculatus* Zone (NN12). **s**, **t** *Zygrhablithus bijugatus*, (Deflandre in Deflandre and Fert, 1954) Deflandre (1959), Boughaz-1 Well, Sample depth 2930 m, Qantara Formation, *Sphenolithus distentus* Zone (NP24)

depth intervals 4152 m (top) and 4273 m (base) and attains about 121 m thick, within the upper part of Qantara Formation. In the San El-Hagar-1 Well, the Zone NN3 represents the last defined zone from the study interval. Only the top of this zone can be determined at depth 3066 m and occupies the lowermost part of Rudeis Formation in addition to the studied part of Qantara Formation.

In the present study, the top of *Sphenolithus belemnos* Zone (NN3) was drawn at the highest occurrence of the *Sphenolithus belemnos* species in all three wells (Boughaz-1, El-Temsah-2 and San El-Hagar-1). This fits the original definition of the same zone by Martini (1971). While the lowest occurrence of *Sphenolithus heteromorphus* was used by Bukry (1973) to define the top of CN3 zone (CN2/CN3 boundary). *S. heteromorphus* is abundantly present in the Mediterranean Miocene record, and both the lowest occurrence and highest occurrence are biostratigraphically useful (Müller 1978; Theodoridis 1984). The two species *S. heteromorphus* and *S. belemnos* have been reported as co-occurring by some authors (e.g. Bukry 1973 at DSDP Site 140 in the Atlantic Ocean and Takayama and Sato, 1985 at DSDP Site 610 in the North Atlantic Ocean), while Rio et al. (1990) and Fornaciari et al. (1990, 1993) have shown that the ranges of the two species can hardly be considered to overlap. Olafsson (1991) demonstrated that the intervals of high abundance of the two species do not overlap, but they are present in very low abundances between the highest common *Sphenolithus belemnos* and the lowest common *S. heteromorphus*. Marzouk (1998) used the lowest occurrence of *S. heteromorphus* to define the top of NN3 zone in the Ras Budran area, Gulf of Suez.

In this study, the lowest occurrence of *S. belemnos* was used as a secondary marker to define the base of the Zone NN3 in both the Boughaz-1 and El-Temsah-2 wells due to the absence of the marker species *Triquetrorhabdulus carinatus* in both wells as suggested by Abu Shama (2007), Faris et al. (2007, 2009) and Soliman et al. (2012). This zone in El-Temsah-2 Well was underlain by a barren horizon. While in the San El-Hagar-1 Well, the base of this zone cannot be defined. The HO of *S. belemnos* which was used in the Martini (1971) zonal scheme to mark the top of the Zone NN3 is used following several authors (e.g. Fornaciari et al. 1997; McGonigal and Wei 2003). This bioevent occurs slightly below the first occurrence of *Sphenolithus heteromorphus*.

Species recovered in this zone include *Cyclicargolithus floridanus*, *Discoaster druggii*, *Helicosphaera kamptneri*, *Coccolithus pelagicus*, *Micrantholithus vesper*, *Braarudosphaera bigelowii*, *Reticulofenestra pseudoumbilicus*, *Sphenolithus heteromorphus* and *S. abies*, in addition to the marker species *S. belemnos*.

Discoaster druggii zone (NN2)

Discoaster druggii Zone (NN2) is defined by the interval from the LO of *Discoaster druggii* to the HO of *Triquetrorhabdulus carinatus*.

The top of this zone has been recorded in the Boughaz-1 Well at depth 2615 m and its base at depth 2715 m (100 m thick) within the middle part of Qantara Formation. The Zone NN2 in this well unconformably overlies the Latest Oligocene Zone (NP25).

The LO of *Discoaster druggii* is a marker species to define the base of *D. druggii* Zone (NN2) according to Martini (1971). This bioevent was recognized in the Boughaz-1 Well which defines the base of this zone, whereas its top can be defined by the LO of *Sphenolithus belemnos* due to the absence of the marker species *Triquetrorhabdulus carinatus*, and this zone (NN2) lies unconformably above the Latest Oligocene Zone NP25. The highest occurrence of *Triquetrorhabdulus carinatus* is used to define the top of the Zone NN2 (NN2/NN3 boundary). However, the range of the *T. carinatus* appears to be paleogeographically controlled. Several workers have proposed the lowest occurrence of *Sphenolithus belemnos* as an alternative marker bioevent for the NN2/NN3 boundary (e.g. Parker et al. 1985; Olafsson 1989, 1991; Fornaciari et al. 1993; Fornaciari and Rio 1996; Marzouk 1998; McGonigal and Wei 2003; Abu Shama 2007; Faris et al. 2007, 2009; Soliman et al. 2012).

Many authors have noted that it may be difficult to recognize *Discoaster druggii* in overgrown material as Olafsson (1989). Müller (1977) stated that this species is rare in Indian Ocean. Rio et al. (1990) recorded that the *D. druggii* is sporadically occurred. Olafsson (1989) used the lowest occurrence of *Triquetrorhabdulus serratus* in Site 667 in the eastern Equatorial Atlantic as an alternative event to define the base of NN2 Zone. In high latitudes, *D. druggii*, *Sphenolithus belemnos* and *Triquetrorhabdulus carinatus* are rare or absent and there are no convenient substitutes to subdivide the NN1 to NN3 interval (Perch-Nielsen 1985).

Moreover, the zonal assignment of the Zone NN2 is based on the lowest occurrence of *Helicosphaera ampliaperta*, *H. mediterranea*, *H. carteri* and *Helicosphaera kamptneri* (Martini 1971; Perch-Nielsen 1985; Martini and Müller 1986; Marzouk 1998; Faris et al. 2007, 2009). On the other hand, the lowest occurrence of *Calcidiscus tropicus* <6 μm was listed by de Kaenel and Villa (1996) as occurring just above the Zone NN1/NN2 boundary. McGonigal and Wei (2003) used the lowest occurrence of *C. tropicus* to estimate the base of Zone NN2 (CN1b Subzone) in the ODP Leg 189.

This interval contains abundant of *Cyclicargolithus floridanus* and includes *Coccolithus miopelagicus*, *Coccolithus pelagicus*, *Helicosphaera kamptneri* and *Pontosphaera multipora*, in addition to the marker species *D. druggii*.

Sphenolithus ciperoensis zone (NP25)

Sphenolithus ciperoensis Zone (NP25) is defined as the interval from the HO of *Sphenolithus distentus* to the HO of *Helicosphaera recta* and/or the HO of *Sphenolithus ciperoensis*.

This zone has been recorded in three wells. In the Boughaz-1 Well, the *Sphenolithus ciperoensis* Zone (NP25) attains a thickness of about 215 m from depth 2715 m (top) to depth 2930 m (base) within the lower part of Qantara Formation. Whereas in the El-Temsah-2 Well, this zone is considered the last defined biozones and bounded from above and below by barren horizons. It has about 233 m thick from depth 4455 m (top) to depth 4688 m (base) within the lower part of Qantara Formation. Also, the Zone NP25 was the last defined one in the Malha-1 Well. Its top lies at depth 340 m and the base at 390 m within the lower part of Qantara Formation with thickness of about 50 m. The *Sphenolithus ciperoensis* Zone (NP25) in the Malha-1 Well unconformably overlies the Late Cretaceous taxa.

While *Helicosphaera recta* and *Sphenolithus ciperoensis* are useful as markers in many sections in low latitudes, the HO of the equally disappearing *Dictyococcites bisectus* and *Zygrhablithus bijugatus* are the events used for an approximation of the NP25/NN1 boundary in higher latitudes (Perch-Nielsen 1985). Accordingly, the HO of *Reticulofenestra bisecta* was used to determine the top of Latest Oligocene Zone NP25 in the all three wells (Boughaz-1, El-Temsah-2 and Malha-1). In the Boughaz-1 Well, the base of this zone has been defined by the HO of *Sphenolithus predistentus*. The NN1 Zone was not recorded in the studied wells and representing a major hiatus at the Oligocene/Miocene boundary.

Okada and Bukry (1980) used the end acme of *C. abisectus* to define the CN1a/CN1b (mid of Zone NN1).

This interval includes *Coccolithus pelagicus*, *Helicosphaera kamptneri*, *H. euphratis*, *Pontosphaera multipora*, *Cyclicargolithus floridanus* and *Sphenolithus ciperoensis Cyclicargolithus abisectus*.

Sphenolithus distentus zone (NP24)

This zone is defined as the interval from the LO of *Sphenolithus ciperoensis* to HO of *S. distentus*.

This zone was recorded only in the Boughaz-1 Well, and it was the last recorded biozones in the present study. The top of this zone (NP24) was defined in Boughaz-1 Well at depth 2930 m within the lowermost part of Qantara Formation. The base cannot be defined because this zone lies unconformably above the Latest Cretaceous interval.

The LO of *Pontosphaera enormis* has been shown to be a useful event for the subdivision of the upper Oligocene and is an approximation of the NP24/NP25 boundary (Martini 1981a). *Sphenolithus predistentus* usually disappears before the HO of *S. distentus* and *Helicosphaera recta* (Perch-Nielsen 1985). This bioevent was used in Boughaz-1 Well to define the top of Zone NP24.

This zone (NP24) includes the following association: *Coccolithus pelagicus*, *Cyclicargolithus abisectus*, *Cyclicargolithus floridanus*, *Helicosphaera kamptneri*, *H. euphratis* Haq, *H. recta*, *Pontosphaera multipora*, *Reticulofenestra lockeri*, *Sphenolithus ciperoensis*, *S. dissimilis*, *S. predistentus* and *Zygrhablithus bijugatus* (Table 1).

Stages boundaries

Middle/Late Miocene boundary (Serravallian/Tortonian boundary)

The Middle/Late Miocene boundary is generally defined at the base of Tortonian stage (Berggren et al. 1985). The Serravallian/Tortonian boundary stratotype in Sample 4 in Rio Mazzapiedi Section (north Italy) was assigned by Martini (1971, 1975) to the calcareous nannoplankton *Discoaster hamatus* Zone (NN9) based on the highest occurrence of *D. hamatus* taxa. This is the same level as the lowest occurrence of planktonic foraminifera *Neogloboquadrina acostaensis* (Cita et al. 1965). According to magnetochronologic considerations and on the fact that the lowest occurrence of *N. acostaensis* occurs in the DSDP Site 563 within Zone (NN8), so, Berggren et al. (1985) placed the Serravallian/Tortonian boundary within the calcareous nannoplankton *Catinaster coalitus* Zone (NN8). El Heiny and Morsi (1992)

Table 1 Standard calcareous nannofossil biostratigraphy and the present study bioevents

Age		Stage	Martini (1971)	Boundary events	Okada and Bukry (1980)	Boundary events	Bassiuni et al., (2014)	Boundary events	Present study	Boundary events
Early Pliocene		Zanclean		C. rugosus		C. rugosus	Not studied		Not studied	C. rugosus
Miocene	Late	Messinian	*Amaurolithus tricorniculatus* (NN12)	*D. quinqueramus*	*A. tricorniculatus* (CN10): *C. acutus* (CN10b); *T. rugosus* (CN10a)	*C. acutus*; *D. quinqueramus*	Not studied		NN12	*D. quinqueramus*
Miocene	Late	Messinian	*Discoaster quinqueramus* (NN11) b	*A. primus*	*D. quinqueramus* (CN9): *A. primus* (CN9b)	*A. primus*	Barren		NN11	
Miocene	Late	Tortonian	*Discoaster quinqueramus* (NN11) a	*D. quinqueramus*	*D. berggrenii* (CN9a)	*D. berggrenii*	Barren		NN11	*D. quinqueramus, D. berggrenii, D. Surculus*
Miocene	Late	Tortonian	*Discoaster calcaris* (NN10)	*D. hamatus*	*D. neohamatus* (CN8): *D. neorectus* (CN8b); *D. bellus* (CN8b)	*D. neorectus*; *D. hamatus*	Barren		NN10: NN10b; NN10a	*D. bollii*; Unconformity surface
Miocene	Late	Tortonian	*Discoaster hamatus* (NN9)	*D. hamatus*	*D. hamatus* (CN7): *C. calyculus* (CN7b); *H. carteri* (CN7a)	*C. calyculus*; *D. hamatus*	Barren		Hiatus	Unconformity surface
Miocene	Middle	Serravallian	*Catinaster coalitus* (NN8)	*C. coalius*	*C. coalitus* (CN6)	*C. coalius*; *D. kugleri*	Barren		NN8	*C. miopelagicus*
Miocene	Middle	Serravallian	*Discoaster kugleri* (NN7)	*D. kugleri*	*D. exilis* (CN5): *D. kugleri* (CN5b)	*D. kugleri*	Barren		NN7	*Cy. floridanus*
Miocene	Middle	Serravallian	*Discoaster exilis* (NN6)	*S. heteromorphus*	*D. exilis* (CN5): *C. miopelagicus* (CN5a)	*S. heteromorphus*	NN6	*Cy. floridanus*; *S. heteromorphus*	NN6	*S. heteromorphus*
Miocene	Middle	Langhian	*Sphenolithus heteronorphus* (NN5)	*H. ampliaperta*	*Sphenolithus heteromorphus* (CN4)	*H. ampliaperta*	NN5: NN5c; NN5b; NN5a	*H. walberdorfenensis*; *D. waltrans*; *H. perch-nielseniae*; *H. ampliaperta*	NN5	*H. ampliaperta*
Miocene	Early	Burdigalian	*Helicosphaera ampliaperta* (NN4)	*S. belemnos*	*Helicosphaera ampliaperta* (CN3)	*S. heteromorphus*	NN4: NN4c; NN4b; NN4a	*H. euphratus*; *H. mediteriana*; *S. belemnos*	NN4	*S. belemnos*
Miocene	Early	Burdigalian	*Sphenolithus belemnos* (NN3)	*T. carinatus*	*Sphenolithus belemnos* (CN2)	*S. belemnos*; *S. belemnos*	NN3: NN3b; NN3a	*S. belemnos*; *S. disbelemnos*; *T. carinatus*	NN3	*S. belemnos*
Miocene	Early	Burdigalian / Aquitanian	*Discoaster druggii* (NN2)	*D. druggii*	*T. carinatus* (CN1): *D. druggii* (CN1c)	*D. druggii*	NN2	Unconformity surface	NN2	*D. druggii*
Miocene	Early	Aquitanian	*Triquetrorhabdulus carinatus* (NN1)	*H. recta*	*T. carinatus* (CN1): *D. deflandrei* (CN1b); *C. abisectus* (CN1a)	*C. abisectus*; *S. ciperoensis*	Big hiatus		Big hiatus	*D. bisectus*
Oligocene	Late	Chattian	*Sphenolithus ciparonsis* (NP25)		*Diotyococcites bisectus* (CP19 b)		Big hiatus		NP25; NP24	*S. predistentus*
Eocene	Middle	Lutitian					NP16		Not studied	

Unconformity surface (dashed line)

Highest occurrence

Lowest occurrence

in the eastern Nile Delta area placed the Middle/Late Miocene boundary at the base of *D. hamatus* Zone (NN9). The Middle/Late Miocene boundary lies within *D. hamatus* Zone (CN7) (Xu and Wise 1997).

Faris et al. (2007) detected this boundary in the offshore area (Ras El Barr-1 and Bougaz E-1 wells), Nile Delta area, where continuous sedimentation straddled the Middle/Late Miocene boundary. They recorded an important earliest Late Miocene hiatus in the Bougaz E-1 Well, where earliest Late Miocene nannofossil Discoaster hamatus Zone (NN9) was not detected, and this boundary is recognized at the lowest occurrence of planktonic foraminiferal Neogloboquadrina acostaensis. On the other hand, the Middle/Late Miocene boundary is placed at the base of D. hamatus Zone (NN9) in Ras El Barr-1 Well.

Hilgen et al. (2005) in the Global boundary Stratotype Section and Point (GSSP) at Monte Dei Corvi placed the Serravallian/Tortonian boundary at the base of D. hamatus Zone (NN9).

In the present study (Boughaz-1 Well), the Late Miocene unconformably overlies the Middle Miocene. This unconformity surface is recognized by the missing of calcareous nannofossil zones NN7-NN9.

Early/Middle Miocene boundary (Burdigalian/Langhian boundary)

The Early/Middle Miocene boundary is equivalent to the base of the Langhian stage (Berggren et al. 1985). The base of the Langhian is linked biostratigraphically to the first occurrence of the planktonic foraminiferal *Praeorbulina* spp. taxa Berggren et al. (1985) which occurs in the stratotype section and worldwide above the lowest occurrence of nannofossil *Sphenolithus heteromorphus* and just below the highest occurrence of the *Helicosphaera ampliaperta* taxa, as well as within the upper part of nannofossil *Helicosphaera ampliaperta* Zone (NN4) of Martini (1971).

In terms of calcareous nannoplankton, the Early/Middle Miocene boundary was placed by many authors at the base of the *Sphenolithus heteromorphus* Zone (NN5) (e.g. Martini 1971; Bukry 1973; Perch-Nielsen 1972; Miller 1981). On the other hand, this boundary can only be approximated roughly with the highest common occurrence of *Helicosphaera ampliaperta* in the Mediterranean region or the acme end of *Discoaster deflandrei* in low-latitude oceanic sediments (Rio et al. 1990; Fornaciari and Rio 1996). In the Gulf of Suez area, this boundary lies at the level of the highest occurrence of *Helicosphaera ampliaperta*, top of the Rudeis Formation (Marzouk 1998; Sadek 2001), where in Soliman et al. (2012), this boundary passed within the NN4 Zone.

By planktic foraminifera, the Early/Middle Miocene boundary in the Nile Delta wells (Bougaz E-1, Rommana-1X) was placed at the base of *Globorotalia fohsi peripheroronda* Zone (Faris et al. 2007). On terms of calcareous nannofossils, the Early/Middle Miocene boundary falls within *Helicosphaera ampliaperta* Zone (NN4) and at the top of Helicosphaera ampliaperta Zone (NN4) in Bougaz E-1 and Rommana-1 X, respectively.

Faris et al. (2009) recognized the Early/Middle Miocene boundary in the Gulf of Suez area (Wadi Gharandal surface section), at the base of *Orbulina universa* Zone which falls within the *Helicosphaera ampliaperta* Zone (NN4), and in the offshore Darag-1 Well, the boundary can be approximated at the top of *Helicosphaera ampliaperta* Zone (NN4).

In the present study, the Early/Middle Miocene boundary was recognized in all three wells of the Nile Delta (Boughaz-1, El-Temsah-2 and San El-Hagar-1) and was drawn at the base of the *Sphenolithus heteromorphus* Zone (NN5). The Early/Middle Miocene boundary lies within the Rudeis, Sidi Salem and Qawasim formations in the Boughaz-1 Well, El-Temsah-2 Well and San El-Hagar-1 Well, respectively. On the other hand, at North Sinai (Malha-1 Well), the Early/Middle Miocene boundary cannot be recognized, where the Middle Miocene unconformably overly the topmost Oligocene and it defined by the missing of the calcareous nannofossil zones NN1 to NN4.

Oligocene/Miocene boundary (Chattian/Aquitanian boundary)

In the following, some important calcareous nannoplankton bioevents can be distinguished around this boundary:

The highest occurrence of *Helicosphaera recta* This event defines the NP25/NN1 boundary according to Martini (1971). Because the taxon is rare, the event was replaced by the lowest occurrence (LO) of *Reticulofenestra bisecta* (Berggren et al. 1995). In the Mediterranean region (synthesis of data by Fornaciari and Rio (1996)), this event is not isochronous and hence not reliable for biostratigraphic correlation.

The highest occurrence of *Reticulofenestra bisecta* This event is used to approximate the NP25/NN1 boundary (Berggren et al. 1995; Rio et al. 1990). In the Mediterranean, this event has been recorded in the lower part of the NN1 Zone Fornaciari and Rio (1996) and considered to be the best approximation for the Oligocene/Miocene boundary.

The highest occurrence of *Reticulofenestra abisecta* Okada and Bukry (1980) used the lowest common occurrence (LCO) of *Reticulofenestra abisecta* for the definition of the CN1a/CN1b boundary (O/M) in low-latitude zonation. This event was used also in Mediterranean stratigraphy Theodoridis (1984) but its reliability was questioned by other authors Martini and Müller (1986) and Fornaciari and Rio (1996). This bioevent has been used as a biostratigraphic indicator in the Central Paratethys: it can be correlated with the NP 25/NN 1 (O/M) boundary according to Báldi-Béke (1984) and Bystrická (1979).

The highest occurrences of *Dictyococcites bisectus* and *Zygrhablithus bijugatus* The HOs of *Dictyococcites bisectus* and *Zygrhablithus bijugatus* are used as bioevents for an approximation of the NP25/NN1 (O/M) boundary in higher latitudes (Perch-Nielsen 1985).

In the studied wells, the NN1 Zone was not recorded and representing a hiatus at the Oligocene/Miocene boundary, so, this boundary cannot accurately be detected. In the present study, The LO of *Discoaster druggii* which is the marker species to define the base of *Discoaster druggii* Zone (NN2) was recognized in the Boughaz-1 Well at depth 2715 m within the Qantara Formation and this zone lies unconformably above the Latest Oligocene Zone NP25. On the other hand, the HO of *D. bisectus* was used to determine the top of Latest Oligocene Zone NP25 in three wells (Boughaz-1, El-Temsah-2 and Malha-1).

Summary and conclusions

In this study, the Oligo-Miocene sequence was studied in the five wells, three of which are located at the northeastern reaches of the Nile Delta (Boughaz-1, El-Temsah-2 and San El-Hagar-1). While, the last two wells are located at the northwest Sinai region (Bardawil-1 and Malha-1). Five rock units were defined in this succession and arranged from the top to base as follows: (1) Qawasim Formation: conformably overlies the Sidi Salem Formation in the Boughaz-1 and El-Temsah-2 wells and conformably overlies the Kareem Formation in the San El-Hagar-1 Well. (2) Sidi Salem Formation: unconformably overlies the Rudeis Formation in the Boughaz-1 Well, conformably overlies the Qantara Formation in the El-Temsah-2 Well, only part of which was studied in The Bardawil-1 Well, and it unconformably overlies the Qantara Formation in the Malha-1 Well. (3) Kareem Formation: Early Miocene in the San El-Hagar-1 Well and conformably overlies the Rudeis Formation. (4) Rudeis Formation: lies conformably above the Qantara Formation and unconformably below the Sidi Salem Formation in the Boughaz-1 Well and it lies conformably above and below the Qantara and the Kareem formations respectively in the San El-Hagar-1 Well. (5) Qantara Formation: Ranged in age from the Late Oligocene-Early Miocene in this study. It unconformably overlies the Late Cretaceous formations in the Boughaz-1 Well and conformably underlies the Rudeis Formation in the Boughaz-1 and San El-Hagar-1 wells. In the El-Temsah-2 Well, it conformably underlies the Sidi Salem Formation, but in the Malha-1 Well, it unconformably overlies and underlies the Late Cretaceous formations and the Sidi Salem Formation.

Twelve calcareous nannofossil biozones of the Late Oligocene-Late Miocene were defined and correlated with their corresponding biozones in Egypt and other parts of the world. These arranged from the top to base as *Amaurolithus tricorniculatus* Zone (NN12), *Discoaster quinqueramus* Zone (NN11), *Discoaster calcaris* Zone (NN10), *Catinaster coalitus* Zone (NN8), *Discoaster kugleri* Zone (NN7), *Discoaster exilis* Zone (NN6), *Sphenolithus heteromorphus*

Zone (NN5), *Helicosphaera ampliaperta* Zone (NN4), *Sphenolithus belemnos* Zone (NN3), *Discoaste*r *druggii* Zone (NN2), *Sphenolithus ciperoensis* Zone (NP25) and *Sphenolithus distentus* Zone (NP24). According to the defined biozones, the Middle/Late Miocene boundary cannot be detected in any studied well due to the absence of the *Discoaster hamatus* Zone (NN9), while the Early/Middle Miocene boundary can be placed at the top of the Zone (NN4). In this study, the Miocene rocks unconformably overlie the Oligocene sediments and this unconformity surface represented by the absence of the calcareous nannofossil Zone (NN1). Therefore, the Oligocene/Miocene boundary can be drawn unconformably at the top of the Zone (NP25).

Acknowledgments The manuscript is extracted from the PhD Thesis of the corresponding author. We would like to thanks for the Egyptian General Petroleum Corporation (EGPC) for giving us the cutting samples of the studies wells. Great thanks go to The Scientific and Technological Research Council of Turkey (TUBITAK) and Prof. Ercan Ozcan (Geological Engineering department, Faculty of Mine, Istanbul Technical University, Turkey) for supporting the corresponding author in Turkey during the research working part of her PhD Thesis. Additionally, the authors are much more grateful to the editor and the anonymous reviewers for their constructive comments, corrections and helpful suggestions which greatly improved the manuscript.

References

Abu Shama AM (2007) Biostratigraphy and distribution of calcareous nannofossils of the Miocene rocks from the onshore Mallaha-1X and Abu Roda-1 wells, Northwestern Sinai. Egypt J Paleont 7: 147–169

Arafa AA (1982) Calcareous nannofossils from the Kareem Formation (Middle Miocene), Gulf of Suez area, Egypt. N Jb Geol Paläont Mh 1982:449–455

Arafa AA (1991) Nannoplankton and planktonic foraminiferal zonation of the lower Miocene sequence in Gebel Hadahid, south west Sinai, Egypt. Egypt J Geol 35(1–2):275–284

Backman J (1980) Miocene-Pliocene nannofossils and sedimentation rates in the Hatton-Rockall basin, NE Atlantic Ocean

Báldi-Béke M (1984) A dunántúli paleogén képzodmények nannoklaktonja. Geol Hungar Sér Paleont 7:43

Ball J (1952) Contribution to the geography of Egypt. Egypt Surv Dept (reprint):308 pp

Berggren WA, Kent DV, Van Couvering JA (1985) The Neogene, part 2. Neogene geochronology and chronostratigraphy In: Snelling NJ (ed) The Chronology of the Geological Record Geol Soc London Mem 10: pp 211–260

Berggren A, Kent DV, Swisher CC, Aubry MP (1995) A revised Cenozoic geochronology and chronostratigraphy. In: Berggren WA, Kent DV, Hardenbol (eds.), Time Scales and Global Stratigraphic Correlations. SEPM Spec Pubi, 54:129–212

Boukhary M, Abd El Naby A, Faris M, Morsi A (2012) Plankton stratigraphy of the Early and Middle Miocene Kareem and Rudeis Formations in the central part of the Gulf of Suez. Egypt Hist Biol 24(1):49–62

Bramlette MN, Sullivan FR (1961) Coccolithophorids and related nannoplankton of the Early Tertiary in California. Micropaleont 7:129–174

Bramlette MN, Wilcoxon JA (1967) Middle Tertiary calcareous nannoplankton of the Cipero Section. Trinidad, Tulane WI, Stud Geol 5: 93–31

Bukry D (1973) Low-latitude coccolith biostratigraphic zonation. Edgar NT, Saunders JB et al Init Repts DSDP 15:685–703

Bukry D, Bramlette MN (1969) Some new and stratigraphically useful calcareous nannofossils of the Cenozoic. Tulane studies in Geology and Paleontology, 7(3):131–142

Bystrická H (1979) Rupelian in the Banská Bystrica Basin. Geologický Zborník. Geol Carpath 30(1):109–122

Cita MB, Premoli Silva IA, Rossi R (1965) Foraminiferi planctonici del Tortoniano-tipo. Riv Ital Paleontol 71:217–305

de Kaenel E, Villa G (1996) Oligocene-Miocene calcareous nannofossil biostratigraphy and paleoecology from the Iberia Abyssal Plain. In: Whitmarsh RB, Sawyer DS, Klaus A, Masson DG (eds) Proc ODP Sci Results 149, College Station, TX (Ocean Drilling Program), pp79–145

El Heiny I (1979) Paleogeography of Neogene deposits in Egypt. Ann. Geol. Paays Hellen. Tamc hors seric 1:83–390

El Heiny I, Martini E (1981) Miocene foraminiferal and calcareous nannoplankton assemblage from the Gulf of Suez region and correlations. Rev Geol Medit 8(2):101–108

El Heiny I, Morsi S (1992) Stratigraphic correlation of Neogene sediments in the eastern Nile Delta and Gulf of Suez, Egypt. EGPC, 11th Explor Int Conf. Cairo 2:166–193

Ellis HC (1981) Calcareous nannoplankton biostratigraphy Deep Sea Drilling Project Leg 50. In: Hussong DM, Uyeda S et al (eds) Init Repts DSDP 60:507–533

El Sheikh HA (1995) Oligo-Miocene Calcareous nannoplankton biostratigraphy in some wells in North Sinai-Egypt. Bull Fac Sci Asiut Univ 24(1-f):67–82

Evans AL (1988) Neogene tectonic and stratigraphic events in the Gulf of Suez rift area, Egypt. Tectonophysics 153:235–247

Fadiya LS, Salami MB (2012) Middle Miocene carbonate crash in the Niger Delta. Evidence from calcareous nannofossils. J Nannoplankton Res 32(2):59–70 Int Nannoplankton Assoc Inc

Faris M, Samir AM, Shabaan M (2007) Calcareous nannofossil biostratigraphy of the subsurface Miocene sequence, Northeast Nile Delta, Egypt. The 5th Int Conf Geol Afr (1): P-P VII-1– VII-31 Ass-EGP

Faris M, Samir AM, Shabaan M (2009) Calcareous nannofossil biostratigraphy of the Lower and Middle Miocene sequence in the Gulf of Suez area, Egypt. The 6th Int Conf Geol Afr P-P VII-17 – VII-44 Ass-EGP

Flores JA, Sierro FJ, Glason G (1992) Calcareous plankton analysis in the pre-evaporitic sediments of the ODP Site 654 (Tyrrhenian Sea, Western Mediterranean). Micropaleont 38(3):279–288

Fornaciari E, Rio D (1996) Latest Oligocene to early Middle Miocene quantitative calcareous nannofossil biostratigraphy in the Mediterranean region. Micropaleont 42:1–36

Fornaciari E, Raffi I, Rio D, Villa G, Backman J, Olafsson G (1990) Quantitativse distribution patterns of Oligocene and Miocene calcareous nannofossils from the western equatorial Indian Ocean. In: Duncan RA, Backman J, Peterson LC et al Proc ODP, Sci Results 115, College Station, TX (Ocean Drilling Program), pp 237–254

Fornaciari E, Backman J, Rio D (1993) Quantitative distribution patterns of selected lower to middle Miocene calcareous nannofossils from the Ontong Java Plateau. In: Berger WH, Kroenke LW, Mayer LA et al Proc ODP, Sci Results 130, College Station, TX (Ocean Drilling Program), pp 245–256

Fornaciari E, Di Stefano A, Rio D, Negri A (1996) Middle Miocene quantitative calcareous nannofossil biostratigraphy in the Mediterranean region. Micropaleont 42(1):37–63

Fornaciari E, Rio D, Ghibaudo G, Massari F, Iaccarino S (1997) Calcareous plankton biostratigraphy of the Serravallian (Middle Miocene) stratotype section (Piedmont Tertiary Basin, NW Italy). Mem Sci Geol 4:127–144

Gartner S (1967) Calcareous nannofossils from Neogene of Trinidad, Jamaica, and Gulf of Mexico. Paleontol Contributions Univ of Kansas 29:1–7

Gartner S (1969) Correlation of Neogene planktonic foraminifer and calcareous nannofossil zones. Trans. Gulf Coast Assoc Geol Soc 19: 585–599

Gartner S, Bukry D (1975) Morphology and phylongey of the coccolithophycean family Ceraholitaceae. J Res U S Geol Surv 3: 451–456

Gartner S, Chow J (1985) Calcareous macrofossil biostratigraphy, Deep Sea Drilling Project Leg 85, eastern equatorial Pacific. In: Mayer L, Theyer F, Thomas E, et al, Inil. Repts. DSDP 85:609–619

Gartner S, Shyu JP (1996) Aspects of calcareous nannofossil biostratigraphy and abundance in the Pliocene and late Miocene of Site 905. In: Mountain GS, Miller KG, Blum P, Poag CW, Twichell DC (eds) Proc ODP, Sci Results 150, College Station, TX (Ocean Drilling Program), pp 53–63

Ghorab MA, Ebied Z, Tewfik N (1964) Oligocene and Miocene rock stratigraphy of the Gulf of Suez region. Stratigr Committ EGP Cairo:1–142

Haq BU, Al-Qahtani AM (2005) Phanerozoic cycles of sea-level change on the Arabian Platform. GeoArabia 10(2):127–159

Haq BU, Hardenbol J, Vail PR (1988) Mesozoic and Cenozoic chronostratigraphy and cycles of sea-level change. Soc Econ Paleontologists and Mineralogists 42:71–108

Hay WW (1964) The use of the electron microscope in study of fossils. Annu Rep Smithsonian Inst 1963:409–415

Hay WW (1970) Calcareous nannofossils from cores recovered on Leg, 4. Init Repts DSDP 4:455–501

Hay WW, Mohler HP, Wade ME (1966) Calcareous nannofossils from Nal'chik (northwest Caucasus). Eclogae Geol Helv, 59:379–399

Hay WW, Mohler HP, Roth PH, Schmidt RR Boudreaux J (1967) Calcareous nannoplankton zonation of the Cenozoic of the Gulf Coast and Caribbean-Antillean area, and transoceanic correlation. Trans Gulf Coast Assoc Geol Soc 17:428–480

Hewaidy AA, Farouk S, Ayyad HM (2014) Integrated biostratigraphy of the upper Oligocene–middle Miocene successions in west central Sinai, Egypt. J Afr Earth Sci 100:379–400

Hilgen F, Aziz HA, Bice D, Iaccarino S, Krijgsman W, Kuiper K, Zachariasse WJ (2005) The global boundary stratotype section and point (GSSP) of the Tortonian stage (Upper Miocene) at Monte Dei Corvi. Episodes-Newsmagazine of the International Union of Geological Sciences, 28(1):6–17

Huang L (1997) Calcareous nannofossil biostratigraphy in the Pearl River Mouth Basin, South China Sea, and Neogene reticulofenestrid coccoliths size distribution pattern. Mar Miocroplantol 32:31–57

Huang TY, Huang TC (1984) Neogene biostratigraphy of Taiwan. In: Ikebe N, Tsuch R (eds) Pacific Neogene Datum planes Univ Tokyo Press, pp 209–216

Jiang MJ, Gartner S (1984) Neogene and Quaternary calcareous nannofossil biostratigraphy of the Walvis Ridge. In: Moore TC, Rabinowitz PO et al Init Repts DSDP 74:561–595

Kamptner E (1948) Coccolithen aus dem Torton des Inneralpinen Wiener Beckens. Anzeiger. Österreichische Akademie der Wissenschaften. Mathematische-Naturwissenschafliche Klasse. Wien, 157:1–16

Kamptner E (1954) Untersuchungen über den Feinbau der Coccolithen. Archiv für Protistenkunde, 100:1–90

Kamptner E (1956) Das Kalkskelett von Coccolithus huxleyi (Lohmann) Kamptner und Gephyrocapsa oceanica Kamptner (Coccolithineae). Arch. Protistenkd, 101:99–202

Mandur MM (2003) Stratigraphical and paleontological studies on some Miocene successions of southwest Sinai, Egypt. Ph. D. Thesis Ain Shams Univ 220 pp

Marino M, Flores JA (2002) Data report: Calcareous nannofossil stratigraphy at Sites 1088 and 1090 (ODP Leg 177, Southern Ocean). In: Gersonde R, Hodell DA, Blum P (eds) Proc ODP Sci Results 177:1–14 [CD-ROM]. Available from: Ocean Drilling Program, Texas AandM Univ, College Station TX 78745–9547, USA

Martini E (1971) Standard Tertiary and Quaternary calcareous nannoplankton zonation. In: Farinacci A (ed) Proc 2nd Int Conf Planktonic Microfossils Roma: Rome (ed Tecnosci) 2:739–785

Martini E (1975) Calcareous nannoplankton from the Karpatian in Austria (Middle Miocene). Proc. 6th Congr. Medit. Neogene Strat. 1:125–128

Martini E (1976) Cretaceous to Recent calcareous nannoplankton from the Central Pacific Ocean (DSDP Leg 33). In: Schlanger SO, Jackson ED et al. Init Repts DSDP 33:383–423

Martini E (1981a) Nannoplankton in der Ober-Kreide, im Alttertiàr und im tieferen Jungtertiàr von Süddeutschland und dem angrenzenden österreich. Geol Bavarica 82:345–356

Martini E, Müller C (1986) Current tertiary and quaternary calcareous nannoplankton stratigraphy and correlations. Newsl Stratigr 16:99–112

Martini E, Worsley T (1971) Tertiary calcareous nannoplankton from the western equatorial Pacific. Init Repts DSDP 7:1471–1507

Marzouk AM (1998) Nannofossil biostratigraphy of the subsurface Miocene section in the Ras Budran Area, Gulf of Suez, Egypt. N Jb Geol Paläont Abh 210:19–40

Marzouk AM, Soliman SIM (2004) Calcareous nannofossil biostratigraphy of the Paleogene sediments on an onshore-offshore transect of Northern Sinai, Egypt. J Afr Earth Sci 38:155–168

Mazzei R, Raffi I, Rio D, Hamilton N, Cita MB (1979) Calibration of late Neogene calcareous plankton datum planes with the paleomagnetic record of Site 397 and correlation with Moroccan and Mediterranean sections. Init Repts DSDP 47(1):375–389

McGonigal KL, Wei W (2003) Miocene calcareous nannofossil biostratigraphy, ODP Leg 189, Tasmanian Seaway. In: Exon NF, Kennett JP, Malone MJ (eds). Proc ODP Sci Results 189:1–39

Miller LP (1981) Tertiary calcareous nannoplankton and benthic foraminiferal biostratigraphy of the Point Arena area. California Micropaleontol 27(4):419–443

Müller C (1970) Nannoplankton aus dem Mittel-Oligozän von Norddeutschland und Belgien. Neues Jahrbuch für Geologie und Paläontologie Abhandlungen, 135:82–101

Müller C (1974) Calcareous nannoplankton, Leg 25 (Western Indian Ocean). In: Simpson ESW, Schlich R et al. Init Repts DSDP 25: 579–633

Müller C (1977) Distribution of calcareous nannoplankton in Oligocene to Holocene sediments of the Red Sea and Indian Ocean reflecting paleoenvironment. In: Heirtzler JR, Bolli HM, Davies TA, Saunders JB, Sclater JG. Ind Ocean Geol Biostrat, pp 409–422

Müller C (1978) Neogene calcareous nannofossils from the Mediterranean-Leg 42A of the Deep Sea Drilling Project. Init Repts DSDP 42:727–751

Odin GS, Takahashi M, Cosca M (2001) 40Ar/39Ar geochronology of Middle Miocene calcareous nannofossil biohorizons in Central Japan. Chem Geol 171:239–252

Okada H (2000) Neogene and quaternary calcareous nannofossils from the Blake ridge, Sites 994, 995, and 9971. In: Paull CK, Matsumoto R, Wallace PJ, Dillon WP (eds). Proce ODP Sci Results 164:331–341

Okada H, Bukry D (1980) Supplementary modification and introduction of code numbers to the low-latitude coccolith biostratigraphic zonation (Bukry 1973; 1975). Mar Micropaleont 5:321–325

Olafsson G (1989) Quantitative calcareous nannofossil biostratigraphy of upper Oligocene to middle Miocene sediment from ODP Hole 667A and middle Miocene sediment from DSDP Site 574. In: Ruddiman W, Sarnthein M et al. Proc ODP Sci Results 108:9–22

Olafsson G (1991) Quantitative calcareous nannofossil biostratigraphy and bio-chronology of early through late Miocene sediments from DSDP Hole 608. Medd Stockholm Univ Inst Geol Geok 203:28 pp

Parker ME, Clark M, Wise SW (1985) Calcareous nannofossils of Deep Sea Drilling Project Sites 558 and 563, North Atlantic Ocean: biostratigraphy and the distribution of Oligocene braarudosphaerids. Init Repts DSDP 82:559–589

Perch-Nielsen K (1972) Remarks on Late Cretaceous to Pleistocene coccoliths from the North Atlantic. Init Repts DSDP 12:1003–1069

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

Pospichal JJ (2003) Calcareous nannofossils from continental rise Site 1165, ODP Leg 188, Prydz Bay, Antarctica. In: Cooper AK, O'Brien PE, Richter C (eds). Proc ODP Sci Results 188:1–14

Proto-Decima F, Medizza F, Todesco L (1978) Southern Atlantic Leg 40, calcareous nannofossils. In: Bolli HM, Ryan WBF et al. Init Repts DSDP 40:571–634

Raffi I, Flores JA (1995) Pleistocene through Miocene calcareous nannofossils from eastern equatorial Pacific Ocean. In: Pisias NG, Mayer LA, Janecek TR, Palmer-Julson A, van Andel TH (eds). Proc ODP Sci Results 138:233–286

Raffi I, Rio D, d'Atri A, Fornaciari E, Rocchetti S (1995) Quantitative distribution patterns and biomagnetostratigraphy of middle and late Miocene calcareous nannofossils from equatorial Indian and Pacific oceans (Legs 115, 130, and 138). In: Pisias NG, Mayer LA, Janecek TR, Palmer-Julson A, van Andel TH (eds). Proc ODP Sci Results 138:479–502

Rio D, Fornaciari E, Raffi I (1990) Late Oligocene through early from western equatorial Indian Ocean (Leg 115). In: Duncan RA, Backman J, Peterson LC et al. Proc ODP Sci Results 115:175–235

Rizzini A, Vezzani F, Cococcetta V, Milad G (1978) Stratigraphy and sedimentation of Neogene-Quaternary, section in the Nile Delta area (A.R.E.). Mar Geol 27:327–348

Roth PH (1970) Oligocene calcareous nannoplankton biostratigraphy. Eclogae Geologicae Helvetiae, 63:799–881

Roth PH (1974) Calcareous nannofossils from the northwestern Indian Ocean Leg 24, Deep Sea Drilling Project. In: Fisher RL, Bunce ET (eds). Init Repts DSDP 24:969–994

Sadek C (2000) Stratigraphic studies on some Miocene deposits (Gharandal Group) in the Gulf of Suez, north Hammam Faraun area, Egypt. B Sci Thesis, 177 pp

Sadek C (2001) Biostratigraphic contribution to the Miocene formations (Gharandal Group), north Hammam Faraun area, Sinai, Egypt. EGP J Paleont 1:253–261

Samir MZ (2013) Genesis of the Nukhul Sandstones, west central Sinai. EGP J Applied Sci Research 9(1):375–392, ISSN 1819-544X.

Shackleton NJ, Baldauf JG, Flores JA, Iwai M, Moore TG Jr, Raffi I, Vincent E (1995) Biostratigraphic summary for Leg 38. In: Pisias NJ, Mayer LA, Janecek TR, Palmer-Julson A, van Andel TH (eds). Proc ODP Sci Results 138:517–536

Siesser G, de Kaenel P (1999) Neogene calcareous nannofossils: Western Mediterranean biostratigraphy and paleoclimatology. In: Zahn R, Comas MC, Klaus A (eds). Proc ODP Sci Results 161:223–237

Slezak J, Koszarski A, Koszarski L (1995) Calcareous nannoplankton stratigraphy of the terminal flysch deposits from the Skole Nappe (Oligocene-Miocene, Polish Carpathians, Krosno beds). 5th INA Conf in Salamanca Proc pp 267–277

Soliman SA, Ćorić MJH, Piller WE, El Beialy SY (2012) Lower and Middle Miocene biostratigraphy, Gulf of Suez, Egypt based on dinofldgellate cysts and calcareous nannofossils. Palynology 36(1):38–79

Takayama T, Sato T (1985) Coccolith biostratigraphy of the North Atlatic Ocean, Deep Sea Drilling Project Leg 94. In: Bruddiman WF, Kidd RB, Thomas E, (eds). Init Repts DSDP 66:589–639

Tanaka Y, Takahashi M (1998) Calcareous nannofossil biostratigraphy of the lower part of the Miocene Arakawa Group in the Karasuyama area, Tochigi Prefecture, central Japan. J Geol Soc Jpn 104:779–793

Tazzi M (1996) Biostratigraphia a nannofossili calcarei del limite Tortoniano/Messiniano nel bacino di Taza-Guereif (Marocco) e nel sile 978 (Mare di Alboran). Thesis, Univ. Parma (unpubl.)

Theodoridis S (1984) Calcareous nannofossil biozonation of the Miocene and revision of the helicoliths and discoasters. Utrecht Micropaleont Bull 32:1–271

Varol O (1983) Proposed calcareous nannofossil zonation scheme for the Miocene to Holocene of Southeast Asia. Geol Soc Malaysia Bull pp 37–46

Wallich GC (1877) XXXIV.—Observations on the Coccosphere. J Nat Hist 19(112): 342–350

Womardt WW, Chang JZW, Vail PR (1992) Three component sequence stratigraphy. Gulf Coast Assoc Geol Soc 42:363–380

Xu Y, Wise SW (1997) Calcareous nannofossils from Leg 156, Northern Barbados ridge complex. In: Shipley TH, Ogawa Y, Blum P, Bahr J.M (eds.), Proc. ODP, Sci. Results 156:49–56

Zaghloul ZM, Taha AA, Hegab O, El Fawal F (1977b) The Neogene-Quaternary sedimentary basins of the Nile Delta. EGP J Geol 21(1): 1–19