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NEW INSIGHT INTO THE MIDDLE EOCENE CALCAREOUS NANNOPLANKTON BIOSTRATIGRAPHY AND PALEOENVIRONMENT FROM FAYOUM AND BENI SUEF AREAS, EGYPT

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Abstract. The present study deals with calcareous nannoplankton paleoenvironmental and biostratigraphic implications as well as the genesis and the stratigraphic significance of an event bed recognized from the middle Eocene Beni Suef Formation in the sections of Gebel Na'alun (Fayoum area) and Gebel Homret Shaibun (Beni Suef area), Egypt. Calcareous nannoplankton biostratigraphy indicates that the Beni Suef Formation in the two areas is synchronous, covering an interval that may be correlated with the calcareous nannoplankton Zone NP17. Paleoenvironmental implications from calcareous nannoplankton suggests deposition of sediments in the Beni Suef Formation under relatively stable, temperate and mesotrophic conditions, with a short interval of eutrophication in the basal part of the Homret Shaibun section.

Introduction

The middle-upper Eocene strata in the Fayoum and Nile Valley are among the most studied Eocene strata in Egypt (e.g. Beadnell 1905; Said 1962; Bishay 1966; El-Badry & Eid 1987; Faris & Strougo 1992; Saber 1998; Helal 2002; Abdallah et al. 2003; Morsi et al. 2003; Strougo & Faris 2008; Abu El Ghar 2012; Strougo et al. 2013; King et al. 2014; Hegab et al. 2016; Saber & Salama 2017; Ghandour 2020; Sayed et al. 2022). In the Fayoum Depression, they are highly enriched in diverse marine and non-marine vertebrate fossils. They have attracted scientific attentions particularly after the selection of Wadi Al-Hitan, SW Fayoum by UNESCO as an important World Heritage Site in 2005 (e.g. Seiffert et al. 2008; Peters et al. 2009; Abdel-Fattah et al. 2010; Strougo et al. 2013; King et al. 2014).

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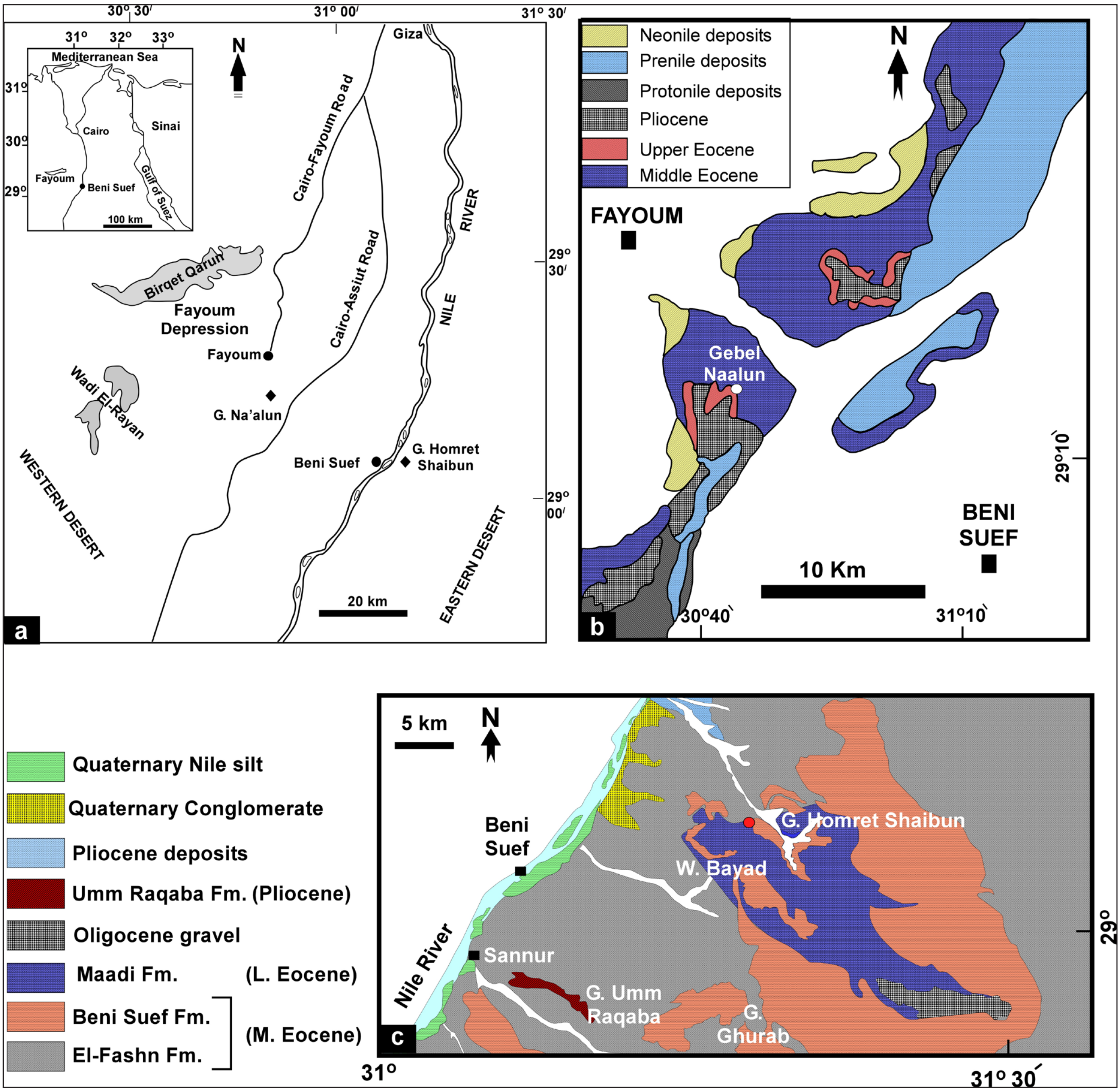

Fig. 1 - Location (a) and geologic maps (b and c) for the study areas. Geological maps are modified after Conoco 1987.

These strata display different sedimentary characteristics compared with their counterparts in the Nile Valley area. However, the Gebel (G.) Na'alun section, which is located SE of the Fayoum Depression (Fig. 1) displays intermediate sedimentary characteristics between the two areas (Strougo 1992). The litho-and biostratigraphic subdivisions of the middle-upper Eocene strata at Gebel Na'alun are often contradictory among stratigraphers (e.g. El-Badry & Eid 1987; Strougo 1992; Abdallah et al. 2003; Abu El Ghar 2012). Strougo (1992) subdivided the middle-upper Eocene strata at Gebel Na'alun into four units arranged from base to top as follows: the Beni Suef, Gehannam, Shaibun and Birqet Qarun formations. The Beni Suef and Shaibun formations display an affinity towards the Nile Valley Basin (Gebel Homret Shaibun, Beni Suef area), whereas the Gehannam and Birqet Qarun formations bear the characteristics of the Fayoum Basin. Other stratigraphic studies favoured the subdivision of the middle-upper Eocene strata at Gebel Na'alun into two rock units; the Gehannam Formation below and the Birqet Qarun Formation above (Fig. 2).

Apart from being a target of several studies, paleoenvironmental investigation of the middle Eocene strata in the Fayoum and Beni Suef areas

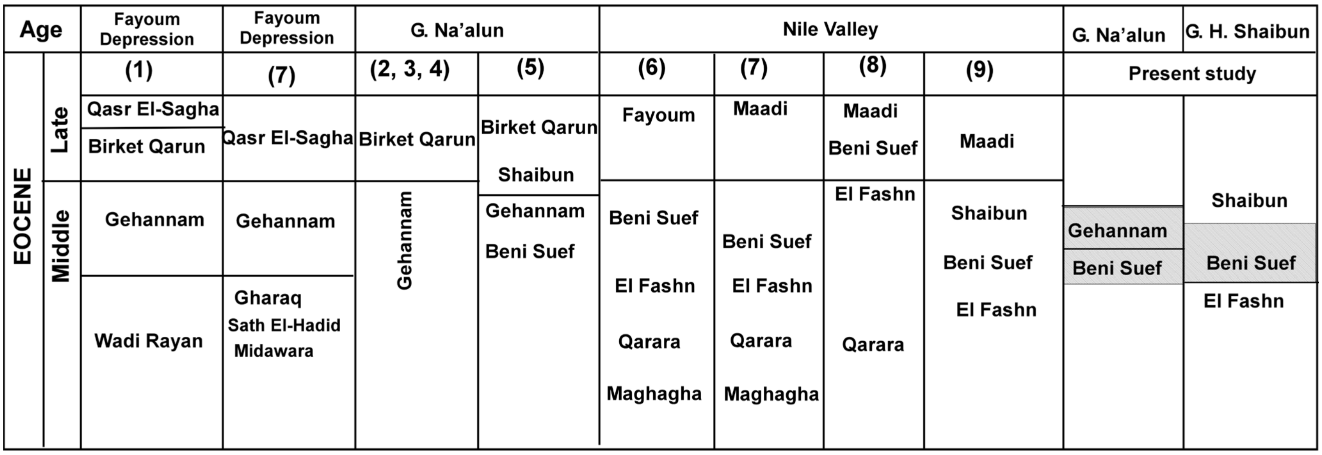

Fig. 2 - Lithostratigraphic subdivision of the Middle-Upper Eocene strata in the Fayoum and Beni Suef areas adopted in different studies. (1) Said 1962, (2) Saber 1998; (3) Abdallah et al. 2003; (4) Abu El Ghar 2012 (5) Strougo 1992, (6) Bishay 1966 (7) Said 1990; (8) Saber & Salama 2017; (9) Strougo et al. 1983.

using the distribution patterns and statistical analysis of calcareous nannoplankton has not been addressed previously. The present study, therefore, employs updated calcareous nannoplankton biostratigraphy in combination with event stratigraphy approach to resolve and correlate the middle-upper Eocene strata of the Gebel Na'alun (Fayoum area) and Gebel Homret Shaibun (Beni Suef area) sections. In addition, statistical analysis of calcareous nannoplankton records allows a reconstruction of the paleoenvironment under which these sediments were deposited.

Geologic setting

In the northern parts of the Egyptian Western Desert, surface and subsurface Eocene deposits covering a wide range of lithologies including sandstones, shales, marls and limestones were recognized (Strougo et al. 2013; King et al. 2014). They were deposited under fluvial and marginal to shallow marine conditions within narrow and elongated intracratonic basins developed during Late Cretaceous tectonic activity (El Zarka 1983; El Hawat 1997). These basins were bounded by positive landmasses representing sites of non-deposition and/or erosion (Salem 1976). The Eocene stratigraphic section in Egypt displays a general shallowing upward pattern reflecting the progressive tectonic uplift of the African craton in response to the compressive tectonics between Africa and Eurasia (El Hawat 1997). During Early and Middle Eocene, the southern Tethyan margin including Egypt was occupied by an extensive carbonate ramp that changed during the late Middle Eocene (late Bartonian) into a siliciclastic-dominated depositional setting (Aigner 1982; Said 1990; Strougo & Faris 2008; King et al. 2014), possibly associated with the uplift of East Africa and the initiation of northerly drainage (Underwood et al. 2013). The middle and upper Eocene succession is almost continuous in the Fayoum, Nile Valley and Western Desert, with rare discontinuities indicated by omission surfaces, largely below biostratigraphic resolution (King et al. 2014). Paleogeographic maps showed that, the Tethyan shoreline extended close to latitude 27° during the Middle Eocene (Said 1990).

The Fayoum Depression contains a thick rock succession ranging from Middle Eocene to Recent. The succession is almost entirely of sedimentary origin with the exception of Oligocene basaltic beds in the northern end of the depression. The middle-upper Eocene facies characteristics are different in west and east Fayoum. The strata at Gebel Na'alun (Fig. 1) display facies characteristics intermediate between west Fayoum and the Nile Valley towards the east (Strougo 1992; Morsi et al. 2003; Strougo & Faris 2008). The basal strata were named as Ravine Beds by Beadnell (1905) and later named as the Gehannam Formation by Said (1962). This name was adopted in many studies (e.g. El-Badry & Eid 1987; Saber 1998; Helal 2002; Abdallah et al. 2003; Abu El Ghar 2012 and reference therein). However, Strougo (1992) and Strougo & Faris (2008) subdivided the middle-upper Eocene succession at Gebel Na'alun into the Beni Suef Formation at the base, overlain by the Gehannam, Shaibun and Birqet Qarun formations (Fig. 2). The Beni Suef and Shaibun formations bear similarities with the middle-upper Eocene strata in the Nile Valley, east Fayoum (Bishay 1966; Bassiouni et al. 1980), whereas the Gehannam and Birket Qarun formations are typical of the west Fayoum facies (Said 1962; Morsi et al. 2003; Strougo & Faris 2008). On the other hand, the middle-upper Eocene succession at Gebel Homret Shaibun, Beni Suef area, is subdivided into the El-Fashn, Beni Suef, and Shaibun formations (Fig. 2). The strata are continuous, horizontal and vertically unaffected by structural complications (El Zarka 1983; El Hawat 1997; Saber & Salama 2017).

Material and methods

Two stratigraphic sections (Fig. 3) covering the Beni Suef Formation were studied at Gebel Na'alun and Gebel Homret Shaibun. The work strategy was to look for event bed (s) in the strata and to define their characteristics and stratigraphic position. Fifty-nine fresh rock samples (21 from Gebel Na'alun and 38 from Gebel Homret Shaibun) were collected for biostratigraphic investigations. For smear slide preparation, a small portion of each sample was soaked in 25 ml distilled water and after complete disaggregation of the material, a drop or two of slightly turbid suspension was placed on a glass slide. The suspension drops were distributed on the slide via plastic pipette. The slides were then placed over a hot plate to achieve complete dryness. A mounting medium, D.P.X., was utilized to mount a coverslip to each glass slide. Calcareous nannoplankton abundance was determined by counting at least 300 specimens per slide using a light microscope (Axiolab A) with 1000 x magnification. The counted number of fields of view was between 5 and 620. In addition, two vertical traverses across each slide (170 fields of view/traverse) were scanned in order to identify any rare and biostratigraphically important species. Specimens images were captured with an AxioCam ERc5s digital microscopy camera through ZEN 3.4 blue edition software.

Principal component analysis (PCA) and hierarchical cluster analysis (HCA) (Q-mode) were performed using PAST version 4.07b (Hammer et al. 2001) through Ward's algorithm and the Euclidean similarity index (linkage). The calcareous nannoplankton taxa with <2% relative abundance (RA) were excluded from the statistical analysis. The arcsine square root transformation on the RA was applied before the multivariate data analysis (Auer et al. 2014; Kallanxhi et al. 2018; Bindiu-Haitonic et al. 2021).

Results

Sedimentary characteristics

The Beni Suef Formation occupies the base of the section at Gebel Na'alun adjacent to the cultivated area. The base of the formation is unexposed and the measured strata represent the oldest exposed rocks in the area (Figs. 3 and 4A). The upper boundary of the Beni Suef Formation is placed at the transition from marls and argillaceous limestones to the overlying light green shales of the Gehannam Formation (Fig. 4B). At Gebel Homret Shaibun, the calcareous light grey mudstones of the Beni Suef Formation abruptly overlie the white chalky limestones of El-Fashn Formation that are exposed at the base of the mountain (Figs. 3 and 4E). The transition from the Beni Suef Formation to the overlying Shaibun Formation is delineated at the contact between the second resistant limestone bed of the Beni Suef Formation and the overlying calcareous mudstones and yellow marls of the Shaibun Formation (Fig. 4F).

The sediments of the Beni Suef Formation are relatively similar at Gebel Na'alun and Homret Shaibun. They consist mainly of clay-rich mudstones which are in some parts calcareous alternating with cliff forming sparsely fossiliferous and burrowed limestones. Mudstones appear as distinct recessive units between the more resistant limestones. The mudstones are light to grayish green and mostly structureless. The limestones are in some places argillaceous, massive to thickly bedded with sharp irregular bed contacts. At Gebel Homret Shaibun, shales are more calcareous and the limestone is harder, whiter and less burrowed.

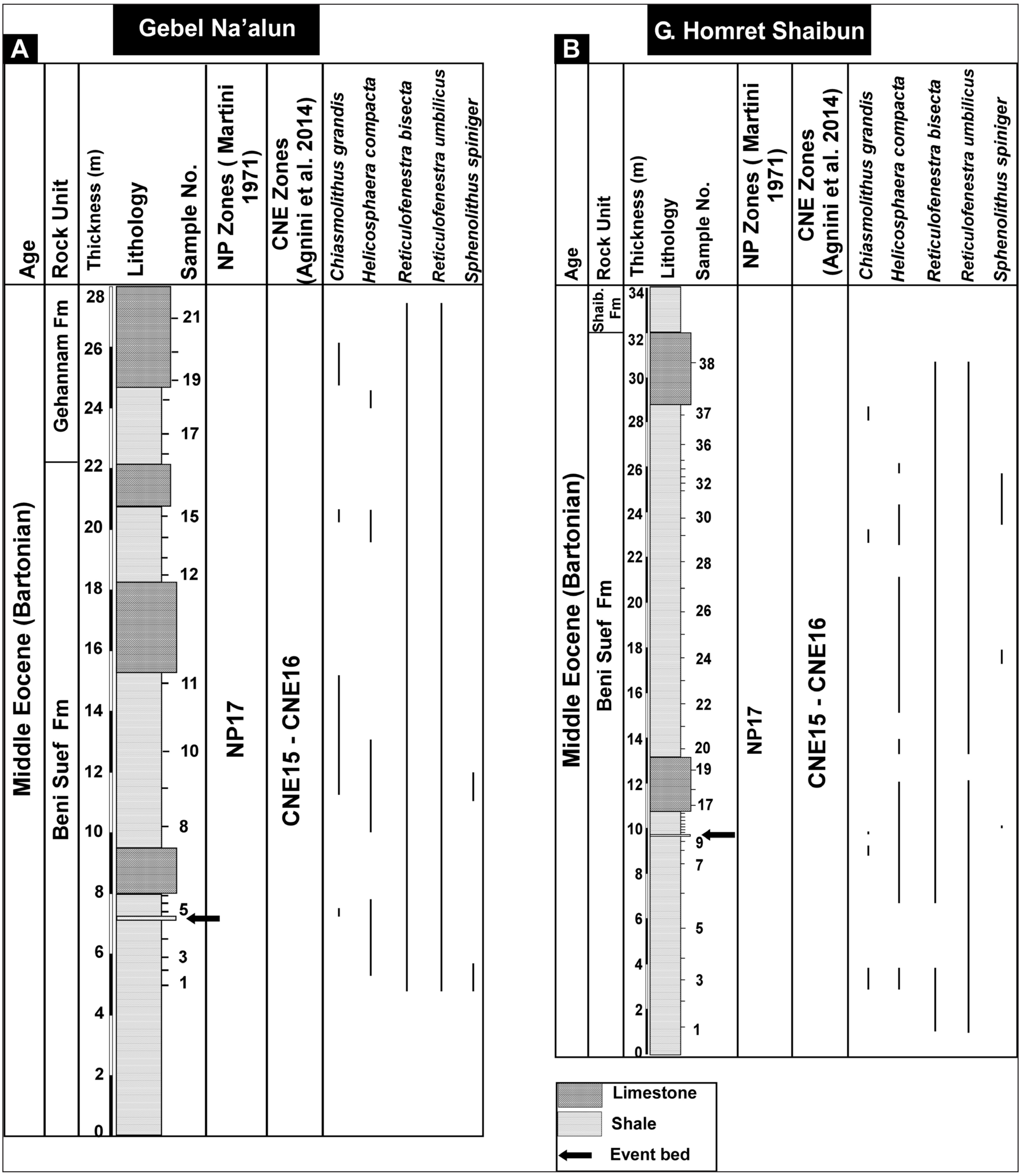

Fig. 3 - The measured stratigraphic sections at Gebel Na'alun and Homret Shaibun area.

A single sandstone bed was recognized in the basal part of the Beni Suef Formation. Though it is thin, it provides a good clue for correlation and verifies the stratigraphic setting of the nannoplankton-bearing strata. This bed at G. Na'alun consists of a 2.5 to 5 cm thick sharp erosively based sandstone. It displays undulated parallel lamination, wave ripples and very small scale hummocky cross-stratification (HCS; Fig. 4C-D). At Gebel Homret Shaibun, a metre below the first

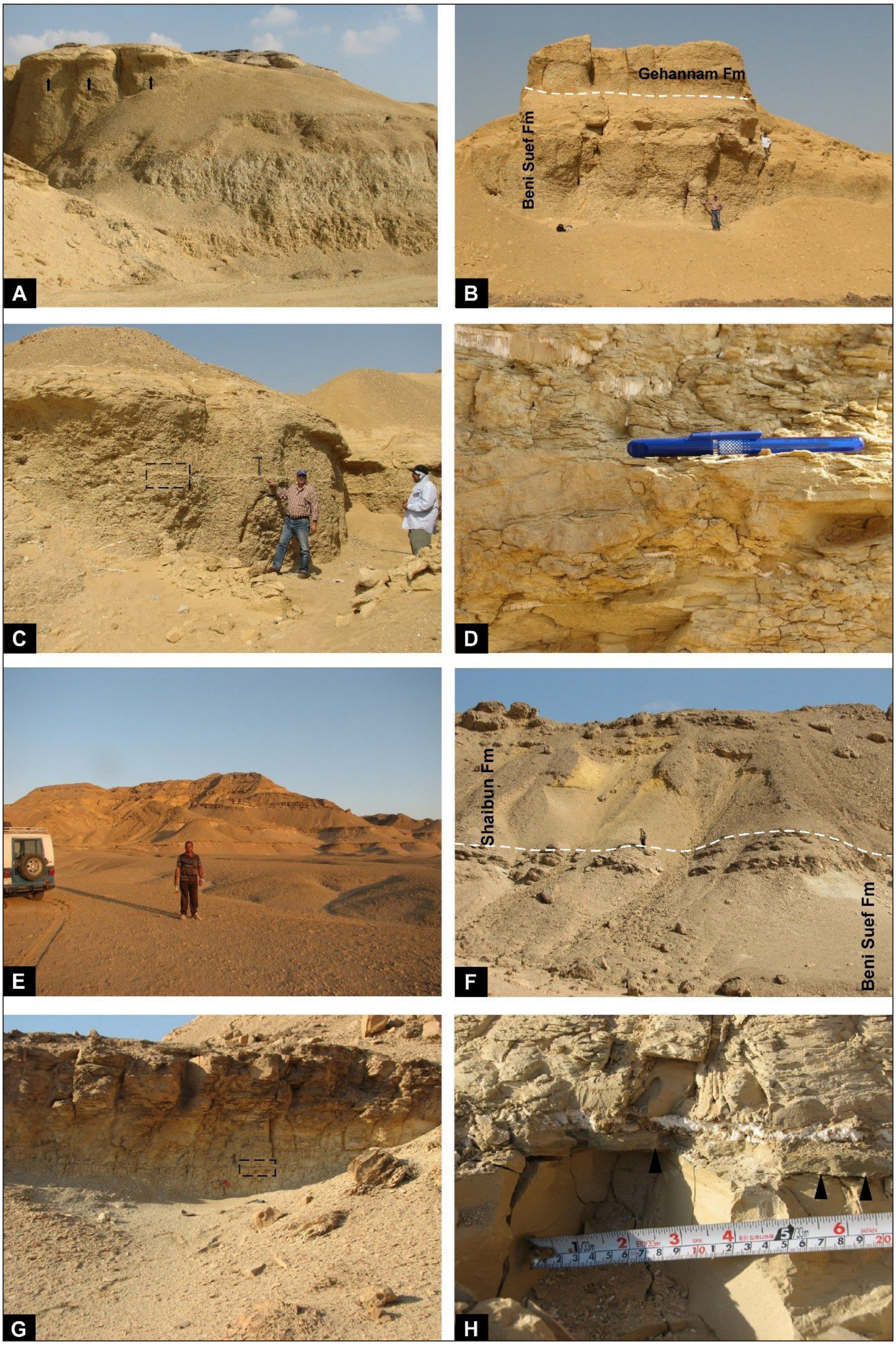

Fig. 4 - Field photographs of the Beni Suef Formation in the Gebel Na'alun and Homret Shaibun. A and C) The basal part of the Beni Suef Formation at Gebel Na'alun (black arrows in A show the location of the event bed). B) The contact between the Beni Suef and the overlying Gehannam Formation at Gebel Na'alun. D) Close up view showing the HCS that characterize the event bed at Gebel Na'alun, E) The base of the Gebel Homret Shaibun section. F) The contact between the Beni Suef and the overlying Shaibun Formation at Gebel Homret Shaibun. G and H) The location and the characteristic feature of the event bed at Gebel Homret Shaibun.

limestone bed, the equivalent bed (about 1.5-2 cm thick) consists of sharp based light green massive fine-grained sandstone (Fig. 4G and H). Secondary gypsum layers separate this fine-grained sandstone bed from the overlying and underlying deposits.

Calcareous nannoplankton diversity, abundance and preservation

In the Homret Shaibun section, the preservation of calcareous nannoplankton is good and the diversity is high, with 59 identified species. The assemblage is clearly dominated by the *Reticulofenestra minuta* (between 0% and 53.93%) followed by *R. dictyoda* (between 0.30% and 59.33%), *Cyclicargolithus floridanus* (between 0% and 36.21%), *R. reticulata* (between 0% and 23.98%), *Coccolithus pelagicus* (between 0% and 24.61%), and *R. bisecta* (between 0% and 11.63%) (Fig. 5). The relative abundance (RA) of *Reticulofenestra minuta* is high in most of the samples, excepting the interval between sample 3 and sample 7, where this species was not identified and samples 8, 15, 20, 24, and 37 where the RA of this species does not exceed 10%. *Reticulofenestra dictyoda* registered two intervals with a higher relative abundance, in the lower and middle part of the section, being negatively correlated with the RA of *R. minuta*. The RA of *Cyclicargolithus floridanus* showed an increasing trend through the upper part of the section where reaches the highest values. *Reticulofenestra reticulata* was absent in the lower part of the section, between sample 3 and 6, with a peak of abundance in the middle part of the section, in sample 25. *Coccolithus pelagicus* recorded a slightly low fluctuation along the studied section, with a peak of abundance in the lowermost part of the profile followed by its absence in the next two samples. The RA of *Reticulofenestra bisecta* was higher in the middle part of the section, followed by a fluctuation towards the upper part.

In the Homret Shaibun assemblage another important taxon is the genus *Pontosphaera* (*P. duocava, P. panarium, P. pectinata, P. plana, P. multipora, P. pygmaea, P. enormis, P. formosa, P. versa*), which reaches the highest RA (20.52%) in sample 17. Among the identified species within the genus *Pontosphaera, P. pygmaea* exhibits a high peak of abundance in the middle part of the section (19.21%) but is absent in most of the studied samples. The genus *Helicosphaera* is represented by four species (*H. compacta, H. clarissima, H. lophota, H. bramlettei*), the most

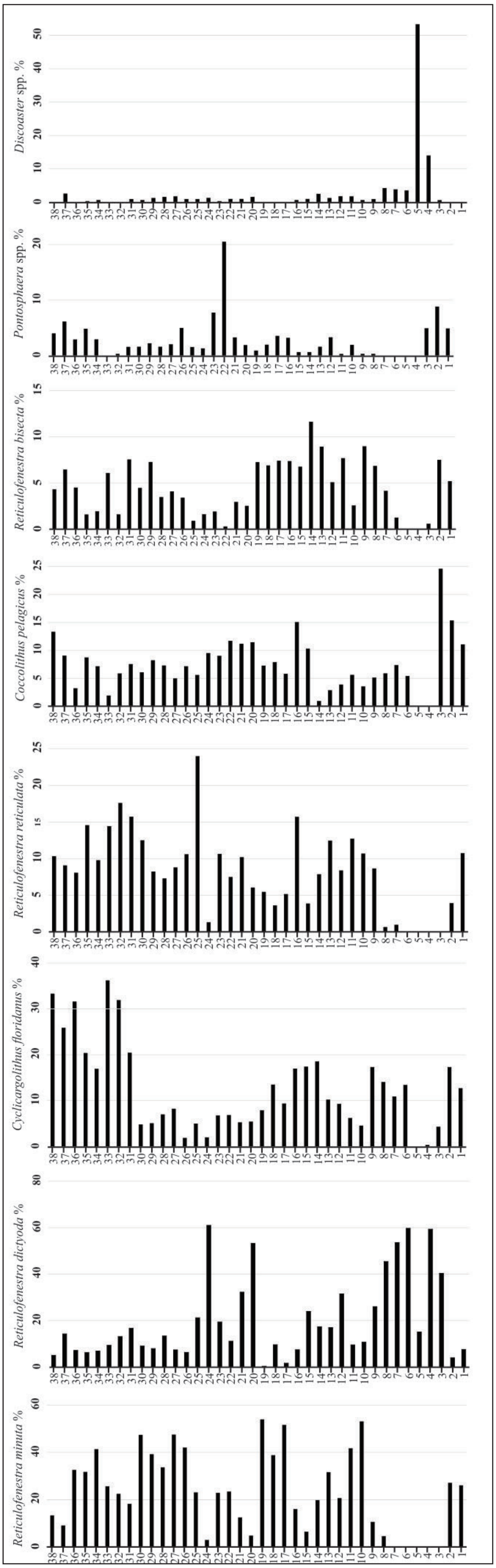

Fig. 5 - Abundance patterns of the dominant and subdominant calcareous nannoplankton species from Homret Shaibun section, plotted along the sampling interval.

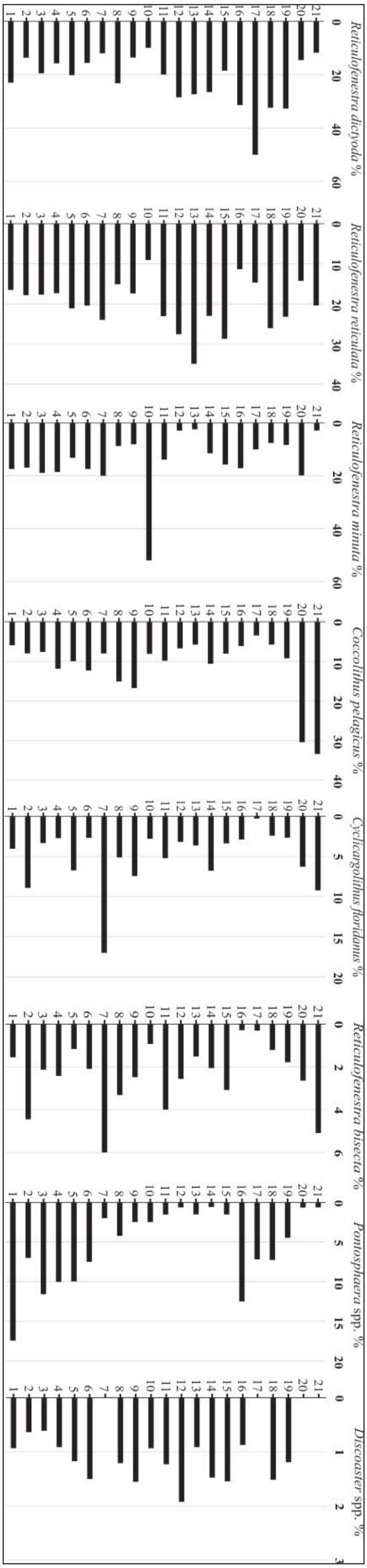

Fig. 6 - Abundance patterns of the dominant and subdominant calcareous nannoplankton species from Gebel Na'alun section, plotted along the sampling interval.

abundant one being *H. lophota* with a maximum abundance of 3.22%. The genus *Discoaster* is represented by five species (*D. barbadiensis, D. deflandrei, D. saipanensis, D. tanii, D. nodifer*). The RA of *Discoaster* spp. showed a high peak in the lowermost part of the section where this genus is mostly represented by *D. saipanensis* (up to 21.66%). From the Braarudosphaeraceae family, genus *Braarudosphaera* (*B. bigelowii, B. perampla*), *Micrantolithus* (*M. astrum, M. flos*) and *Pemma* (*P. basquense*) are discontinuously present in the assemblage and in low abundance (2.23% and 2.66%, respectively). Some other identified taxa, rarely present along the section or in low abundance are listed in Appendix.

The Shannon diversity index (H) is low (mean 2.28) and varies from 1.4 to 2.6. Evenness (E) varies from 0.21 to 0.92 and Species Richness is low/moderate (mean 27) and varies from 9 to 40 species per sample.

The calcareous nannoplankton assemblage from the Gebel Na'alun section is in a good state of preservation and comprises 53 taxa. The most abundant species is *Reticulofenestra dictyoda* (between 11.78% and 32.42%) followed by *Reticulofenestra reticulata* (between 9.03% and 34.95%), *Reticulofenestra minuta* (between 2.43% and 52.02%), *Coccolithus pelagicus* (between 3.43% and 33.43%) and *Cyclicargolithus floridanus* (between 0.31% and 34.95%) (Fig. 6). The RA of *R. dictyoda* does not show a high fluctuation along the studied section but a peak of abundance can be recognized in the upper part of the section, in sample 17. The species *R. reticulata* recorded a RA with minor fluctuations with a peak of abundance in sample 13 and the RA of *R. minuta* exhibited the highest value in the middle part of the section, in sample 10. For *Coccolithus pelagicus* and *Cyclicargolithus floridanus* species the RA pattern follows the same variation as for the other mentioned above species, with highest values in the upper part of the profile (samples 20 and 21) and in the lower part of the profile (sample 7), respectively.

Other species recorded a continuous presence in the studied materials and these are: *Coccolithus formosus* (mean 1.18%), *Reticulofenestra bisecta* (mean 2.43%), *Reticulofenestra umbilicus* (mean 3.39%). Important species but with discontinuous presence along the studied section are: *Discoaster* spp. (*D. barbadiensis, D. deflandrei, D. saipanensis, D. tanii, D. nodifer, D. septemradiatus* – mean 0.95%), *He-*

	Coccolithus pelagicus	*Reticulofenestra reticulata*	*Cyclicargolithus floridanus*	*Discoaster spp.*	*Reticulofenestra minuta*	*Reticulofenestra dictyoda*	*Reticulofenestra bisecta*	*Reticulofenestra umbilicus.*	*Potnosphaera spp.*
Coccolithus pelagicus		**0.430**	**0.620**	0.045	0.090	**0.430**	**0.605**	**0.862**	**0.533**
Reticulofenestra reticulata	0.104		0.299	0.037	**0.370**	0.131	0.155	**0.671**	**0.421**
Cyclicargolithus floridanus	-0.065	-0.137		0.125	**0.563**	0.011	0.000	0.072	0.128
Discoaster spp.	-0.261	-0.272	-0.201		0.048	0.447	0.099	0.017	0.210
Reticulofenestra minuta	-0.222	-0.118	0.076	-0.257		**1.82E**	0.030	0.000	**0.965**
Reticulofenestra dictyoda	-0.104	-0.198	**-0.325**	0.100	**-0.687**		0.004	0.014	**0.426**
Reticulofenestra bisecta	-0.068	-0.187	**0.458**	-0.216	0.282	**-0.367**		0.054	0.009
Reticulofenestra umbilicus	-0.022	-0.056	-0.235	0.308	**-0.427**	0.315	-0.252		0.269
Pontosphaera spp.	0.082	0.106	-0.200	-0.165	0.005	-0.105	**-0.333**	-0.146	

Tab. 1 - Pearson's correlation matrix of selected calcareous nannoplankton taxa from the Beni Suef Formation.

licosphaera spp. (*H. compacta, H. clarissima, H. lophota, H. bramlettei* – mean 0.71%), *Reticulofenestra daviesii* (mean 1.74%), *Reticulofenestra lockeri* (mean 1.29%), *Pemma basquense* (mean 0.79%), *Pontosphaera* spp. (*P. duocava, P. enormis, P. pygmaea, P. panarium, P. plana, P. multipora* – mean 5.39%), and *Zygrablithus bijugatus* (mean 1.75%).

The Shannon diversity index (H) is low (mean 2.65) and varies from 2.2 to 2.9. Evenness (E) varies from 0.29 to 0.70 and Species Richness is low/moderate (mean 33) and varies from 16 to 39 species per sample.

Some small differences can be emphasized between the two studied sections regarding the assemblage's composition and these are the absence of: *Blackites spinosus*, *Coronocyclus nitescens*, and *Discoaster septemradiatus*, from the Homret Shaibun section, and the absence of: *Braarudosphaera perampla*, *Coccolithus biparteoperculatus*, *Neococcolithes minutus, Pontosphaera formosa*, *Pontosphaera versa,* and *Sphenolithus radians*, from the Na'alun section. It is worth mentioning that the above-mentioned species occur rarely and in very low abundance in the studied material.

Based on the Pearson's correlation (Table 1) *Reticulofenestra dictyoda* shows a negative correlation with *Cyclicargolithus floridanus* and *Reticulofenestra minuta*. Some other negative correlations are between: *Reticulofenestra bisecta* and *Reticulofenestra dictyoda*, *Reticulofenestra umbilicus* and *Reticulofenestra minuta*, and between *Pontosphaera* spp. and *Reticulofenestra bisecta*. Regarding positive correlations, the following taxa display higher values: *Coccolithus pelagicus* with *Reticulofenestra reticulata, Cyclicargolithus floridanus, Reticulofenestra dictyoda, Reticulofenestra bisecta, Reticulofenestra umbilicus* and *Pontosphaera* spp.; *Reticulofenestra reticulata* with *Reticulofenestra minuta, Reticulofenestra umbilicus* and *Pontosphaera* spp.; *Cyclicargolithus floridanus* with *Reticulofenestra minuta*; *Reticulofenestra minuta* with *Reticulofenestra dictyoda* and *Pontosphaera* spp.; and *Reticulofenestra dictyoda* with *Pontosphaera* spp..

The identified calcareous nannoplankton species assign the Beni Suef Formation, from both studied sections, to a middle Eocene (Bartonian) age. The Beni Suef Formation in the two areas covers an interval that may be correlated with the *Discoaster saipanensis* Zone (NP17) (Martini 1971), which is defined from the last occurrence (LO) of *Chiasmolithus solitus* to the first occurrence (FO) of *Chiasmolithus oamaruensis* but both species are not firmly identified from the studied material. The co-occurrence of *Chiasmolithus grandis* and

Reticulofenestra bisecta allow us to recognize the presence of the NP17 Zone in both studied sections (Fig. 3). The species *Chiasmolithus grandis* (which has its LO in the NP17 Zone – Perch-Nielsen, 1985) was identified in 17% of the samples and *Reticulofenestra bisecta* (with its FO within the NP17 Zone – Perch-Nielsen, 1985) appears in 97% of the samples and reaches a relative abundance up to 11.63%. Two other species with their FO in the NP16 Zone (Perch-Nielsen, 1985; Young et al., 2017) are *Reticulofenestra umbilicus* (its presence was identified in all samples) and *Helicosphaera compacta* (recognized in 59% of the studied material) that can support the attribution of the studied material to the NP17 Zone. The species *Sphenolithus spiniger* (with its LO in the NP17 Zone – Fornaciari et al., 2010) was also recognized in the studied samples but only in 10 samples and in very low number.

Calcareous nannoplankton statistics

The HCA and PCA is based on the most abundant taxa (>2% in most of the samples): especially *Reticulofenestra minuta* (average abundance 20.68%), *Reticulofenestra dictyoda* (19.79%), *Reticulofenestra reticulata* (12.77%), *Cyclicargolithus floridanus* (10.10%) and *Coccolithus pelagicus* (8.97%).

The multivariate cluster analysis separated the assemblages into two main groups: cluster 1 divided into five sub-clusters (1a to 1e) and cluster 2 with three sub-clusters (2a to 2c) (Fig. 7).

Cluster 1 groups 30 samples (12 samples from the Homret Shaibun section and 18 samples from the Gebel Na'alun section). **Sub-cluster 1a** contains 7 samples and is characterized by moderate RA values for *Reticulofenestra dictyoda* (with an average of 28.41%). Some other abundant species in this sub-cluster are *Reticulofenestra minuta* (mean of 11.46) and *Reticulofenestra reticulata* (mean of 8.37%). **Sub-cluster 1b** comprises 11 samples separated based on the moderate RA values of *Reticulofenestra reticulata* (mean of 20.38%), followed by *Reticulofenestra dictyoda* (mean of 19.75%) and *Reticulofenestra minuta* (mean of 15.13%). **Sub-cluster 1c** with only 2 samples was separated based on the highest abundance of *Coccolithus pelagicus* (mean of 31.94%). In these two samples (N20 and N21) there are also other species with a high abundance affecting the position of these samples within the PCA graphic (Fig. 8), the samples being intercalated with those from sub-cluster 1a and sub-cluster 2b. **Sub-cluster 1d** is represented by 4 samples with the highest abundance of *Reticulofenestra reticulata* (with an average of 27.94%). The species *Reticulofenestra dictyoda* is another abundant taxon (mean of 30.25%) within this assemblage. **Sub-cluster 1e** with 6 species was separated based on the highest abundance of *Reticulofenestra dictyoda* (with an average of 47.61%).

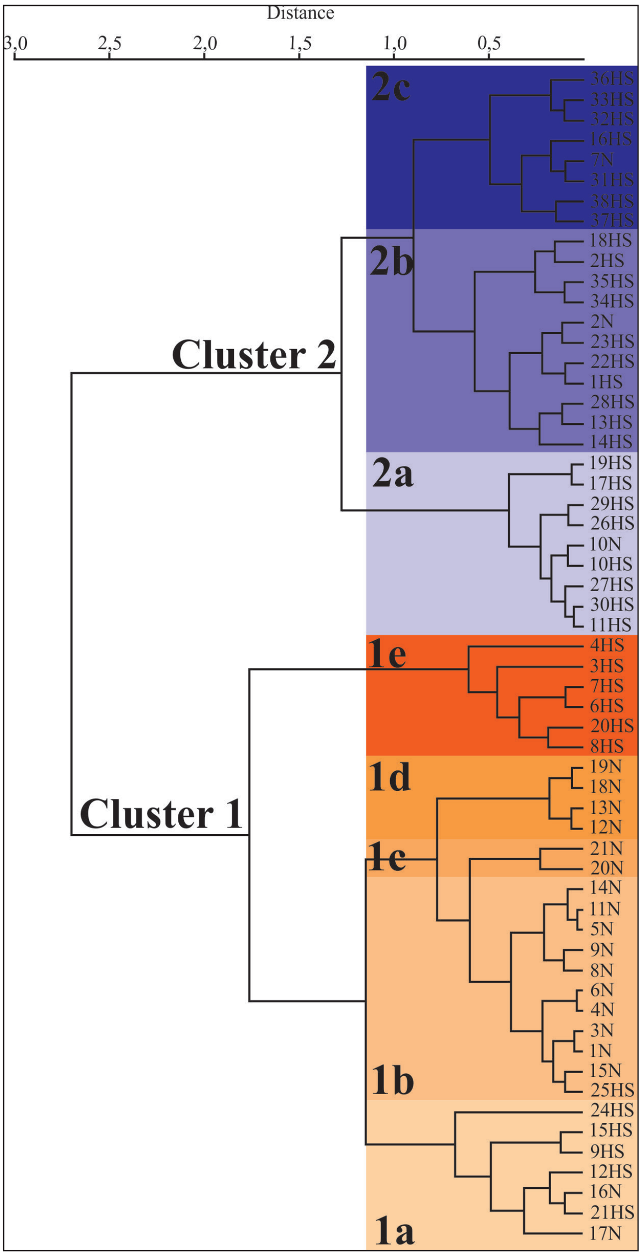

Fig. 7 - Multivariate hierarchical clustering analysis (Ward's method) performed on selected calcareous nannoplankton taxa in both studied sections (N - Gebel Na'alun samples and HS - Homret Shaibun samples).

Cluster 2 is formed by 28 samples (25 samples from Homret Shaibun section and 3 samples from the Gebel Na'alun section). **Sub-cluster 2a** consists of 9 samples characterized by the highest

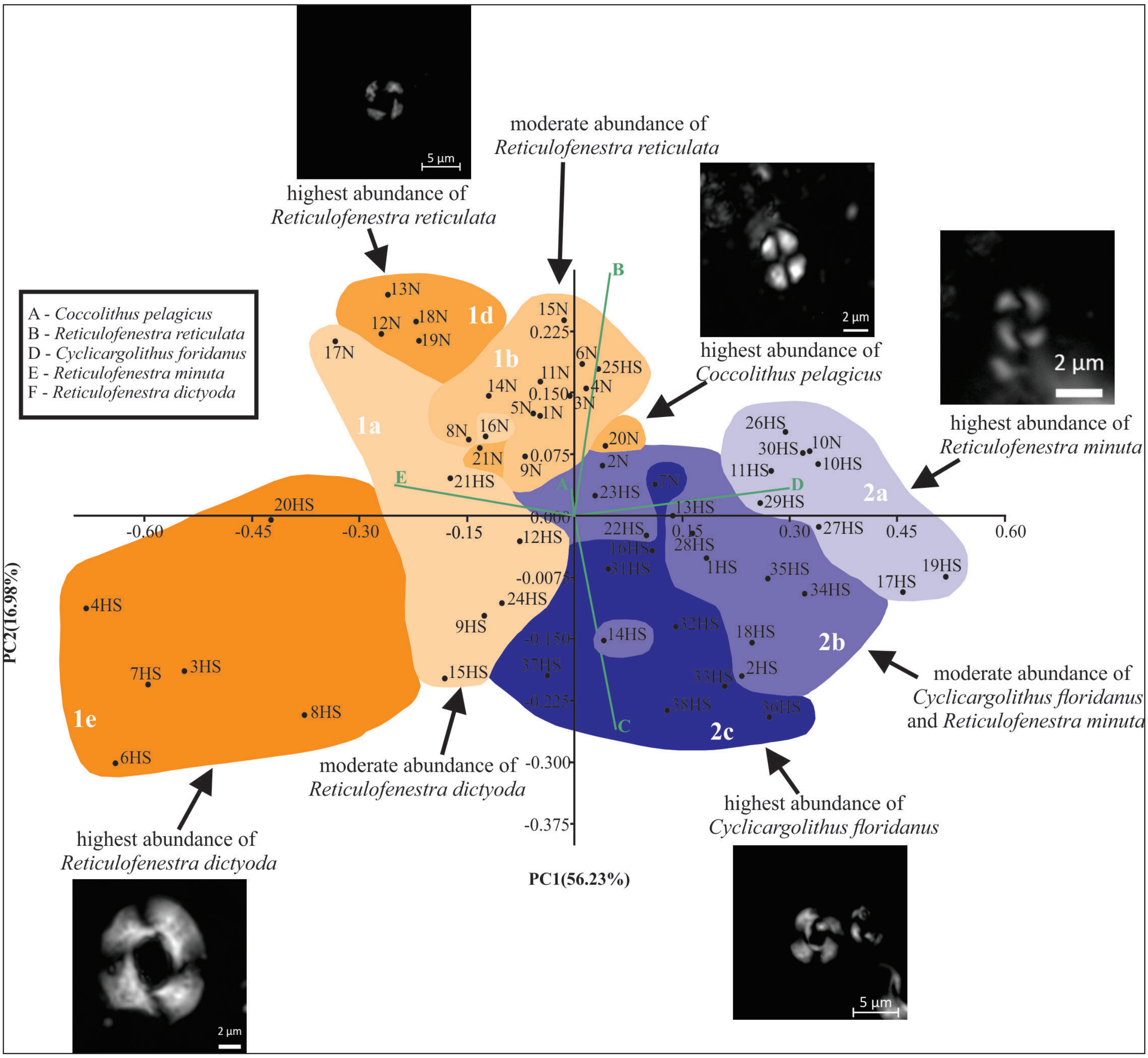

Fig. 8 - Principal Component Analysis carried out using selected calcareous nannoplankton taxa in both studied sections.

abundance of *Reticulofenestra minuta* taxon (with an average of 47.61%). **Sub-cluster 2b** is formed by 11 samples and was separated based on the moderate RA values of *Cyclicargolithus floridanus* (with a mean of 12.64%) and *Reticulofenestra minuta* (with a mean of 27.57%). **Sub-cluster 2c** comprises 8 samples with the highest abundance of *Cyclicargolithus floridanus* (with an average of 26.67%), followed by *Reticulofenestra minuta* (mean of 19.66%) and *Reticulofenestra reticulata* (14.35%).

PC1 is negatively loaded by *Reticulofenestra dictyoda* and positively by *Reticulofenestra minuta*. The loadings of the other species are too low to be significant. Within PC2, the most meaningful taxa are *Reticulofenestra reticulata* (positive loadings) and *Cyclicargolithus floridanus* (negative loadings).

Discussion

Event bed in the Beni Suef Formation as a tool for long-distance correlation

Except for slight lateral variations, the sediments of the Beni Suef Formation are more or less similar at Gebel Na'alun (Fayoum) and Gebel Homret Shaibun (Beni Suef) suggesting a possible single basin of deposition. The deposition was in a tectonically stable setting. It is therefore likely that most sedimentary units would have similar characteristics across the whole basin and any event will affect the sedimentation in different parts of the same basin simultaneously. However, the outcomes (event bed) of this event may be slightly different from one place to another but they indicate a similar depositional process. The event bed of wide extension and lateral distribution can be of regional to interregional significance. In the Beni Suef Formation, the event bed is traceable in Gebel Na'alun and Gebel Homret Shaibun. The event bed though of different characteristics in the two areas, but it has more or less a similar stratigraphic position. It provides an isochronous surface that can be a reliable datum for precise correlation. Aigner (1982) successfully applied the concept of event stratification to Eocene deposits of Egypt using shell beds. Event shell beds are a reliable tool for correlation and are useful for high resolution stratigraphy on a regional scale due to their wide geographic distribution and their isochronous character.

In the present study, the event bed is represented by sharp erosively based sandstones interbedded within offshore mudstones. Two main processes are responsible for delivering sands to the offshore (Walker 1984). The first includes the formation of density (turbidity) currents originated by sediment failure from an overcharged delta front and shoreface (Wright et al. 1988) and from hyperpycnal flows at river mouths (Mulder & Syvitski 1995; Mutti et al. 2003). The second process includes hurricane and winter storm wave actions, which induce combined downwelling currents (Duke 1990). The absence of classic turbidite Bouma sequence excludes the possible role of turbidity currents. The laminae undulation and the presence of hummocky cross stratification (HCS) clearly indicate deposition by the action of storm waves (Dott & Bourgeois 1982; Swift et al. 1983). Erosive based sandy beds, interlayered in offshore mud on modern temperate shelves are commonly interpreted as a result of storm wave actions (Swift & Thorne 1991). Hummocky cross stratification forms most likely in response to a combination of waning storm-generated unidirectional flow with superimposed oscillatory storm wave action (Swift et al. 1983). The storm sandstones are deposited rapidly within short duration; hours to days depending on the duration of the storm. Storm can alter the hydrodynamic conditions considerably and can cause rapid accumulation of sediment with significant change in grain size (Xiao et al. 2013). The presence of storm sandstones implies that there were co-existing shoreface sandstones within the basin to the south. The variation in the grain size of the storm bed in the Gebel Na'alun vs Homret Shaibun implies that the area of Gebel Na'alun was shallower than that of the G. Homret Shaibun. The massive fine-grained sandstones to siltstones at Gebel Homret Shaibun probably indicate distal end of storm bed, whereas the relatively coarse sandstones at Gebel Na'alun probably indicate more proximal position in the basin. Due to the reduction of intensity of the storm basinward, the finer grade materials start to settle rapidly and hence no sedimentary structures were formed.

Calcareous nannoplankton biostratigraphy

Deposits belonging to the Beni Suef Formation were studied in Fayoum-Nile Valley (Strougo 1992) and in Gebel Na'alun area (Strougo & Faris 2008) and the described calcareous nannoplankton assemblage, in the Beni Suef Formation was diverse and slightly different from that described in the current study. In both these previous studies, the presence of *Chiasmolithus solitus* was identified near the base of the Beni Suef Formation, with a sporadic occurrence or a complete absence in the rest of the formation. Based on this presence, the authors suggested the occurrence of the *Discoaster tanii nodifer* Zone (NP16) in the lower part of the Beni Suef Formation. Most part of the Beni Suef Formation was attributed to the *Discoaster saipanensis* Zone (NP17) and *Chiasmolithus oamaruensis* Zone (NP18) (Strougo 1992; Strougo & Faris 2008). Strougo & Faris (2008) reported the presence of *Istmolithus recurvus*, below the first occurrence of *Chiasmolithus oamaruensis*, placing this occurrence in the Bartonian and not in the Priabonian. This age was sustained by the planktonic foraminiferal assemblage, which was characteristic of the P13 and P14 zones. Saber & Salama (2017) considered the Beni Suef Formation in the Beni Suef area as Late Eocene (Priabonian) based on planktonic foraminiferal studies.

In the present study, the deposits belonging to the Beni Suef Formation contain Middle Eocene calcareous nannoplankton assemblages characterized by the presence of species belonging to Noelaerhabdaceae family, which are the most abundant and the absence of the marker species (*Chiasmolithus solitus, Chiasmolithus oamaruensis*). But, based on the presence and/or absence of some other taxa (e.g. *Chiasmolithus grandis, Helicosphaera compacta, Reticulofenestra umbilicus, Reticulofenestra bisecta, Sphenolithus spiniger*), the studied deposits can be placed within the *Discoaster saipanensis* Zone (NP 17) of Martini (1971). This zone is defined by the last occurrence (LO) of *Chiasmolithus solitus* and the first occurrence (FO) of *Chiasmolithus oamaruensis* and can be correlated to CP14b of Okada & Bukry (1980) which is defined by the LO of *Chiasmolithus solitus* or LO of *Discoaster bifax* to LO of *Chiasmolithus grandis* and FO of *Chiasmolithus oamaruensis*. The species *Chiasmolithus solitus, Discoaster bifax* and *Chiasmolithus oamaruensis* were not identified in the studied material but *Chiasmolithus grandis* was reported, in low numbers, in nine samples, from both studied sections. Within the Gebel Homret Shaibun section this taxon appears in the lower part of the section whereas in the Gebel Na'alun section it has a discontinuous presence from the lower part through the top of the section. Shafik (1983) considered that an assemblage containing both *Chiasmolithus oamaruensis* and *Chiasmolithus grandis* is latest Middle Eocene in age. Thus, taking into consideration that *Chiasmolitus oamaruensis* is missing from both studied sections, it is certainly assumed that the age of the studied material is older than the above-mentioned age. Marino & Flores (2002) reported that *Chiasmolithus grandis* is scattered and rare in the uppermost part of its range. Thus, the rare presence of this species in the studied material can be attributed to the fact that the studied deposits fall within the NP17 Zone.The FO of *Helicosphaera compacta* was recorded within the NP17 Zone (Perch-Nielsen, 1985). In the studied material, this species occurs in more than half of the samples, with a more consistent presence in the Gebel Homret Shaibun section. Based on the biozonation scheme of Agnini et al. (2014), the NP17 biozone corresponds to the upper part of CNE15 Zone and the entire CNE 16 Zone, defined as the interval from base of *Reticulofenestra bisecta* to the top *Sphenolithus obtusus* which covers the upper part of the NP16 Zone and lower part of NP17 Zone, and the upper part of subzone CP14a and lower part of CP14b. It is worth mentioning that *Reticulofenestra bisecta* is a common species observed in the studied material but *Sphenolithus obtusus* was totally absent from both studied sections. The distribution of the last-mentioned taxon has a very short interval between the upper NP16 and lower NP17 Zones (Agnini et al., 2011; Bown & Dunkley Jones, 2012). The absence of this species is possibly attributed to the stratigraphic position of the studied sections, being higher within NP17 Zone.

Paleoenvironmental interpretation

The calcareous nannoplankton assemblages can be separated in well-defined assemblages as can be seen on HCA and PCA graphics (Figs.. 7 and 8), and they reflect the paleoenvironmental gradient along the studied sections.

The samples from Homret Shaibun and Gebel Na'alun sections were grouped by the cluster analysis into two main clusters. Within both main clusters (Cluster 1 and 2), eight sub-clusters (1a, 1b, 1c, 1d, 1e, 2a, 2b, and 2c) could be identified. The PCA analysis shows that these sub-clusters are grouped together and are separated along principal component 2 (PC1 being an expression of paleoproductivity and PC2 is correlated to palaeotemperature) based on their *Reticulofenestra reticulata, Coccolithus pelagicus, Reticulofenestra minuta, Cyclicargolithus floridanus* and *Reticulofenestra dictyoda* content. Thus, based on this grouping we can assume that different paleoenvironmental conditions persisted during the deposition time of the studied material.

The *Reticulofenestra reticulata* assemblages (sub-clusters 1b and 1d) are mainly restricted to the Gebel Na'alun section, except one sample (25HS). This species is associated with oligotrophic conditions (Villa et al. 2008). Wei et al. (1992) attributed a cool water preference for this species, being more abundant at high-latitudes sites. But, the position of this assemblage within the PCA graph can suggests that this taxon can proliferate in warmer waters too.

The *Coccolithus pelagicus* assemblage (sub-cluster 1c) indicates warm to temperate waters (Wei and Wise 1990; Persico and Villa 2004; Villa et al. 2008). This species is known to occupying eutrophic surface waters and upwelling areas (Haq 1980; Rahman and Roth 1990; Kameo and Sato 2000).

The *Reticulofenestra minuta* assemblage (sub-cluster 2a and partially sub-cluster 2b) is associated with high-productivity eutrophic conditions, with a higher input of continental sediments and with a high tolerance to environmental stress (Haq 1980; Wade & Bown 2006; Bartol et al. 2008; Auer et al. 2014; Kallanxhi et al. 2018). Some other studies associated this species with shallow marine-settings (Trif et al. 2022) or deeper environments (Bindiu-Haitonic et al. 2021) and with a stratified water-column (Ćorić & Rögl 2004; Ćorić & Hohenegger 2008).

The *Cyclicargolithus floridanus* (sub-cluster 2c) and *Cyclicargolithus floridanus* + *Reticulofenestra minuta* assemblages (sub-cluster 2b) can be interpreted as indicative for a meso-eutrophic environment with nutrient-rich sea-surface waters (Aubry 1992; Monechi et al. 2000). These assemblages characterize most of the Homret Shaibun section, especially its upper part. The species *Cyclicargolithus floridanus* is known from environments with stable temperature, salinity and nutrient content (Auer et al. 2014).

The *Reticulofenestra dictyoda* assemblage (sub-clusters 1a and 1e) highlights temperate surface waters, this taxon being abundant in high latitude sites (Schneider et al. 2011). Thus it has considered a taxon adapted to cooler conditions and has been associated with mesotrophic environments (Schneider et al 2011; Kalb & Bralower 2012). It is assumed that *R. dictyoda* comes from the *Toweius crassus* lineage, which prefers high latitudes environments (Haq & Lohmann 1976; Gallagher 1989). The increase in the abundance of *R. dictyoda* from high to low latitudes is evidence of the cooling trend of the surface waters. The global extension of the genus *Reticulofenestra* was used as evidence of cooling and increased productivity during the Eocene (Aubry 1992).

Thus, based on the palaeoecological preferences of the most abundant species, the Beni Suef Formation was deposited during different environmental conditions, generally a meso-eutrophic and warm to temperate environment alternating with shorter periods characterized by oligotrophic and cooler conditions.

Conclusions

Middle-upper Eocene deposits are widely distributed in the Fayoum and Nile Valley areas. The stratigraphic subdivision and rock unit nomenclature are controversial among specialists. The mud-dominated stratigraphic units at the base of Gebel Na'alun and Gebel Homret Shaibun are equivalent based on the presence of a storm-induced thin sand bed at the same stratigraphic level. Therefore, the stratigraphic subdivision of the Gebel Na'alun includes the Beni Suef and Gehannam formations, whereas that at Gebel Homret Shaibun includes the Beni Suef and Shaibun formations. The Beni Suef Formation in the Gebel Na'alun and Gebel Homret Shaibun is synchronous belonging to the upper part of the Middle Eocene based on calcareous nannoplankton content. The sediments of the Beni Suef Formation yielded calcareous nannoplankton assemblage belonging to the *Discoaster saipanensis* (NP17) Zone. The palaeoenvironmental setting in which the middle Eocene deposits at the Homret Shaibun and Gebel Na'alun sections were deposited can be considered as a stable, temperate and mesotrophic environment, with small or no fluctuations in nutrient supply content, and with a short interval of eutrophic conditions in the lower part of Homret Shaibun section.

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Appendix

Calcareous nannoplankton species from the Beni Suef Formation

Blackites tenuis (Bramlette & Sullivan, 1961) Sherwood, 1974
Blackites spinosus (Deflandre & Fert, 1954) Hay & Towe, 1962
Braarudosphaera bigelowii (Gran & Braarud 1935) Deflandre, 1947
Braarudosphaera perampla Bown 2010
Campylosphaera dela (Bramlette & Sullivan, 1961) Hay & Mohler, 1967
Chiasmolithus sp. Hay et al., 1966
Chiasmolithus grandis (Bramlette & Riedel, 1954) Radomski, 1968
Clausicoccus fenestratus (Deflandre and Fert, 1954) Prins, 1979
Coccolithus biparteoperculatus (Varol, 1991) Bown & Dunkley Jones, 2012
Coccolithus formosus (Kamptner, 1963) Wise, 1973
Coccolithus pelagicus (Wallich 1877) Schiller, 1930
Coccolithus eopelagicus (Bramlette & Riedel, 1954) Hay, Mohler & Wade 1966
Cruciplacolithus sp. Hay & Mohler in Hay et al., 1967
Coronocyclus nitescens (Kamptner, 1963) Bramlette and Wilcoxon, 1967
Cyclicargolithus floridanus (Roth & Hay, in Hay et al., 1967) Bukry, 1971
Cyclicargolithus luminis (Sullivan, 1965) Bukry, 1971
Discoaster sp. Tan Sin Hok 1927
Discoaster barbadiensis Tan Sin Hok, 1927
Discoaster deflandrei Bramlette & Riedel, 1954
Discoaster saipanensis Bramlette & Riedel, 1954
Discoaster tanii Bramlette & Riedel, 1954
Discoaster nodifer (Bramlette & Riedel, 1954) Bukry, 1973
Discoaster septemradiatus (Klumpp 1953) Martini 1958
Ericsonia orbis Bown 2016
Helicosphaera sp. Kamptner, 1954
Helicosphaera compacta Bramlette & Wilcoxon, 1967
Helicosphaera clarissima Bown, 2005
Helicosphaera lophota (Bramlette & Sullivan, 1961) Locker, 1973
Helicosphaera bramlettei (Müller, 1970) Jafar & Martini, 1975
Lanternithus sp. *Stradner*, 1962
Lanternithus minutus Stradner, 1962
Micrantholithus sp. Deflandre in Deflandre & Fert 1954
Micrantholithus astrum Bown, 2005
Micrantholithus flos Deflandre in Deflandre & Fert, 1954
Neococcolithes sp. Sujkowski, 1931
Neococcolithes dubius (Deflandre in Deflandre and Fert, 1954) Black, 1967
Neococcolithes minutus (Perch-Nielsen, 1967) Perch-Nielsen, 1971
Pemma basquense (Martini, 1959) Báldi-Beke, 1971
Pontosphaera duocava (Bramlette & Sullivan, 1961) Romein, 1979
Pontosphaera enormis (Locker, 1967) Perch-Nielsen, 1984
Pontosphaera formosa (Bukry & Bramlette, 1969) Romein, 1979
Pontosphaera multipora (Kamptner, 1948 ex Deflandre in Deflandre & Fert, 1954) Roth, 1970
Pontosphaera panarium (Deflandre in Deflandre & Fert, 1954) Aubry, 1986
Pontosphaera pectinata (Bramlette & Sullivan, 1961) Sherwood, 1974
Pontosphaera plana (Bramlette & Sullivan, 1961) Haq, 1971
Pontosphaera pygmaea (Locker, 1967) Bystricka & Lehotayova, 1974
Pontosphaera versa (Bramlette & Sullivan, 1961) Sherwood, 1974
Reticulofenestra bisecta (Hay, Mohler and Wade, 1966) Roth, 1970
Reticulofenestra daviesii (Haq, 1968) Haq, 1971
Reticulofenestra dictyoda (Deflandre in Deflandre & Fert, 1954) Stradner in Stradner & Edwards, 1968
Reticulofenestra erbae (Fornaciari et al., 2010) Bown & Newsam 2017
Reticulofenestra hampdenensis Edwards, 1973
Reticulofenestra hillae Bukry & Percival, 1971
Reticulofenestra lockeri Müller, 1970
Reticulofenestra minuta Roth, 1970
Reticulofenestra reticulata (Gartner & Smith, 1967) Roth & Thierstein, 1972
Reticulofenestra stavensis (Levin & Joerger, 1967) Varol, 1989
Reticulofenestra umbilicus (Levin, 1965) Martini & Ritzkowski, 1968
Rhabdosphaera gracilenta (Bown & Dunkley Jones, 2006) Dunkley Jones et al., 2009
Sphenolithus moriformis (Brönnimann & Stradner, 1960) Bramlette & Wilcoxon, 1967
Sphenolithus radians Deflandre in Grassé, 1952
Sphenolithus spiniger Bukry, 1971
Trochoaster simplex Klumpp 1953
Umbilicosphaera bramlettei (Hay & Towe, 1962) Bown et al., 2007
Varolia boomeri Bown & Dunkley Jones, 2006
Zygrhablithus bijugatus (Deflandre in Deflandre and Fert, 1954) Deflandre, 1959