

# Response of foraminiferal assemblages on the middle Eocene climatic optimum and following climatic transition in the shallow tropical sea (the south Fayoum area, Egypt)

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**Abstract** Foraminiferal assemblages from 4 sections (totaling 158 samples) were quantitatively analysed to reconstruct paleoenvironmental changes in inner to outer shelf, tropical epicontinental sea of the southern Peritethys area around the middle Eocene climatic optimum. In comparison with bathyal oceanic sites, shelf assemblages from Fayoum area are strongly influenced by climatically forced sea-level oscillations and aridification in cooling post-MECO interval. Pre-MECO interval can be characterized by gradual deepening and hypoxic, eutrophic bottom water. The maximal deepening during the temperature peak was associated with destruction of hypoxic bottom water. Sea-level fall, nutrient decrease and salinity increase in marginal part of basin due to decreased continental runoff caused by aridification was suggested for post-MECO cooling interval. Clastic-carbonate system of the warming period and thermal maximum was changed to only carbonate system of cooling post-MECO period.

**Keywords** Foraminifera · Middle Eocene climatic optimum · Paleoecology · Egypt

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## Introduction

The middle Eocene is a pivotal interval in the evolution of Cenozoic climate to determining the processes through transition from ‘greenhouse’ to ‘icehouse’. The middle Eocene climatic evolution seems to be characterized by at least one prominent warming event at ~40 Ma, known as the middle Eocene climatic optimum (MECO). This event interrupted the cooling trend of the middle Eocene. The MECO in the oceanic record was identified firstly in the Southern Ocean deep-sea cores (Bohaty and Zachos 2003; Sexton et al. 2006; Bohaty et al. 2009). A 500-kyr-long duration for the MECO was characterized by increasing  $\delta^{13}\text{C}$  and decreasing  $\delta^{18}\text{O}$ , with minimum  $\delta^{18}\text{O}$  values lasting ~40 kyr at 40.1 Ma coincident with a short-lived negative  $\delta^{13}\text{C}$  excursion. Southern Ocean deep-water temperatures warmed by up to 4 °C and lasted for 500 kyrs before rapidly cooling. Increase in  $\text{CaCO}_3$  mass accumulation rates followed the event (Bohaty et al. 2009). Reconstructed  $\text{CO}_2$  concentrations are mainly between 700 to 1000 ppm with a secular decline to 450 ppm. The  $\text{CO}_2$  decline is compatible with a rapid (<10<sup>4</sup> years) transition from warm, largely ice-free conditions to cooler climates with ice sheets (Doria et al. 2011). The appearance of these small Cenozoic ice sheets (Miller et al. 1991; Ehrmann and Mackensen 1992; Browning et al. 1996) preceded the large-scale ice sheet expansion in the earliest Oligocene (Zachos et al. 1996, 2001; Coxall et al. 2005).

In low latitudes, the MECO can be well biostratigraphically correlated with interval from the FO (first occurrence) to the LO (last occurrence) of *Orbulinoides beckmanni* (Bohaty et al. 2009; Edgar et al. 2010).

Publications dealing with effects of the MECO on microorganisms were comprehensive summarized by Boscolo Galazzo et al. (2015), and showed different imprint of global warming to local paleoenvironmental changes. Studied

micropaleontological records of the MECO are based on different organisms and originated from different geographical areas and paleobathymetric zones. Therefore, complex reconstruction of changes in ecosystems is not yet possible (Boscolo Galazzo et al. 2015).

Previous preliminary studies indicated that sections in the south Fayoum area might be correlated with the middle Eocene and thus also with the MECO and following climatic transition. Up to now, any detailed studies have not been focused to this area. The main goal of this paper is a detailed quantitative study of foraminiferal fauna from four sections. Those data enable to interpret the influence of the global middle Eocene climatic events on the paleoenvironment in the shallow tropical sea in this area.

### Geological setting

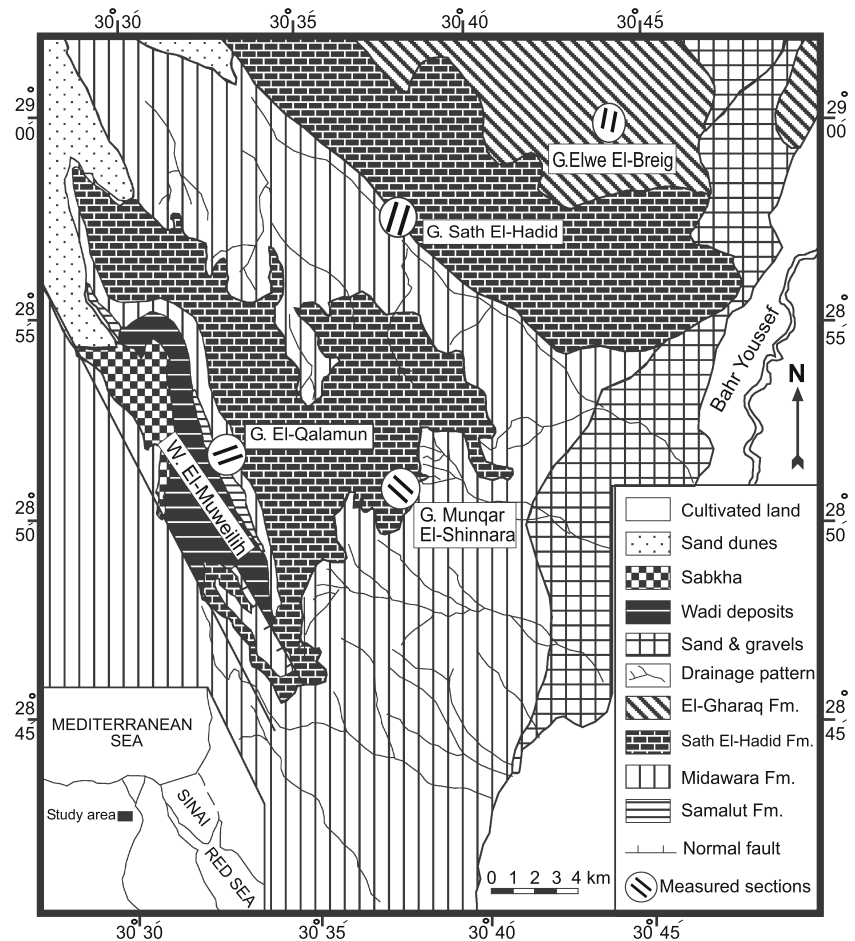
The attempted area is a hilly quadrangle between Bahr Yousef and Wadi El-Muweilih, south Fayoum, Egypt (Fig. 1). It covers an area of approximately 1100 km<sup>2</sup>, between Lat. 28° 40' and 29° 01' 0" N and Long. 30° 28' 0" and 30° 50' 0" E. The

area is somewhat difficult to access from Fayoum depression. It is easier accessible from west Beni Sueif governorate along the Assiut-Cairo desert road.

Geomorphologically, the area comprises several hills (e.g. Gebel Sath El-Hadid, Gebel Elwe El-Breg, Gebel Munqar El-Shinnara and Gebel El Qalamun). These hills are surrounded by Wadi El Rayan sand dunes in the west and northwestern areas; sandy gravel ground and cultivated land at the east. To the southwest, it is bounded by Wadi El Muweilih Sabkha and Wadifill deposits.

Several studies were dealt with the geological aspects of the Fayoum depression; review was summarized by Helal (2002), Abdallah et al. (2003) and Abu El-Ghar (2012). The majority of these studies were directed to Wadi El Rayan and northern parts of the Fayoum depression while the south and southeastern parts received a little attention. The most relevant works concerned the area are those of Beadnell (1905), Iskander (1943), Ansary (1955), Abdel-Kireem (1971), Abdou and Abdel Kireem (1975), Shamah (1981, 1994), Bassiouni et al. (1984), Haggag (1985), Allam et al. (1991), Strougo (1992), Boukhary et al. (1993), Shamah and Helal (1993, 1994), Shamah et al. (1994), Haggag and Bolli

**Fig. 1** Locations of studied sections



(1995, 1996), Elewa et al. (1998), Omar (1999), Abdallah et al. (2002, 2003), Abu El-Ghar (2012) and Strougo et al. (2013).

Stratigraphically, the bulk of the exposed rocks in the study area belongs to the middle Eocene and covered by the Pliocene rocks and Quaternary clastics. The middle Eocene rocks are divisible into five rock units, with some contradictory opinions between different authors (for details, refer to Shamah 1981, Khalifa et al. 1993, Strougo 1992, Swedan 1992 and Boukhary et al. 1993), the matter which is out the scope of the present work. These rock units are as follows: (1) Gharaq Formation (top), (2) Sath El Hadid Formation, (3) Midawara Formation, (4) Muweilih Formation and (5) Samalut Formation (base).

## Material and method

South Fayoum area was investigated and the main hillocks in the area were documented, described and thoroughly sampled. Four stratigraphic sections were chosen for micropaleontological analysis (Figs. 1 and 2a–d):

1. Section A: WadiMuweilih, Gebel Qalamun section (Lat. 28° 54' 45" N, Long. 30° 35' 0" E; Fig. 2a).
2. Section B: Sath El Hadid (Lat. 28° 55' 60" N and Long. 30° 40' 60" E; Fig. 2b).
3. Section C: Munqar El Shinnara (Lat. 28° 52' 0" N and Long. 30° 37' 60" E; Fig. 2c).
4. Section D: Elwe El Breig (Lat. 29° 0' 0" N, Long. 30° 43' 60" E; Fig. 2d).

The collected rock samples (158 samples) were treated by normal washing techniques for their microfaunal content. Two hundred grams of the washed residue are sieved in a nest of dry sieves arranged in the following order <500  $\mu\text{m}$ , <350  $\mu\text{m}$ , <250  $\mu\text{m}$ , <125  $\mu\text{m}$ , <63  $\mu\text{m}$ . The successive cuts are inspected for its microfaunal content. The picked fauna was counted and used for simple and multivariate statistical analysis using the PAST software (Hammer et al. 2001). The data was interpreted biostratigraphically and paleoecologically.

## Stratigraphy

### Samalut Formation (Lutetian)

The formation was defined by Bishay (1961) to describe the Eocene rocks with abundant *Nummulites gizehensis* (Forskal) lineage outcropping to the east of the Nile Valley between Beni Hassan, south of Minia, to the north of Samalut. He

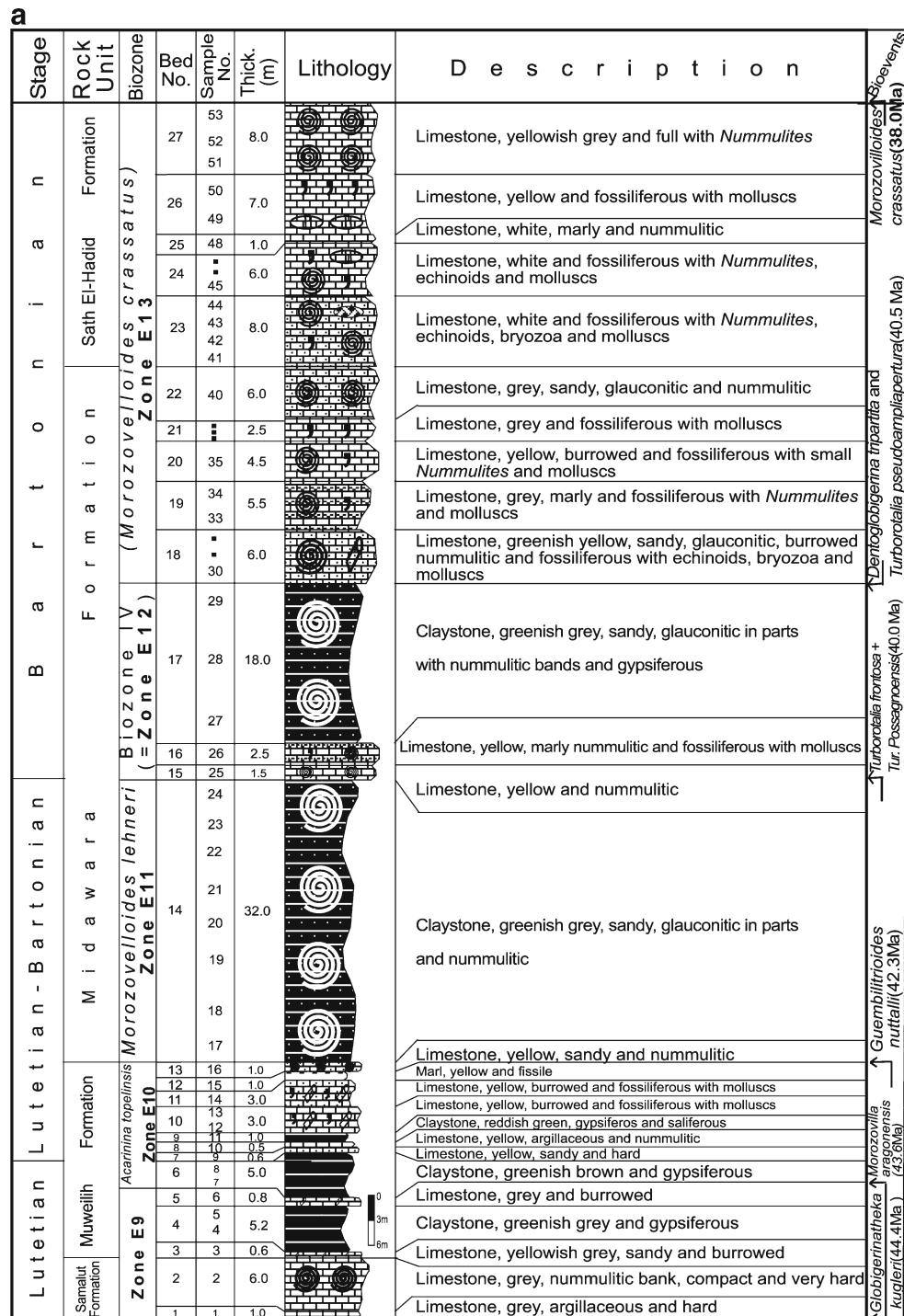
proposed the 160 m of poorly bedded to massive creamy white to yellow nummulitic limestones exposed northeast of El-Matahra El-Sharqiya between Samalut and Minia as the type section of this formation. The Samalut Formation conformably overlies the Minia Formation with a topographic break in some areas as in Zaweit Sawada section. The upper boundary of the Samalut Formation witnessed different opinions in different sites and authors. Some authors argued that Samalut Formation underlies (1) the Mokattam Formation (Krashennnikov and Ponikarov 1964; Said 1971; Hassaan et al. 1990; Abu El Ghar et al. 2005); (2) the Maghagha Formation (Bishay 1961, 1966; Philobos and Keheila 1979; Keheila 1983; Mansour and Philobos 1983; Kenawy et al. 1988); (3) the Sannor Formation (Middle Eocene) (Boukhary and Abdel Malik 1983); and (4) the Middle Eocene Qarara Formation (Abdel Shafy et al. 1984).

The nummulitic carbonates of the Samalut Formation were widely recorded and studied from the Nile valley. It was recorded from the vicinity of Mallawi to El-Fashn on both sides of the River Nile (Amer et al. 1970). The Samalut Formation was also identified from the area east and southeast of El-Minia (Said 1971; Hanna 1974; Philobos and Keheila 1979; Boukhary and Abdel Malik 1983; Abdel Shafy et al. 1984; Hassaan et al. 1990; Helal 1996).

In the study area, the Samalut Formation represents the base of the succession and is only recorded at the entrance of Wadi Muweilih. It attains a very limited occurrence in the extreme southern part of the area (section A) with a thickness of  $\pm 7$  m (Fig. 2a). Samalut Formation is composed of yellow to grey limestones, hard, crystalline with abundant *N. gizehensis* lineage. The base of the Samalut Formation is unexposed in the study area. Further southwest of the study area, about 10 km, the Samalut Formation rest over the snow-white limestone with dark grey siliceous concretions of the upper most Minia Formation (Khalifa 1981). The Samalut Formation unconformably underlies the Muweilih Formation through ferruginated conglomeratic bed ( $\pm 50$  cm thick).

The recovered planktonic foraminiferal fauna from the Samalut Formation is belonging to the zone E9 (*Globigerinatheka kugleri*/*Morozovella aragonensis* Concurrent-range zone; Fig. 3). According to Wade et al. (2011) and Berggren and Pearson (2005), this zone was defined as concurrent range of the nominate taxa between the last occurrence (LO) of *Globigerinatheka kugleri* and the high occurrence (HO) of *Morozovella aragonensis*. Berggren and Pearson (2005) equated this zone with *Globigerinatheka kugleri*/*M. aragonensis* concurrent-range zone P11 of Berggren et al. (1995), *G. kugleri*/*Subbotina frontosa* partial-range zone P11 of Berggren and Miller (1988), upper part of *G. kugleri* zone P11 of Berggren (1969) and upper part of *G. kugleri* zone of Bolli (1957, 1966).

Berggren and Pearson (2005) declared that the estimated age of zone E9 is 45.8–43.6 Ma; middle Eocene (Lutetian).



**Fig. 2** Lithology, biostratigraphy and sampled interval of the studied sections A–D

Wade et al. (2011) showed that there are two different estimates for this zone: 44.4–43.6 Ma (Cande and Kent 1995) and 43.4–42.6 Ma (Luterbacher et al. 2004); middle Eocene.

On the basis of the identified planktonic foraminifera zone E9 (*G. kugleri*/*M. aragonensis* Concurrent-range zone), the associated *N. gizehensis* Forskall (Fig. 4) and the stratigraphic position, the Samalut Formation is dated to the middle Eocene (Lutetian). This conclusion comes in accordance with the

results of Boukhary et al. (1993), Elewa et al. (1998), Abdallah et al. (2003) and Abu El-Ghar (2012).

### Muweilih Formation (Lutetian)

The Muweilih Formation was introduced by Iskander (1943) in the geology of the Fayoum area to describe the limestones intercalated with claystones in the south

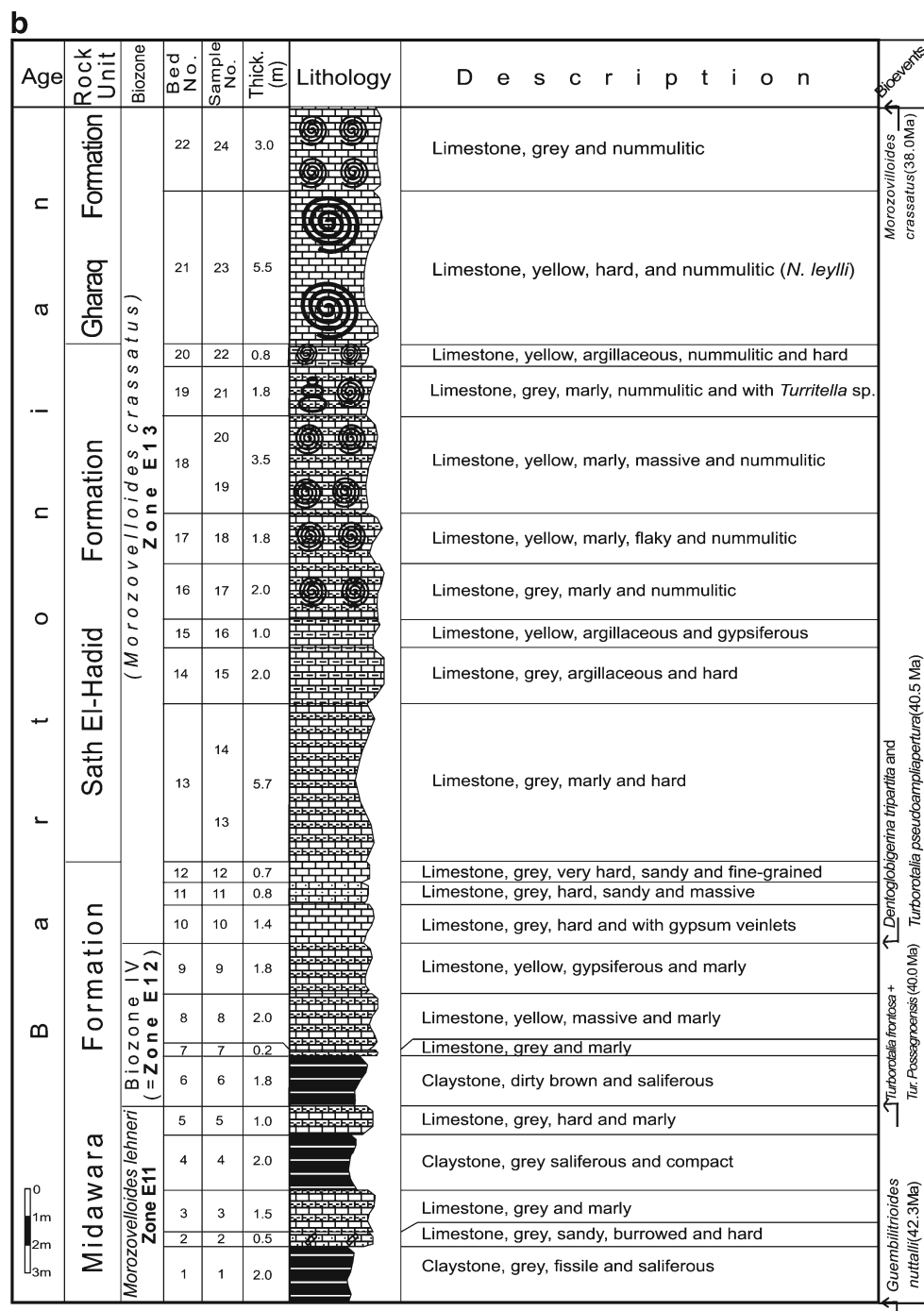


Fig. 2 continued.

part of the depression. Iskander (op. cit.) subdivide the Wadi Rayan series (Beadnell 1905) into four formations (from older to younger): Muweilih, Midawara, Sath El Hadid and Gharaq. The Muweilih Formation is recorded only in the Wadi Muweilih section, southwestern part of the area (section A) with a thickness of about 21.7 m (Fig. 2a). The Muweilih Formation was deposited unconformably over the Samalut Formation and is conformably underlies the Midawara Formation. The Muweilih

Formation is composed of repeated intercalations of claystones and limestones. The lower part is dominated by greenish brown to grey, gypsiferous, saliferous compact claystones. The upper part is dominated by yellowish grey, sandy, burrowed and fossiliferous limestones.

The analysis of the planktonic foraminifera led to the identification of three biozones. The lower part of the Muweilih Formation (samples 3–6, Fig. 2a) is belonging to the zone E9

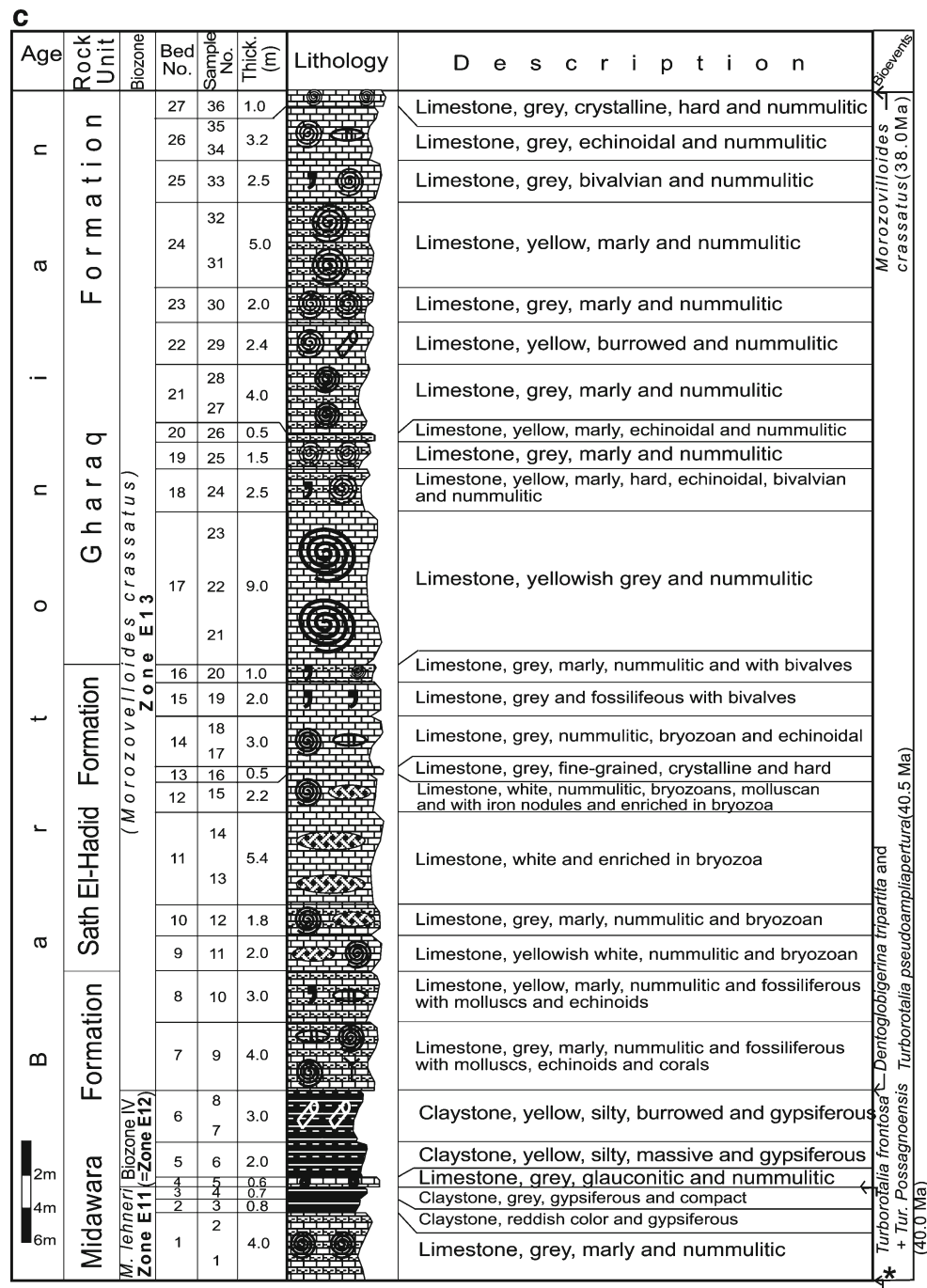


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*G. kugleri*/*M. aragonensis* concurrent-range zone while the samples 7–16 (Fig. 2a) is belonging to zone E10 (*Acarinina topilensis* partial-range zone)

### Zone E10. *A. topilensis* partial-range zone

According to Wade et al. (2011) and Berggren and Pearson (2005), this zone was defined as the partial range of the

nominate taxon between the HO of *M. aragonensis* and the HO of *Guembeltrioides nuttalli*. Berggren and Pearson (2005) showed that zone E10 is equivalent of the lower part of *Globorotalia lehneri* zone P12 of Berggren (1969); lower part of *Morozovella lehneri* zone P12 of Berggren and Miller (1988) and Berggren et al. (1995) and lower part *M. lehneri* zone P12 of Blow 1979.

Cande and Kent (1995) as well as Berggren and Pearson (2005) estimated the age of zone E10 at 43.6–42.3 Ma, late

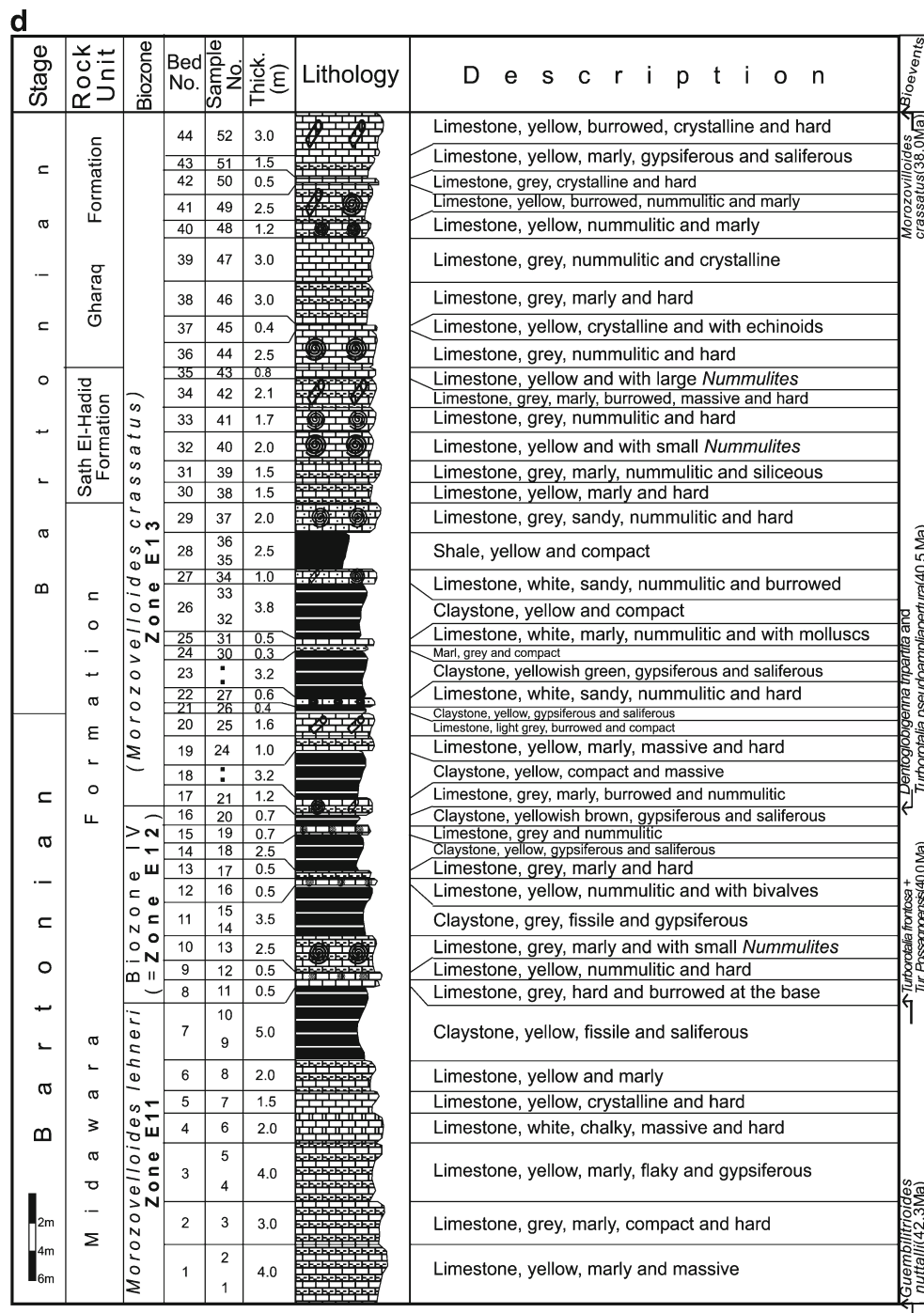


Fig. 2 continued.

middle Eocene (late Lutetian). Wade et al. (2011) advocated the estimation of 43.6–42.3 Ma (as per Cande and Kent 1995); 42.6–41.4 Ma (as per Luterbacher et al. 2004); middle Eocene.

Based on the abovementioned data, the Muweilih Formation represents the interval from the upper part of the zone E9 (*G. kugleri*/*M. aragonensis* concurrent-range zone) to the lower part of the zone E11 (*Morozovelloides lehneri* partial-range zone) which represents the middle Eocene (Lutetian).

### Midawara Formation (Lutetian–Bartonian)

This formation was suggested by Iskander (1943) to describe the Eocene fossiliferous limestones with claystone intercalations exposed in south Fayoum area. The name of this formation was derived from its characteristic topographic feature. It is exposed as separated or connected conical hills or hillocks of relatively low height ranging from 10 to 20 m above ground level. The Midawara Formation conformably overlies the

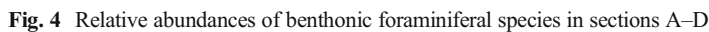


**Fig. 3** Relative abundances of planktonic foraminiferal species in sections A–D. Biostratigraphically significant species are marked by *red colour*

Muweilih Formation and conformably underlies the succeeding Sath El Hadid Formation. The lower contact with the underlying Muweilih Formation is only recorded in the southern part of the area (Wadi Muweilih section), while the upper contact was traced from all over the studied area. The Midawara is widely distributed and is recorded in all measured section. It attains a thickness of 68.5 m in Wadi Muweilih section, 54.7 m in Elwe El Breig section, 15.1 m in Munqar El Shinnara section and 15.7 m in Sath El Hadid section (Fig. 2a–d).

The study of the planktonic foraminifera of the Midawara Formation led to the identification of three biozones. In Wadi Muweilih section (Fig. 2a), the lower part (samples 17–24) of the Midawara Formation is belonging to zone E11 (*Morozovelloides lehneri* partial-range zone); the middle part (samples 25–29) is belonging to biozone IV (equivalent to

zone E12 *O. beckmanni* taxon-range zone) and the upper part (samples 30–40) is belonging to zone E13 (*Morozovelloides crassatus* highest-occurrence zone). In Sath El Hadid section (Fig. 2b), the lower part (samples 1–5) of the Midawara Formation is belonging to the zone E13 (*Morozovelloides lehneri* zone); the middle part (samples 6–9) is belonging to biozone IV (equivalent to zone E12 *O. beckmanni* taxon-range zone) and the upper part (samples 10–12) is belonging to zone E13 (*Morozovelloides crassatus*). In Munqar El Shinnara section (Fig. 2c), the lower part (samples 1–4) of the Midawara Formation is belonging to the zone E11 (*Morozovelloides lehneri* zone); the middle part (samples 5–8) is belonging to biozone IV (equivalent to zone E12 *O. beckmanni* taxon-range zone) and the upper part (samples 9–10) is belonging to zone E13 (*Morozovelloides crassatus*). In Elwe El Breig section (Fig. 2d), the lower part (samples 1–10)



The marker taxon *O. beckmanni* is absent in the study area as in other parts of Egypt and in some areas outside Egypt (Toumarkine 1983; Toumarkine and Luterbacher 1985). Hence, there is a need to use another datum in determining the upper boundary of *Morozovelloides lehneri* zone. Several

Biozone IV is introduced here to describe the interval formally known as zone E12 *O. beckmanni* taxon-range zone and defined as the total range zone of the nominate taxon between its LO and HO (Berggren and Pearson 2005; Wade et al.

2011). This definition agrees with conclusions of Toumarkine and Luterbacher (1985), Berggren and Miller (1988) and Berggren et al. (1995). According to Berggren and Pearson (2005) and Wade et al. (2011), this zone is equivalent to *Porticulasphaera mexicana* zone of Bolli (1957, 1966); *Globigerapsis beckmanni* zone PI3 of Berggren (1969), Blow (1979), Berggren and Miller (1988, p. 373) and Berggren et al. (1995, p. 154).

The absence of *O. beckmanni* in most of the Egyptian assemblages were previously reported in several studies (Krashennikov and Ponikarov 1964; Beckmann et al. 1969; Viotti and El Demerdash 1969; Bassiouni et al. 1974; Abdou and Abdel Kireem 1975; Haggag 1986, 1989a, 1989b; Haggag and Anan 1987; Haggag and Luterbacher 1991; Abul-Nasr 1987; Nishi et al. 1994; Abdallah et al. 2003). The disappearance of this species may be attributed to ecological conditions as our assemblages are near to the neritic 'Midway type' fauna (Vincent et al. 1974, Fluegeman 1999).

The absence of the nominate species, as in our assemblages, led several authors to suggest alternative criteria to define this zone as suggested by Toumarkine and Luterbacher (1985), Haggag (1989a) and Haggag and Luterbacher (1991). According to Toumarkine and Luterbacher (1985), the top of the *M. lehneri* zone (i.e. the base of zone E12 *O. beckmanni*) can be correlated with the LAD of both *T. c. possagnoensis* and *T. c. frontosa* together with the FAD of *T. c. pomeroli*. The datum of these three taxa were accepted in Pearson et al. (2006) (see the Discussion in the aforementioned zone; zone E11 *Morozovelloides lehneri*). Moreover, in our association, the LAD of *Globigerinatheka mexicana curryi* can be correlated with the base of biozone IV.

The upper boundary of this zone is indicated through the following notes:

1. Haggag and Luterbacher (1991) and Haggag (1992) noted that the first appearance of *Globigerina tripartita* (*Dentoglobigerina tripartita* Koch) is considered as the index species for base of the *Truncorotaloides rohri* zone (i.e. the upper boundary of zone E12) in the Wadi Nukhul section, Sinai.
2. Haggag and Luterbacher (1995) noted that the first appearance of *Turborotalia pseudoampliapertura pseudoampliapertura* is isochronous with the base of the *T. rohri* zone (i.e. zone E13 *Morozovelloides crassatus*).

Thus, the concept of Haggag and Luterbacher (1991) and Haggag (1992) is used in this study for tracing the boundary between biozone IV (zone E12 *O. beckmanni*) and the overlying younger zone (zone E13 *Morozovelloides crassatus*).

The estimated age of this zone is 40.5–40.0 Ma; late middle Eocene (Bartonian; Berggren and Pearson 2005). Wade et al. (2011) summarized the age ranges of this zone: 40.5–40.0 Ma

(Cande and Kent 1995); 39.8–39.4 Ma (Luterbacher et al. 2004) and 40.8–40.0 Ma (Pälike et al. 2006); middle Eocene.

### Zone E13 *Morozovelloides crassatus* highest-occurrence zone

Wade et al. (2011) (following Berggren and Pearson 2006) defined this zone as the biostratigraphic interval between the HO of *O. beckmanni* and the HO of the nominate taxon, *Morozovelloides crassatus*. Berggren and Pearson (2005) equated approximately this zone with *T. rohri*–*Morozovella spinulosa* partial-range zone PI4 of Berggren and Miller (1988) and Berggren et al. (1995); approximately equivalent to the *T. rohri*–*Globigerinita howei* partial-range zone PI4 of Blow (1979).

In this study due to the absence of *O. beckmanni*, the lower boundary was traced at the FO of *Dentoglobigerina tripartita* (Haggag and Luterbacher 1991; Haggag 1992). The upper boundary of this zone is not recorded in our sections.

The age of this zone was estimated at 40.0–38.0 Ma (late Bartonian; Berggren and Pearson 2005). Wade et al. (2011) gave three previously published three middle Eocene age ranges of this zone: 40.0–38.0 Ma (Cande and Kent 1995); 39.4–37.7 Ma (Luterbacher et al. 2004); 40.0–38.1 Ma (Pälike et al. 2006).

On the basis of the stratigraphic ranges of the identified biozones (the *Morozovelloides lehneri* zone E11), biozone IV (equivalent to *O. beckmanni* zone E12) and the *Morozovelloides crassatus* zone E13), the Midawara Formation was dated to the Middle Eocene (Lutetian–Bartonian). The biozone IV can be correlated with the middle Eocene climatic optimum.

### Sath El Hadid Formation (Bartonian)

This formation was introduced in the stratigraphy of the south Fayoum area by Iskander (1943). The Sath El Hadid Formation composed of white to yellowish grey biotrital limestones with Bryozoa, Mollusca, corals and echinoids.

The bryofauna includes *Tremogastrina fourtaui*, *Nellia tenella*, *Vincularia maghaghahensis*, *V. davisii*, *Tubecella mamlaris* and *T. papillosa* (Shamah et al. 1994). The mollusks include *Gisortia gigantea*, *Lucina pharaonum*, *Wakulina* sp. and *Spondylus* sp. (Shamah et al. 1994). The Sath El Hadid Formation conformably overlies the Midawara Formation and is conformably underlies the succeeding El Gharq Formation. The lower contact in the type section (Gebel Sath El Hadid section) is gradual and represented by the basal marly bryozoan limestone of the Sath El Hadid and the uppermost glauconitic sandy yellow limestone of the Midawara Formation. There is no evidence of an unconformity surface or hiatus. It is noted that zone E13 *Morozovelloides crassatus* zone is persistently occurred and

extend from the Midawara to the Sath El Hadid formations. This agrees with previous studies, e. g. Iskander (1943), Shamah (1981), Bassiouni et al. (1984), Strougo (1986, 1992), Strougo and Boukhary (1987), Allam et al. (1991), Elewa et al. (1998), Omar (1999), Boukhary et al. (1993), Shamah et al. (1994), El-Safari (1996), Abdallah et al. (2002, 2003), Boukhary and Kamal (2003), Abu El-Ghar (2012) and Strougo et al. (2013).

The upper contact between the white bryozoan limestone of the upper Sath El Hadid Formation and the reddish to pink limestone enriched by *Nummulites lyelli* of the overlying Gharaq Formation is sharp.

The Sath El Hadid Formation attains variable thickness with a general decrease of thickness towards the north. It attains a thickness of 30 m in Wadi Muweilih section, 9.6 m in Elwe El Breig section, 17.9 m in Munqar El Shinnara section and 18.6 m in Sath El Hadid section (Fig. 2a–d).

Planktonic foraminifera indicate zone E13 *Morozovelloides crassatus* defined in the previous chapter. This biozone covers the whole thickness of the Formation. In Wadi Muweilih section, it covers the samples 41–53 (Fig. 2a); in Sath El Hadid section, the samples 13–22 (Fig. 2b); in Munqar El Shinnara section, the samples 11–20 (Fig. 2c); in Elwe El Breig section, the samples 38–43 (Fig. 2d).

On the basis of the stratigraphic position, and the identified zone E13 *Morozovelloides crassatus*, the Sath El Hadid Formation was dated to the middle Eocene (Bartonian).

### El Gharaq Formation (Bartonian)

This formation was introduced in the stratigraphy of the south Fayoum area by Iskander (1943). This name was derived from the name of the last town of the Fayoum province prior to the desert land (El Gharaq El Sultani Town). The El Gharaq Formation attains its maximum thickness in the eastern part of the study area (Munqar El Shinnara section: 33.6 m), and diminishes to the southwest part. The Formation reaches thickness of 17.6 m at Elwe El Breg section, 8.5 m at Sath El Hadid section. The Formation was not recorded in Wadi Muweilih section. It is built by varicoloured yellow, reddish to pink limestones and marly limestones, locally hard and crystalline, highly fossiliferous with large *Nummulites*, mollusca, echinoid, bryozoa and corals. The *Nummulites* is mainly represented by *N. lyelli*, *N. striatus*, *N. discorbinus*, *N. biarritzensis*, *N. cyrenaicus*, *N. bullatus*, *N. ptukhiani* (Shamah et al. 1994). The Bryozoa is less abundant than in Sath El Hadid and only represented by two species: *T. fourtaui* and *N. tenella* (Shamah et al. 1994). The lower contact with the underlying Sath El Hadid Formation is conformable and sharp between the white bryozoan limestones of the uppermost part of the Sath El Hadid Formation and the reddish to pink limestones with *N. lyelli* of the basal part of the El Gharaq Formation. The upper contact of El Gharaq

Formation was not recorded within the study area. It is covered by the Quaternary clastics. This contact is clearly seen at Munqar El Shinnara section as friable gypsiferous claystone and chert nodules with some caliche deposits. Outside the study area, at the entrance of Wadi Hitan area, the El Gharaq Formation is conformably underlied by the Gehannam Formation. The nummulitic marly limestones of the upper most part of the El Gharaq Formation represents the floor of the plain leading to Wadi Hitan entrance track. Furthermore, this greyish white nummulitic limestone is sharply, but conformably, overlaid by the grey calcareous shale of the Gehannam Formation. This contact was described by Iskander (1943) and Strougo et al. (2013).

The analysis of the planktonic foraminifera of the El Gharaq Formation led to the identification of the zone E13 *Morozovelloides crassatus*. This biozone covers the whole thickness of the Formation. In Sath El Hadid section, samples 23–24 (Fig. 2b); in Munqar El Shinnara section, samples 21–36 (Fig. 2c); and in Elwe El Breig section, it covers the samples 44–52 (Fig. 2d).

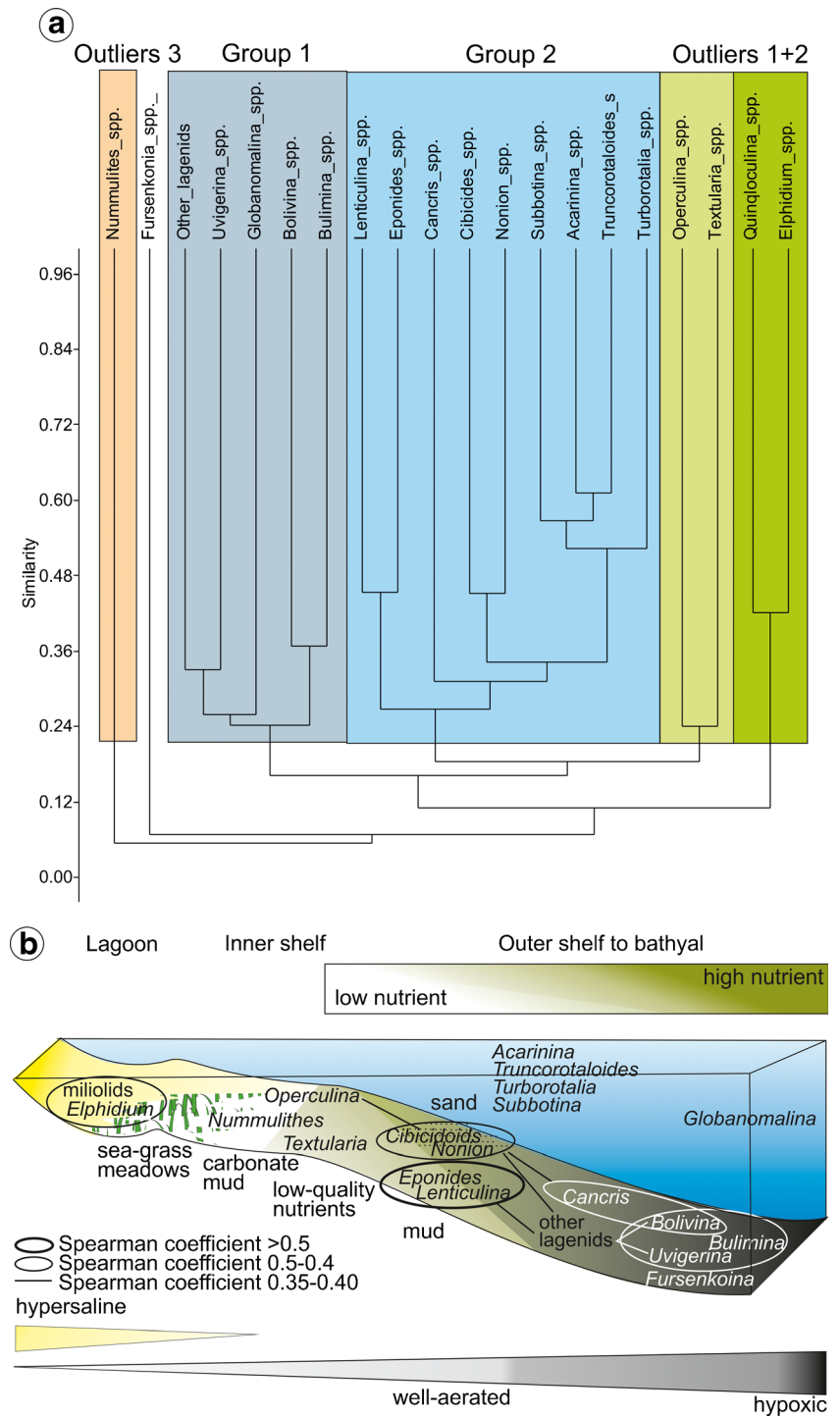
On the basis of the stratigraphic position, the identified zone E13 *Morozovelloides crassatus* and the enrichment with the *N. lyelli* and the associated *Nummulites* (Fig. 4), the El Gharaq Formation was dated to the middle Eocene (Bartonian).

### Foraminiferal assemblages and their paleoecological interpretation

Relations between individual foraminiferal taxa were analysed using cluster analysis (paired group method, Bray-Curtis similarity) as well as values of Spearman correlation coefficient between taxa. Both methods gave well-comparable results (Fig. 5) which enables to distinguish two groups of taxa and three ‘outliers’:

Group (1) clusters high-nutrient and low-oxic markers (*Bolivina*, *Bulimina*, *Uvigerina*), monoserial lagenids and planktonic genus *Globanomalina*. *Fursenkoina* can be classified to this group due to high correlation coefficient between *Fursenkoina* and *Uvigerina* and *Globanomalina* though cluster analysis separate the genus among ‘outliers’. The benthic species represent high-nutrient and low-oxic markers, which instead of indicators of changes in bottom water oxygen levels, may reflect high organic carbon contents of the sediments (Caralp 1989; Hermelin 1992; Sjoerdsma and Van der Zwaan 1992; Sen Gupta and Machain-Castillo 1993; Miao and Thunell 1993; Rathburn and Corliss 1994). Moreover, their distribution may be influenced by variegated quality of organic matter (Caralp 1989; Mojtahid et al. 2010); however, actuoecological studies gave partly contradiction data. Caulle et al. (2014) observed that *Bulimina* is indicative of high organic matter quality and quantity (marine origin); Abu-Zied et al. (2008) recorded that *Bolivina*, *Bulimina* and *Uvigerina* are dependent on a rather continuous

**Fig. 5** Foraminiferal assemblages defined on the basis of statistical analysis: cluster analysis, paired group method, Bray-Curtis similarity (a) and their paleoecological interpretation (b)



abundance of organic matter, eventually of a lower quality. In any case, the distribution of *Bolivina*, *Bulimina*, *Uvigerina* and *Fursenkonia* reflects variations in oxygen content and in quality of nutrients but generally the genera need a lot of nutrients and can tolerate decrease of oxygen. The results of statistical analysis suggest comparable life strategy also for monoserial lagenids. Co-occurrence of this group with planktonic *Globanomalina* points to the deepest paleobiotop for this assemblage.

*Globanomalina* was interpreted as a deep-dweller occurring in the deeper setting localities that lived under thermocline in cold water (Quillevere and Norris 2003; Guasti and Speijer 2007).

Group (1) characterize outer shelf-upper slope paleoenvironment with high nutrient and tolerance to decrease of oxygen content.

Group (2) can be subdivided into strongly correlated pairs of genera: *Lenticulina*—*Eponides* and *Cibicides*—*Nonion*

accompanied by *Cancris*. Together with these benthonic taxa, planktonic genera *Subbotina*, *Acarinina* and *Turborotalia* were clustered.

*Lenticulina* and *Eponides* are considered to be epifaunal genera, probably detritivore, inhabiting rather cold outer shelf to bathyal (Murray 2006, 2014). Moreover, *Lenticulina* is interpreted as oxyphylic taxa (Rosoff and Corliss 1992; Kouwenhoven and Van der Zwaan 2006), but this high oxygen-consuming genus can point to reduced oxygen contents of the bottom water (Kaiho 1994; Van Der Zwaan et al. 1999). Today, *Eponides* lives in variegated environment from arctic slope (Ishman and Foley 1996) to tropical reefs (Araújo and Machado 2008) or subtropical tidal creeks (Chaturvedi et al. 2000) which evokes an idea of opportunistic life strategy rather meso- to oligotrophic.

The co-occurrence of *Nonion* and cibicids might seem contradictory. *Nonion* is associated with highly eutrophic condition of high-quality organic matter of marine origin produced during phytoplankton blooms (Caralp 1989; Mojtabid et al. 2010). Cibicidoids are opportunists connected with low-quality organic matter originated from seasonal nutrient influx (especially small specimens) or characterized proximal settings under the influence of turbidity currents (Mackensen et al. 1995; Altenbach et al. 1999). Cibicidoids are typical oxyphilic, suspension feeder with a wide range of bathyal preferences from shelf to bathyal, preferring sand substrate (Murray 2006, 2014). Co-occurrence of these two taxa may reflect seasonal differences in nutrient source: alternation of season with phytoplankton bloom followed by season with terrigenous input.

*Nonion* and cibicidoids are accompanied by *Cancris* which is moreover according to Spearman correlation coefficient associated with *Bolivina* what agrees with its interpretation as eutrophic marker (Milker et al. 2009). This epifaunal, detritivore, temperature-subtropical genus prefers shelf from 25 to 200 m (Sgarrella and Moncharmont Zei 1993; Murray 2006).

The coexistence of planktonic shallow- and intermediate-dweller from genera *Subbotina*, *Acarinina* and *Turborotalia* indicates very probably seasonal succession of planktonic assemblages. The muricate shallow dweller *Acarinina* is analogous in ecological terms to the modern planktonic foraminifer genus *Globigerinoides*. Previous studies have suggested that *Acarinina* occupied the warm, shallow, mixed layer of the oceans, and had a symbiotic relationship with algae (Pearson et al. 1993; D'Hondt et al. 1994; Kelly et al. 1996; Norris 1996). This ecological strategy is thought to aid the host foraminifera in occupying oligotrophic environments (D'Hondt et al. 1994; Wade 2004).

In contrast, *Subbotina* is asymbiotic and reached the highest  $\delta^{18}\text{O}$  values among the Paleocene planktonic foraminifera indicating calcification in a cool, subsurface, probably thermocline habitat, or during cooler seasons (Boersma and

Premoli-Silva 1983; Corfield and Cartledge 1991; Pearson et al. 1993; D'Hondt et al. 1994; Norris 1996; Coxall and Pearson 2007; Birch et al. 2012). *T. cerroazulensis* is interpreted as an asymbiotic, thermocline shallow dweller (Wade et al. 2008).

Summarizing autecological and paleoecological data, group (2) characterizes outer shelf, well aerated paleoenvironments with variegated nutrient input (quantity and quality) and with thermal stratification.

'Outliers' of large groups (1) and (2) *Operculina*–*Textularia*, *Quinqueloculina*–*Elphidium* and *Nummulites* live generally in inner shelf, oligotrophic environment. In such biotops, they can be accompanied by some *Textularia* spp.

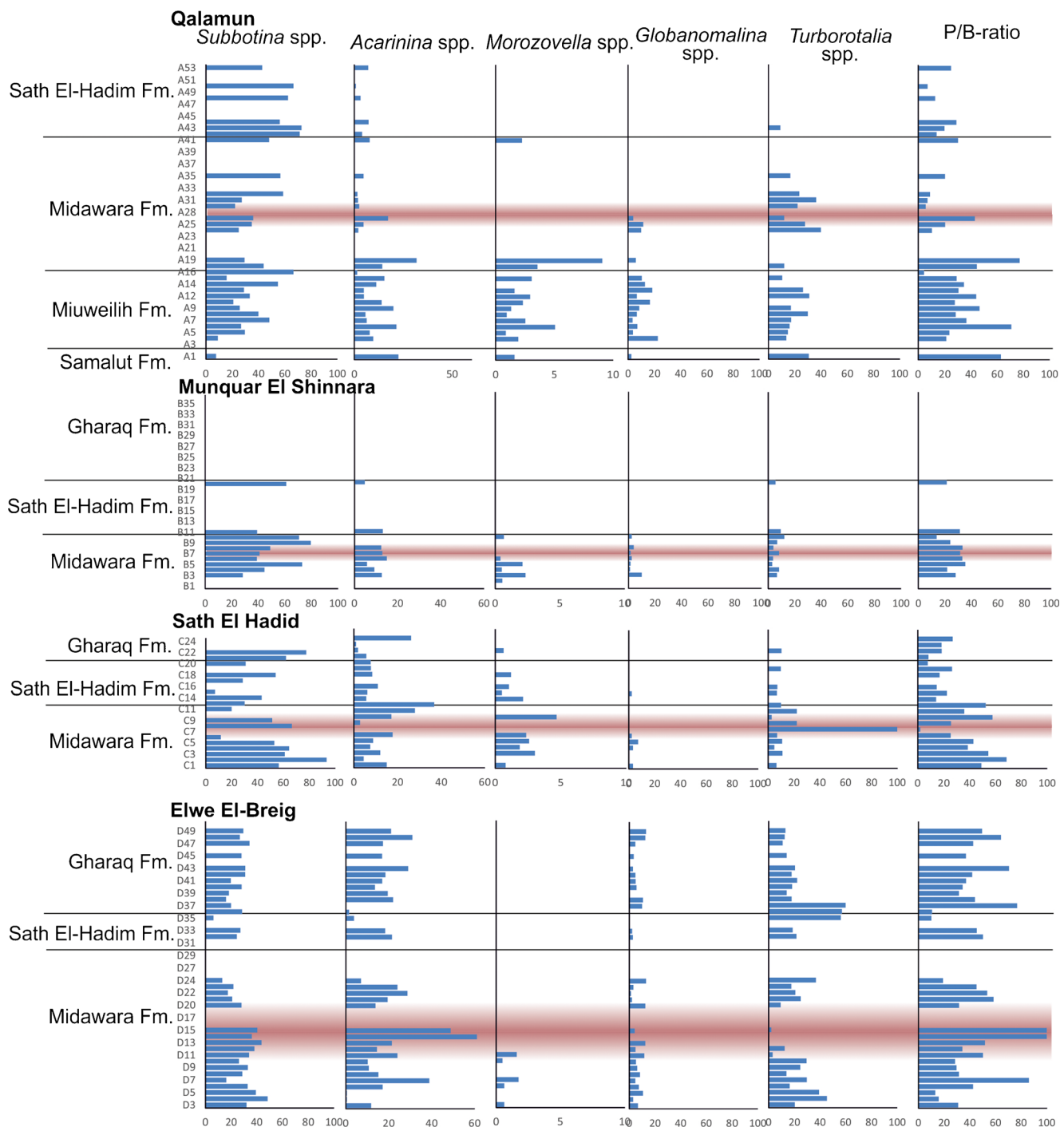
### Pair *Textularia* and *Operculina*

Large foraminifera *Operculina* as other large benthic foraminifera is herbivore and highly adapted to stable, oligotrophic and nutrient-deficient conditions and they cannot respond competitively when nutrient resources become abundant (Hallock 1985). Genus can tolerate slightly hypersaline environment of lagoon to inner shelf (Murray 2014). In general, also a dominance of agglutinated species reflects the oligotrophic character of the benthic ecosystem (Jorissen et al. 1998). Agglutinated foraminifera appear to be less influenced by the quality of food source, and may have developed other feeding strategies (Koho 2008; Alve 2010). This is supported by results of Donnici and Serandrei Barbero (2002) from coastal area of Adriatic Sea where preference of *Textularia agglutinans* for a nutrient-poor environment was recorded.

Pair *Quinqueloculina* spp. and *Elphidium* prefer also oligotrophic environment. Both genera are herbivore and may tolerate salinity increase. Majority species of these genera are epiphytic; therefore, sea floor with seagrass meadows is expected (Murray 2006, 2014). *Quinqueloculina* spp. need sufficient bottom water oxygen concentrations (Blackwelder et al. 1996; Hyams-Kaphzan et al. 2009) while *Elphidium* spp. is a typical opportunistic taxon, which lives in the water-sediment interface and can survive in stressed areas.

The relative abundances of genus *Nummulites* strongly negatively correlated with other genera including nummulitid *Operculina* and in some levels forms monogeneric assemblages. However, similarly to other large foraminifera, the genus inhabited the warm, oligotrophic, lagoon to inner shelf environment (Hallock 1985; Murray 2006). Observation of depth distributions of today's nummulitids showed deeper distribution of *Operculina* than *Nummulites* (Hohenegger et al. 2000).

The abovementioned results are summarized into the model in Fig. 3b.



**Fig. 6** Variance in relative abundances of planktonic foraminiferal genera in relation to the MECO (red belt)

### Paleoenvironmental changes around the middle Eocene climatic optimum

In the world oceans, the existing calibration documented that the MECO is coincident with zone E12 (Sexton et al. 2006; Bohaty et al. 2009). Because *O. beckmanni* was not recorded in the study area, biozone IV as time equivalent of *O. beckmanni* zone was used for dating of the MECO. The

biostratigraphical datum near to the FO of *O. beckmanni* is the LO of *T. frontosa* (Luciani et al. 2010) which was observed also in the studied area and used as the time equivalent of the bottom of E12 zone. The FO of *T. cerroazulensis* and the LO of the *Morozovelloides lehneri* are positioned into the E12 zone (Pearson et al. 2006; Luciani et al. 2010) and were used as additional useful biostratigraphic events (Fig. 4). The biozone IV and the mentioned events were recorded in the

Midawara Fm. Therefore, the study of paleoenvironmental changes around the MECO was focused on the Midawara and overlaid Sath El-Hadid Fm, which are presented in all sections. Interpretation of paleoenvironmental changes were based on lateral and time oscillations of abundances of main foraminiferal genera and species summarized in Figs. 3 and 6 (planktonic taxa) and Figs. 4 and 7 (benthic taxa).

Muweilih Fm. underlain the Midawara Fm. was recorded only in section A, and therefore lateral variability during its deposition cannot be interpreted. Relatively high relative abundances of inner shelf and euryhaline *Elphidium* spp. well agrees with lithology (gypsiferous and saliferous claystones) in the lower part of Formation and suggested interpretation that outer shelf taxa (lagenids) were reworked. This interpretation can be supported by bad preservation of foraminiferal tests. The reworking within the Eocene rocks of the north Eastern Desert of Egypt is known and was described by Shamah and Helal (1994).

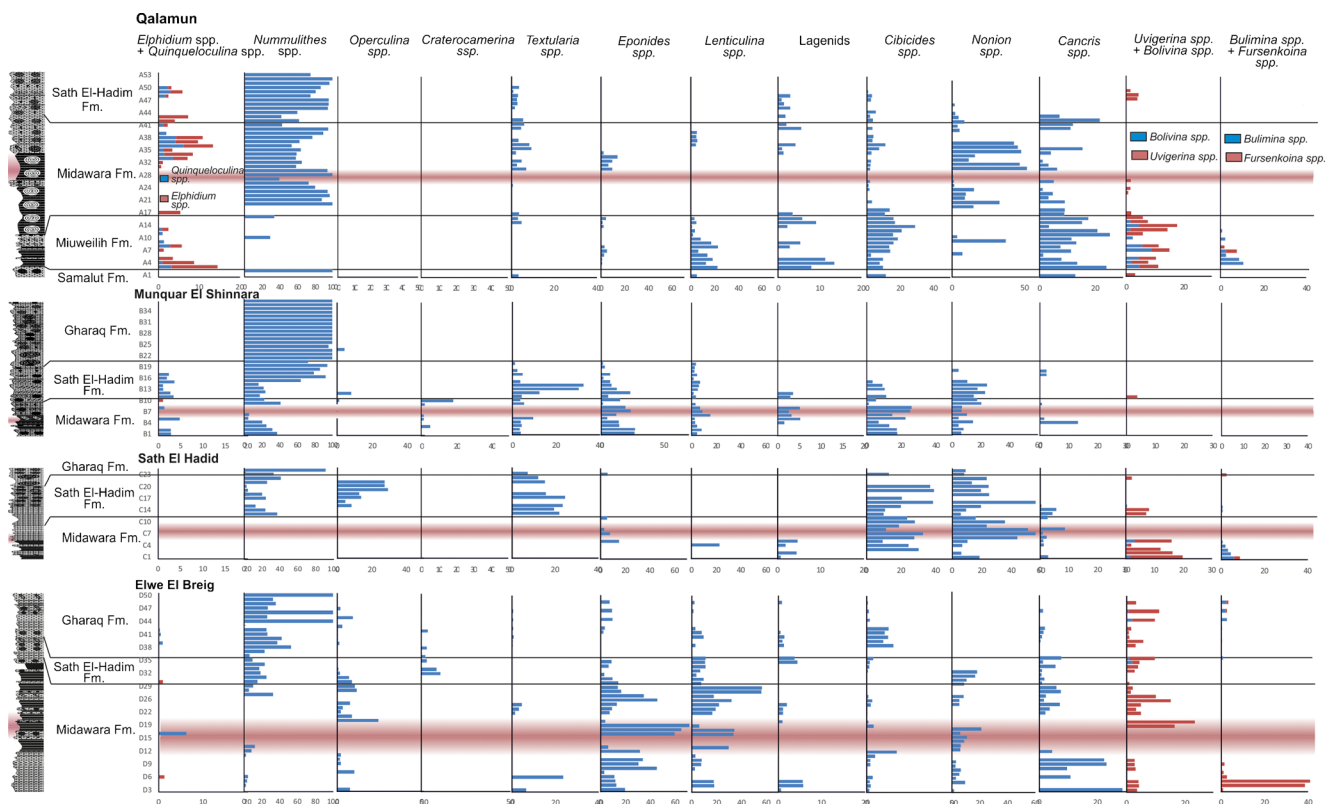
In the upper part of formation, co-occurrence of oxiphylic cibicidoids, eutrophic *Cancris* and low-oxic infauna indicates either seasonal changes of stratified and mixed water with seasonally hypoxic bottom water, or high-oxic environment at the sea-floor and hypoxic in the sediment. Seasonality can be supported by co-occurrence of all genera of planktonic foraminifers in fossil assemblages which originally could represent seasonal aspects (*Subbotina* spp.—cold season, *Acarinina* spp.—warm season). Generally, gradual deepening

of paleoenvironment can be interpreted during deposition of Muweilih Fm. The species composition of *Cancris* spp. and *Cibicides* spp. differs from overlain formations (Fig. 4) which may indicate specific paleoenvironment during deposition of Muweilih Fm.

The lateral variability of younger formations showed depth zonation of studied sections interpreted from ratio of shallow-, intermediate- and deep dwelling plankton as well as presence of inner shelf (*Elphidium* spp., miliolids, large foraminifera) vs. outer shelf to upper slope taxa (*Lenticulina*, lagenids, *Uvigerina*, *Bulimina*, *Fursenkoina*, *Eponides*). Based on these criterions, the sections can be ordered from the deepest to the shallowest in order: section D–C–B–A (Fig. 8).

### The Midawara Fm. before the MECO

Planktonic foraminifera occur in the sections C and D, in the D also deep dwellers *Globanomalina* spp. were recorded. On the other hand, inner shelf *Nummulites* spp. was found in sections A and B. The occurrence of oxyphilic cibicidoids (section B, and lower part of C) and hypoxic *Uvigerina* and *Fursenkoina* (section D and upper part of C) indicate stratification of water column with hypoxic and high-nutrient environment in the deepest part of basin (section D and upper part of section C) and well-aerated environment in the shallower part of basin.



**Fig. 7** Variance in relative abundances of benthic foraminiferal genera in relation to the MECO (red belt)



column with cold bottom water cannot be excluded. The decisive role of nutrient of terrigenous origin is expected due to high abundances of cibicidoids in section B gradually decreasing to the central part of basin (sections C and D). The sufficient riverine nutrient input needed humid climate.

### The Midawara Fm.—after the MECO and Sath El-Hadid Fm

The post-MECO paleoenvironmental changes can be characterized by (1) shallowing which can be interpreted from decrease of plankton abundances and disappearing of deep-dwellers connected with expansion of large foraminifera to all sections. Spatial distribution of genera *Operculina* (occurring in sections C and D) and *Nummulites* (dominated in section A and B) suggests that *Operculina* preferred deeper biotops than *Nummulites*. Also differences in species composition of genus *Nummulites* in individual sections (Fig. 4) indicate different ecological preferences of *Nummulithes* species. (2) Aridification is suggested from substitution of clastic-carbonate sedimentation by only carbonate one what needed reduction of clastic input from continent. The next criterion may be increase of abundances of hypersaline markers miliolids and *Elphidium* spp. and therefore possibility of salinity increase in marginal part of basin. Marked peak of agglutinated Foraminifera at the base of interval as marker of oligotrophy may indicate decrease input of terrigenous nutrients what may be connected with reduction of rainfall. (3) Increase of seasonality is expected from the co-occurrence of markers of high-quality nutrients *Nonion* (shallower sections A–C) and *Uvigerina* (deepest section D) with oxiphylic and low-quality nutrient marker cibicidoids and *Textularia* spp. which are also rather oligotrophic indicators. It evokes seasonal (and/or interannual) changes in nutrient quality and quantity (terrigenous input vs. phytoplankton bloom) and seasonal stratification of water column with hypoxic *Uvigerina* spp. at the seafloor in the deepest part of the basin.

During deposition of Gharaq Fm., paleoenvironment in the south Fayoum area was unified to inner shelf carbonate platform inhabited by *Nummulites* spp. Characteristic species was *N. lyelli* (Fig. 4). In the deepest part of the basin (section D), mixed well-aerated water with cibicidoids was seasonally or interannually alternated by stratified water with bottom hypoxic water with *Uvigerina* spp.

## Discussion

Foraminiferal assemblages from south Fayoum area enabled to interpret the paleoenvironmental changes around the MECO in the inner to outer shelf tropical sea. How can be these changes correlated with processes recorded around this warming event elsewhere in the world oceans?

Paleoenvironmental evolution is focused on changes of productivity connected with oscillation of the oxygen content. There are more scenarios of productivity changes during the middle Eocene warming. The flux of organic matter to the sea floor was not uniform, and increased, decreased or unchanged productivity during the temperature peak was recorded in the world oceans (summarized by Boscolo Galazzo et al. 2015). However, paleoenvironmental changes around the MECO interpreted from foraminiferal assemblages (Luciani et al. 2010; Boscolo Galazzo et al. 2013; Moebius et al. 2013, 2014; Boscolo Galazzo et al. 2015) showed generally increased productivity during the gradual warming preceding the thermal maximum. As a source of nutrients was interpreted continental runoff, in subtropical SE Atlantic specified as seasonal pulses of nutrients (Boscolo Galazzo et al. 2015). Increasing eutrophication culminated in stabilization of eutrophic, oxygen depleted bottom water which can be correlated either with the peak MECO (Moebius et al. 2013, 2014) or followed after the MECO. In the continental margin of the central-western Tethys, maximum eutrophication is connected with rapid deposition of two organic rich intervals following after temperature maximum (Jovane et al. 2007; Luciani et al. 2010; Spofforth et al. 2010; Boscolo Galazzo et al. 2013). However, Moebius et al. (2013) correlated these two organic-rich intervals with two high-productivity intervals recorded in the subtropical NW Atlantic and associated with two peaks of warming. Foraminiferal record indicates different situation in the subtropical SE Atlantic where the flux of organic matter to the seafloor were declined markedly already over the peak warming of the MECO. Paleoceanographic reconstructions suggest that cause of the reduction in the flux of organic matter to the sea floor was increasing of the metabolic rates of pelagic consumers (Boscolo Galazzo et al. 2015).

Comparison of these observations with shelf Fayoum area cannot be done superficially because all compared sections are situated in oceanic bathyal to upper abyssal sites: even the shallowest Tethys Scaglia limestones (Alano di Piave section) was deposited between 800 and 1000 m (Boscolo Galazzo et al. 2013). In the south Fayoum area, paleodepth from tens up to maximally first hundreds of meters is expected. In such shallow-water shelf conditions, the influence of sea-level changes can be significant which can be observed also in the Fayoum area where the peak of the MECO is connected with maximal deepening. High nutrient and hypoxic bottom water was established during warming interval before peak of the MECO which is in agreement with observations from the oceanic bathyal area (Boscolo Galazzo et al. 2013; Moebius et al. 2013, 2014). The high productivity may have been caused by a strong influx of nutrient-bearing fresh water into the basin, due to the increased vigour of the hydrological cycle during the warm period. Maximal deepening connected with thermal peak was associated with disappearance of hypoxic nutrient-rich water in Fayoum area. Boscolo Galazzo et al.

(2015) explained this reduction in the flux of organic matter to the sea floor during peak of the MECO by increased metabolic rates of pelagic consumers. Accepting this explanation for Fayoum area seems very hypothetical.

Contrary to oceanic realm, foraminiferal assemblages from epicontinental sea in post-MECO interval did not return to pre-MECO composition (Boscolo Galazzo et al. 2013; Moebius et al. 2014). Assemblages were strongly influenced by climatically forced sea-level fall and aridification connected with decrease of terrigenous input. Aridification is a common phenomenon accompanying also other cooling intervals (Eocene-Oligocene transition and post-MMCO transition: Dupont-Nivet et al. 2007; Miao et al. 2012). The aridification connected with cooling was described also for the post-MECO interval (Bosboom et al. 2014).

## Conclusions

Quantitatively analysed foraminiferal assemblages from south Fayoum area enabled to interpret paleoenvironmental changes around the MECO in the shallow tropical epicontinental sea. The following trends are the most prominent: (1) Warming and subsequent cooling in the upper layer of water column; (2) climatically forced sea-level oscillation with deepest environment during the MECO; (3) eutrophic and oxygen depleted bottom water in pre-MECO interval; (4) aridification after the MECO connected with decrease of input of nutrient-bearing fresh water into the basin and increase of salinity in the marginal part of basin; (5) increase of seasonality after the MECO; and (6) gradual decrease of amount of nutrient during the post-MECO interval.

Paleoenvironmental changes differ from the middle Eocene evolution in oceanic bathyal sites; however, high productivity just before peak of warming are comparable. Shelf assemblages from Fayoum area are more strongly influenced by climatically forced sea-level oscillation and aridification in cooling interval.

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