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Palaeoenvironments and palaeobiogeographical distribution of the Eocene larger benthic foraminifera and macrofaunal associations in northern Bahariya Depression, Western Desert, Egypt

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Abstract

The Eocene rocks exposed in northern Bahariya Depression constitute from base to top, the Naqb, Qazzun and El-Hamra formations, which made up of highly fossiliferous siliciclastic–carbonate rocks deposited essentially in marginal-marine, neritic, tide-dominated environments. These environments correspond, respectively, to peritidal flat, lagoonal–restricted bays, barrier shoal and platform margin reefal zones situated on a gently sloping homoclinal inner to very proximal mid-ramp settings. Four local larger benthic foraminiferal zones were identified. The proposed zones correspond to the regional larger benthic foraminiferal zones (SBZ12 through SBZ19) of the Tethyan shallow carbonate platforms. These zones allowed assigning a late Ypresian age to the Naqb Formation, an early Lutetian to the Qazzun Formation, and a middle Lutetian–Priabonian to the El-Hamra Formation. Furthermore, five distinctive macrofaunal assemblages were identified and palaeoecologically interpreted. Paleobiogeographically, the identified benthic foraminifera and macrofaunal assemblages show a dominantly Tethyan character and strong affinity to the African, Arabian, Indian and southern Europe marginal-marine carbonate platforms. This study, therefore, contributes to the understanding of the facies architecture and palaeobiogeography of the Eocene carbonate platforms developed along the margins of the circum-Mediterranean domain.

Keywords*:* Palaeoenvironments, Palaeobiogeography, Eocene, Bahariya Depression

1. Introduction

The Eocene shallow carbonate platforms in northern Egypt are dominated by benthic foraminifera and macrofossils mainly of oysters, gastropods, nautiloids, echinoids, bryozoans and algal debris. Larger benthic foraminifera (LBFs), particularly, are helpful skeletal constituents in biostratigraphy, depositional facies and palaeoenvironmental analyses of the Eocene sequences, and they occur abundantly in the shelf regions of tropical and subtropical marginal–marine, coastal lagoons, warm water oligotrophic reefs and carbonate environments [1, 2, 3, 4, 5]. Deposition of the Eocene sediments in Egypt was particularly controlled by regional and eustatic sea-level fluctuations of the Neo-Tethys, as well as tectonic instability and climatic changes, which invoked both irregular marine transgressions and regressions [6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16]. Consequently, large varieties of sedimentary litho- and biofacies were formed in response to these erratic conditions. In the northern plateau of the Bahariya Depression (the area under investigation), located in the north-central part of the Egyptian Western Desert, the Eocene rocks consist of thick-bedded sediments that display shelfal shallow-marine facies characteristics. Therefore, this study aims at providing significant clues on the palaeoecology and regional palaeobiogeographic distribution of some larger benthic foraminifera and macrofauna identified from the Eocene rocks cropping out in northern Bahariya Depression.

2. Geological setting

The Bahariya Depression is a NE-oriented, erosion-related landform, located in the north-central part of the Western Desert of Egypt (Fig. 1). It coordinates between latitudes 27^{o} 48′ and 28^{o} 30′ N and longitudes 28^{o} 35′ and 29^{o} 10′ E, approximately 370 km southwest of Cairo. The Bahariya Depression is roughly oval covering an area of approximately 1800 km^2. It is flanked from all sides by relatively high scarps rising ~250 m above sea level. The Bahariya Depression was deeply excavated most probably during the Neogene by the interplay of tectonics, karstification and deflation, which resulted in the continuous lowering of the depression floor to ~110 m above sea level [17].

The Bahariya Depression superimposes the Bahariya anticline extending from Gebel Ghorabi in the northwest, passing through the central hills in the depression floor to the southern closure of the depression. The origin of the Bahariya anticlinal fold is attributed to the Syrian Arc System (SAS) initiated most probably in the Late Cretaceous and continued intermittently until the late Paleogene. The Bahariya Depression consists mainly of sedimentary successions ranging in age from the Late Cretaceous to the Paleogene. A geological map showing the stratigraphy of the different rock units exposed in the northern sector of the Bahariya Depression is given (Fig. 1). The Quaternary sediments in the Bahariya region are represented by sporadic and isolated occurrences of endorheic playas (dry paleo-lakes), brackish sabkhas, and aeolian nebkhas (coppice-shrub) and sand dunes [18, 19, 20].

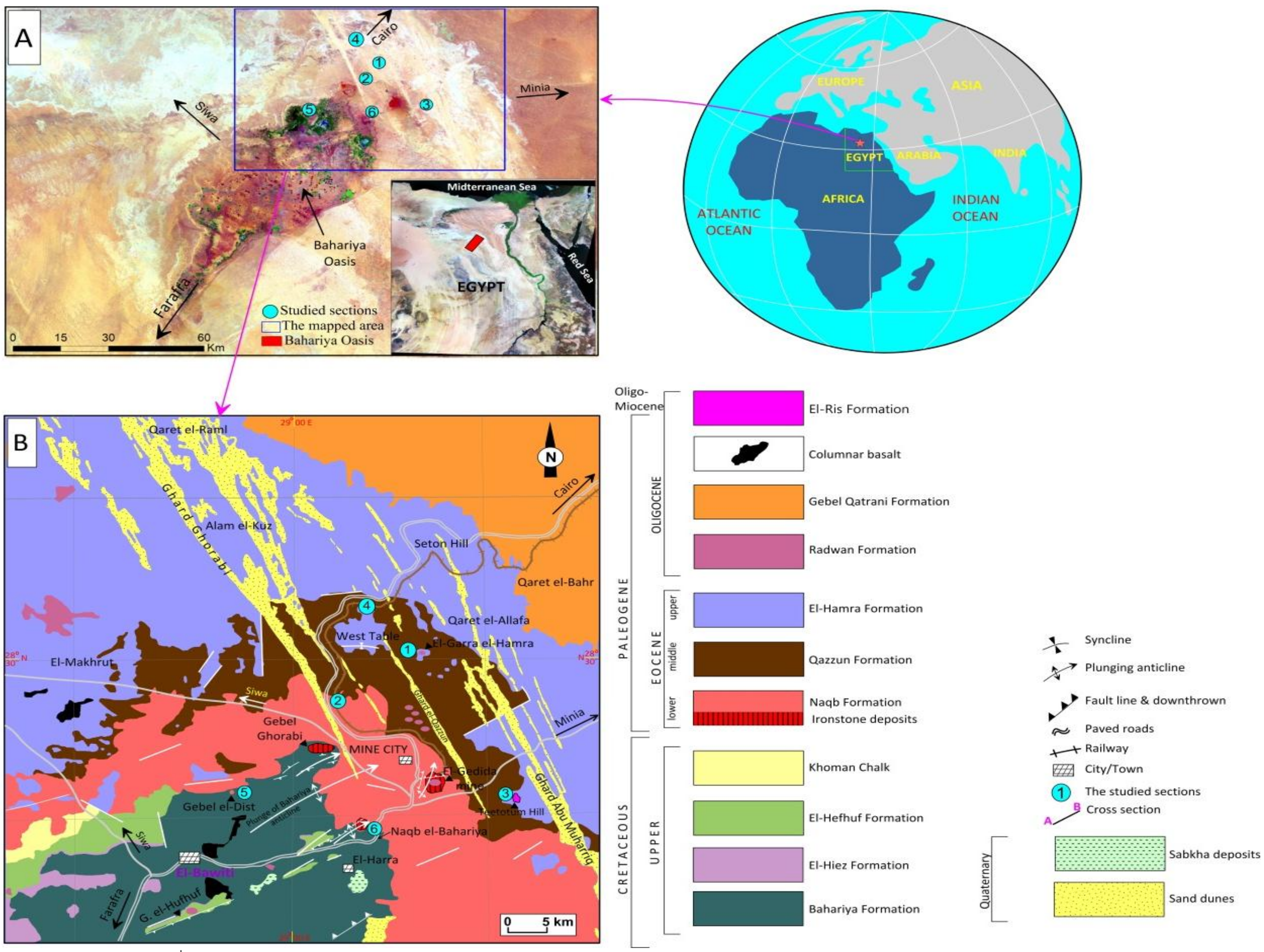

Fig. 1. A) ETM+ Landsat image of the Bahariya Depression showing the locations of the studied sections. **B**) Geological map showing the distribution of the different rock stratigraphic units exposed in the northern Bahariya region [6, 7].

3. Material and methods

A combination of field and petrographic investigations was utilized to enhance the stratigraphical and sedimentological interpretations. Larger benthic foraminifera (mainly *Nummulites*) and macrofauna including oysters, gastropods, nautiloids and echinoids were collected and identified from the Eocene rocks cropping out in ther northern plateau of the Bahariya Depression that helped in age assignment and biostratigraphy of these successions. The stratigraphic sections described in this study are located at Gebel El-Garra El-Hamra (28° 37′ N - 29° 09′ E), which represents the type section of the middle and upper Eocene formations (the Qazzun and the El-Hamra formations, respectively), El-Bahr (28° 38′ N - 29° 03′ E), Teetotum Hill (28° 25′ N - 29° 16′ E), and Gebel El-Dist (28° 25′ N - 28° 55′ E).

4. Lithostratigraphy

The Eocene stratigraphy in the Bahariya northern plateau has been a matter of much controversy. [7] classified the Eocene succession in this region into the Naqb Formation at base, followed upward by the Qazzun and El-Hamra formations, respectively (Fig. 2, 3). This succession overlies the inclined Upper Cretaceous rocks with a pronounced angular unconformity in-between. The Naqb Formation is a carbonate unit attaining a thickness of 20 - 30 m. The Naqb Formation is partly dolomitic, siliceous limestone, rugged and irregularly bedded. It unconformably overlies the tilted strata of the Bahariya Formation (early Cenomanian), and is overlain by the Qazzun Formation with seeming conformity. The Qazzun Formation is composed of bright, clean white chalky limestone with many calcite pockets, assuming a thickness of about ~32 m. The lithology of these two units i.e., the Naqb and Qazzun formations indicates and points to a marked difference in depositional environments; shallow and disturbed by current action at base (the Naqb Formation), while quiet slightly deeper at top (the Qazzun Formation). The Qazzun Formation is followed upward by the El-Hamra Formation that has been lithologically subdivided by [21] into the Lower Hamra Member (~32 m-thick) and Upper Hamra Member (~32 m-thick). The lithology of the El-Hamra Formation as a whole points to gradational development of clastics upward in the section. This probably what led [7] consider the whole section as one unit, only subdivided into two units when conglomerate was recorded in-between [21] The El-Hamra Formation is disconformably overlain by either fluviatile sandstone and ferruginous grits (6.0 to 12 m-thick) belonging to the Oligocene Radwan Formation [7] or by the lacustrine carbonates of the El-Ris Formation of late Oligocene Miocene? age [22].

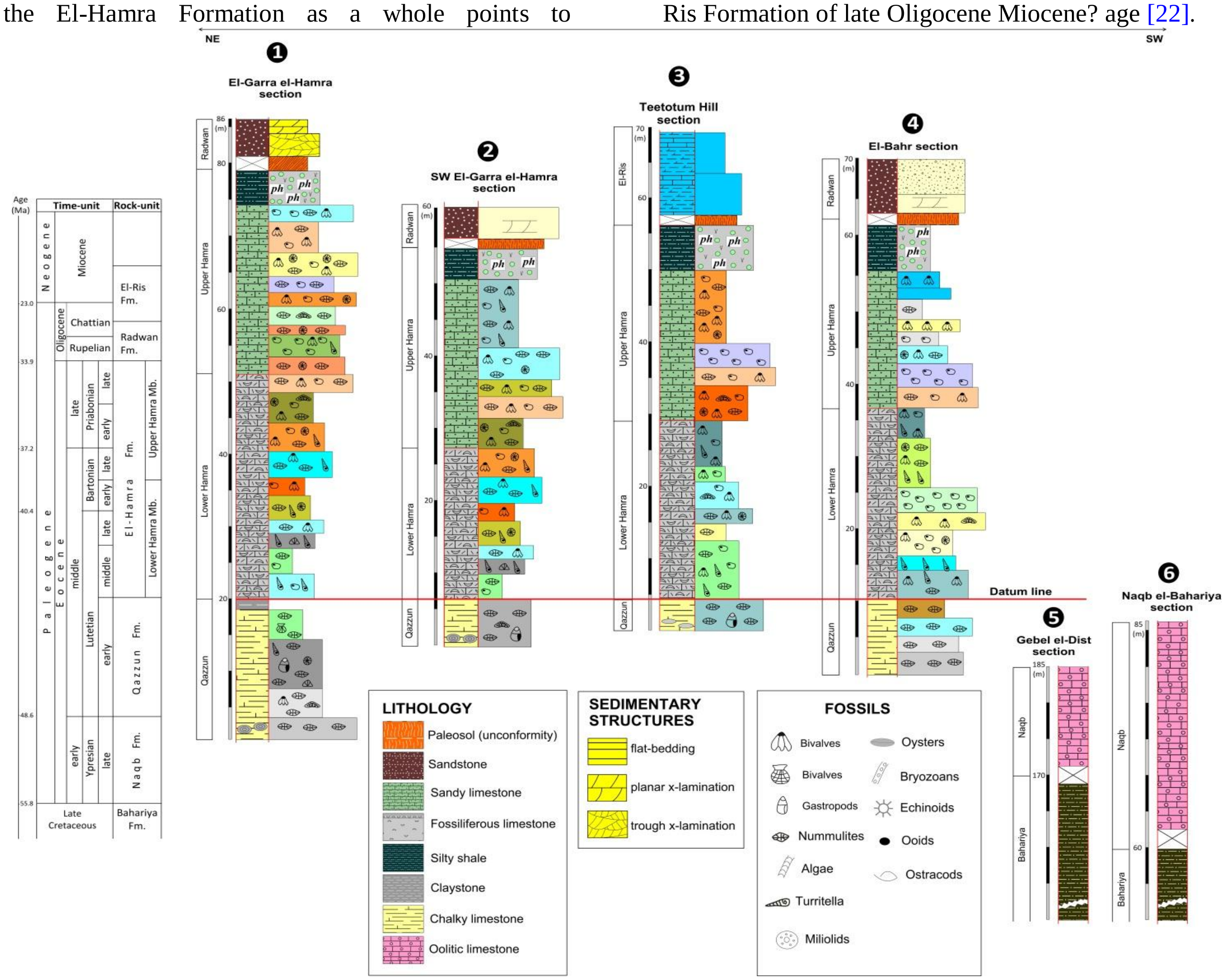

Fig. 2. Graphical lithostratigraphic logs of the studied Eocene sections.

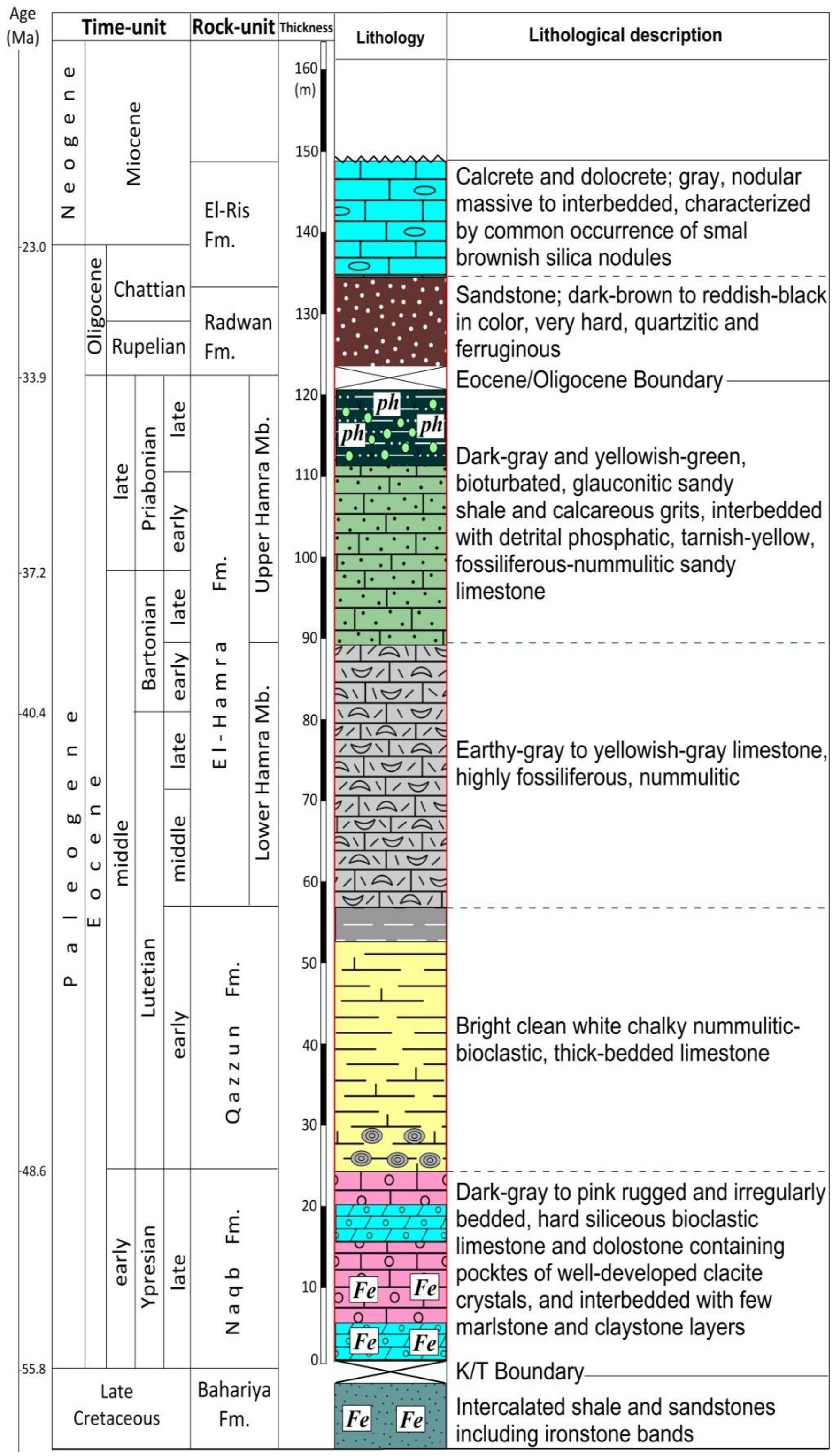

Fig. 3. Composite lithostratigraphic columnar section of the studied Eocene rock units in northern Bahariya Depression.

5. Facies associations and depositional palaeoenvironments

The investigated Eocene rocks consist mainly of sixteen microfacies types (mf1 to mf16) that form four genetically-related facies associations (FA1 through FA4) (Table 1). The FA1 and FA2 generally characterize a nearshore tide-dominated area with tidal flats and shallow subtidal in restricted to open lagoonal environments with restricted salinity, sluggish circulation and a non-diverse fauna. The depositional substrate was constantly influenced by waves [23]. Shallow nearshore and restricted lagoonal environments, down to about 50 m, are characterized by porcelaneous miliolid foraminifera. Shell concentrations characterize the Qazzun and El-Hamra formations in the studied sections, which confirm deposition in a marginal-marine setting, particularly in intertidal and shallow subtidal environments [24]. This interpretation is consistent largely with other analyses of shallow nearshore and restricted lagoonal environments with abundant miliolid foraminifera [25]. The FA3 and FA4 comprise barrier shoal and distal outer lagoonal and platform margin reefal environments, with a high to low/moderate energy, respectively. Larger benthic nummulitid foraminifers generally flourish in shallow carbonate inner and proximal mid-ramp settings [26]. Many nummulitides are limited to the euphotic zone because they prefer habitats within algal and sea grass meadows. Nummulitid foraminifers contribute significantly to the formation of carbonate sediments in reefs and in other shallow-marine carbonate environments [15, 16, 25, 26, 27, 28, 29, 30]. In addition, the frequently high abundance of molluscs, echinoids, bryozoans and calcareous algae suggests a shallow–marine, restricted–saline depositional setting, particularly, open lagoons and fringing reefal environments of moderate-to-low energy [31].

Facies Associations /Microfacies types	**Textural components**	**Interpreted depositional environments**
mf1: Lime-mudstone	0.5–2.0 m-thick, earthy-gray to grayish-brown homogenous micrite with few disseminated quartz grains and bioclastic particles.	Low-energy tidal flat (FZ8) and arid evaporitic coastline (FZ9) environments reflecting a short-term of sea-level fall. It is consistent with the SMF23. Dolomitization most probably took place in the early diagenesis, and is related mostly to hypersaline brines of a tidal flat-inner lagoon setting.
mf2: Dolomicrite	Anhedral to subhedral dolomite rhombs ranging in size from 10 to 15 µm. Hypidiotopic fabric with equigranular texture. Unzoned crystals showing cloudy cores and clear outer peripheries.	
mf3: Foraminiferal dolomicrite	Similar to the above-described mf2, with few skeletal particles, commonly larger benthic foraminifera and bioclastics, which are partially/fully dolomitized.	
mf4: Sandy bioclastic rudstone	It consists mainly of oyster shells, gastropods and minor nummulites showing aggrading neomorphism and embedded in a micritic matrix.	Neritic, littoral-sublittoral, high to moderate-energy subtidal and intertidal zones (FZ7 & FZ8).
mf5: Laminated-glauconitic-anhydritic-sandy shale	laminated glauconitic-gypseous-sandy shale with few small scale cross-bedded sandstone, siltstone and marlstone intercalations. Glauconite grains show yellowish-green to dark-green, rounded to subrounded, fine to medium-grained (100–350µm), well-sorted to poorly-sorted pellets embedded in a dark ferruginous clayey matrix. Glauconite pellets also fill foraminiferal and fossil shells. Anhydrite crystal laths were also common.	Slow sedimentation rates in a reduced shallow-water nearshore tidal flat to restricted inner ramp lagoonal environments (FZ7–9), influenced by wave energy, and continuously received high influx of terrigenous siliciclastic sediments.
mf6: Miliolidal foraminiferal wacke- to packstones	It is made up of abundant larger (*Orbitolites*, *Alveolines*) and miliolidal (*Pseudolacazines*, *Biloculina*, *Quincloculina*, *Rhabdorites*) foraminifera, with a few occurrence of calcareous algae, crinoids, echinoid spines; all are embedded in a microsparitic matrix.	Low-energy neritic, restricted inner ramp lagoonal environment (FZ8), epipelagic euphotic, under a sluggish to open circulation and high saline shallow-water and eutrophic (high nutrient level) conditions.

mf7: Algal foraminiferal wacke- to packstones	This microfacies consists of nummulites, algal debris and small miliolidal foraminifera that are embedded in a microsparitic matrix. Some bioclasts exhibit micritization and/or micrite coatings and patchy neomorphism is present in the micritic matrix.	
mf8: Foraminiferal wackestones	The mf8 consists of floated foraminiferal species distributed within a microsparitic to micritic matrix.	
mf9: Sandy bioturbated bioclastic wacke- to packstones	It is composed of molluscan shell fragments, bryozoan debris and few miliolidal foraminifera that are embedded in a micritic matrix.	
mf10: Ferruginous oolitic–pisolitic wacke- to packstones	Hematitic and goethitic spherical to irregular-shaped and curved grains of ooids (less than 2 mm in diameter) and pisoids (larger-sized) with quartz nuclei and a cortex of concentric hematite/goethite laminae that are cemented by ferroan calcite. Bioclastics are also impregnated by hematite/goethite.	Low-energy, proximal lagoons and restricted bays, with sluggish water.
mf11, 12: Foraminiferal ooidal/pelloidal wacke- to packstones	Coated grains of ooids/pisoids, and pelloids and miliolid foraminmiferal shells embedded in a microsparitic matrix. Some bioclasts enveloped by micrite coatings, others show aggrading neomorphism and filled with sparite cement.	Winnowed platform margin–restricted lagoonal environments (FZ6), with a normal marine salinity, high-energy, open circulation and constant wave action.
mf13: Nummulitic wacke-, pack- to grainstones	It consists of bioclasts mainly nummulites, assilina and operculines with minor oyster shell debris and subordinate ratio of quartz grains, embedded in a micritic matrix, partly microsparitic.	Tropical to subtropical, outer open lagoon–platform margin reefs with photic, warm, open to moderate current circulation, and high nutrient levels (eutrophic) in the platform interior–open marine (FZ7 and FZ9).
mf14: Burrowed bioclastic rudstones	It is composed of bioclasts of oyster shell fragments, gastropods and a few larger benthic foraminifera embedded in microsparitic matrix.	
mf15: Echinoidal wackestones	It consists of echinoid spines, crinoids and other bioclastic shell fragments.	
mf16: Bryozoan framestones	It consists of bryozoan fragments, in addition to larger foraminifers, bioclasts and quartz grains embedded in a micritic, partly sparitic matrix.	

Table 1. Summary of microfacies types, facies associations and their related depositional palaeoenvironments of the studied Eocene rocks exposed in northern Bahariya Depression.

Based on lateral and vertical facies and faunal distributions, it can be concluded that the lower–upper Eocene rocks in the area under study were deposited primarily in marginal-marine environments situated on a gently-dipping homoclinal inner to proximal mid-ramp setting, with restricted salinity and sluggish to good water circulation (Fig. 4). Homoclinal ramps are shallow epeiric and pericontinental platforms distinguished by mild depositional slopes, passing downwards from a shallow nearshore, high-energy facies into deeper-marine offshore facies without a discernible break in slope [32]. The physical characteristics of facies belts are goverened largely by energy levels incluging fair-weather wave base (FWWB) and storm wave base (SWB), differences in ramp topography, and material transport by waves, tides and storms. The dip angle of slope is generally less than 1^0, but steeper dips may occur. The inner ramp setting embraces open marine environments with good water circulation, protected environments with sluggish water circulation, barrier shoal environment marked by oolitic and bioclastic grainstones and packstones, restricted lagoonal environments behind shoals or islands, and peritidal environments [33]. Most common microfacies textures of open and protected inner ramps are bioclastic–nummulitic packstones, grainstones and wackestones. Reefal limestones (mollusc-reefs) are common in open inner ramps.

The facies associations of the Naqb Formation are interpreted to represent deposition in peritidal, coastal lagoons and shoal settings, whereas the Qazzun Formation typifies deposition in a calm, slightly deeper open lagoon–reefal environment. The facies associations of the El-Hamra Formation are considered to represent a noticeable facies change from open lagoon–reefal carbonate facies of the Lower Hamra Member, into shoreline tidal flat–winnowed edge glauconitic siliciclastic–dominated facies of the Upper Hamra Member. The facies characteristics of the Upper Hamra Member with the marked increase of sand, marl and clay content, as well as the prevalence of glaucony facies with primary gypsum layers at top indicate the continuous shallowing-up associated with the gradual rereat of the Priabonian shoreline northward. Caliche nodules formed within the topmost part of the El-Hamra Formation represent also good criteria for full marine regression and subaerial exposure preceding the deposition of the Oligocene fluviatile sandstones.

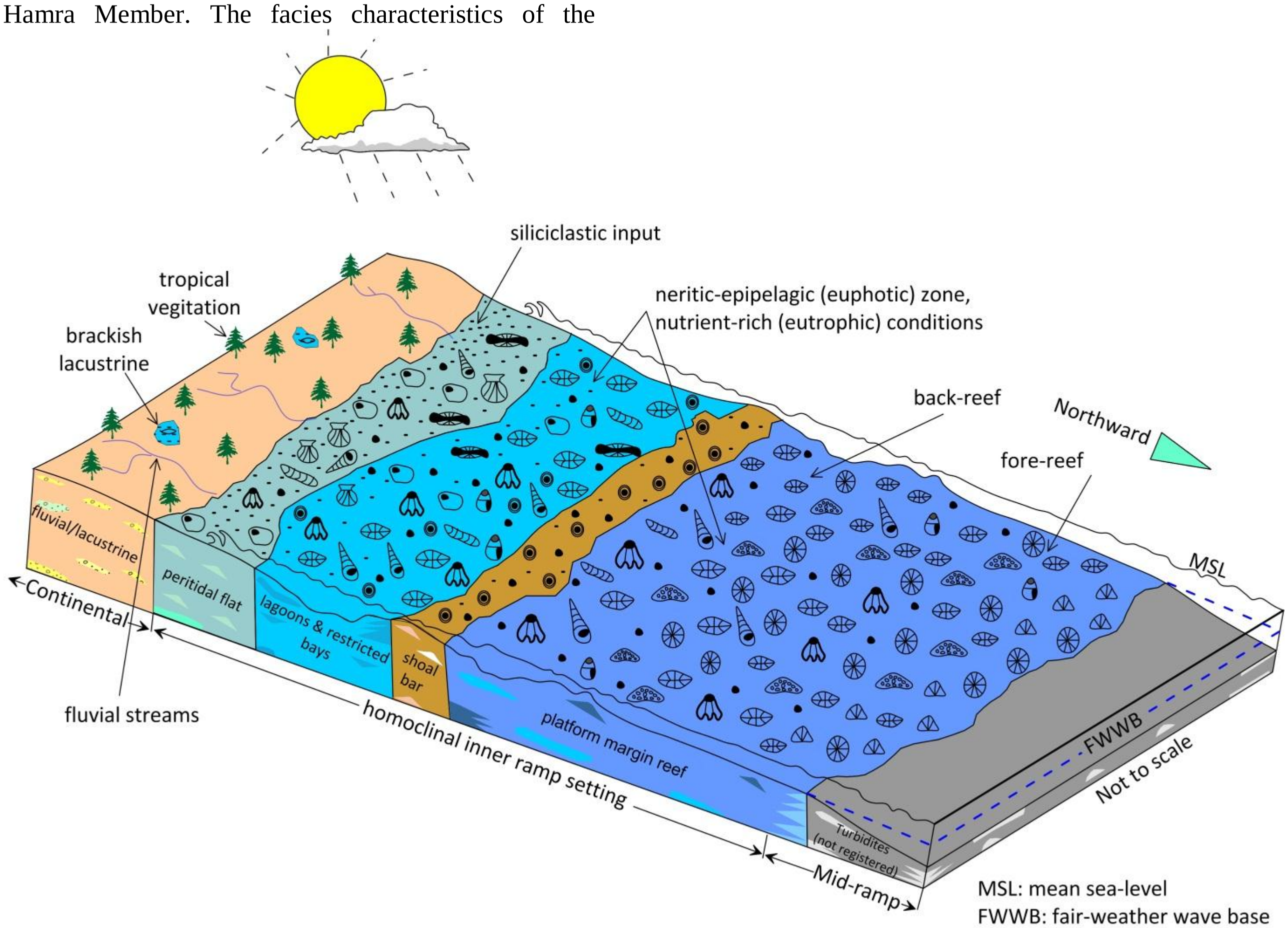

Fig. 4. Depositional model of the studied Eocene siliciclastic–carbonate succession in northern Bahariya Depression.

6. Biostratigraphy and palaeoecological attributes

The lower–middle Eocene rocks exposed in northern Bahariya Depression yield abundant larger benthic foraminifera particularly nummulites, assilines, operculines, orthophragmines, orbitolites, in addition to abundant presence of benthic macrofossils of bivalves, gastropods, nautiloids, echinoids and bryozoans. These benthic fauna were predominantely inhabited in the inner neritic, near-coast tide-dominated zone (<100 m depth), which is characterized by warm water with normal to restricted salinity, and sluggish to open water circulation necessary for transferring nutrients to the lagoons and reefs [24]. Apparently, there was a significant upward change of paleoecological attributes throughout the lower–upper Eocene succession triggered by variation in neritic siliciclastic inflow due to tectonic and climatic instability. In this study, miscellaneous faunal assemblages of both benthic larger foraminifera and macrofossils have been identified and profoundly described below.

6.1. Larger benthic foraminiferal (LBFs) assemblages

Paleontological studies of the Eocene carbonate succession exposed in the northern Bahariya Depression revealed abundant shallow-water larger benthic foraminiferal (LBFs) content [34]. Their frequently high abundance and diversity make them extremely important biostratigraphic tools in assignment the relative age of the studied Eocene rock units. In this study, four local larger benthic foraminiferal zones were identified from the lower–upper Eocene rocks (Fig. 5). These zones correspond to the regional shallow benthic foraminiferal zones (SBZ12 through SBZ19) [35], which established across the Tethyan carbonate platforms. The identified LBFs zones in the studied Eocene succession are arranged from base to top, as follows: (1) *Orbitolites complanatus* Total Range Zone (late Ypresian = SBZ12), (2) *Nummulites praelorioli* Total Range Zone (late Ypresian–early Lutetian = SBZ12 & SBZ13), (3) *Nummulites gizehensis–Nummulites beaumonti* Interval Zone (middle Lutetian–early Bartonian = SB14–SBZ17), and (4) *Nummulites contortus-striatus* Total Range Zone (late Bartonian–Priabonian = SBZ18 & SBZ19). The identified LBFs species are shown in (Fig. 6).

6.1.1. Orbitolites complanatus Total Range Zone

This foraminiferal zone occurs in the upper part of the Naqb Formation, and is marked by common occurrence of *Orbitolites complanatus*. It ranges from 3.0 to 8.0 m-thick at the upper parts of the Naqb El-Bahariya and 4.0 km northeast of mines city sections, respectively. Other foraminiferal species identified in this zone include *Alveolina frumentiformis*, *Assilina praespira*, *Operculina discoidea*, *Planotrillina deserti*, *Nummulites subramondi*, *Rhabdorites minima* and miliolids in the form of *Quinqueloculina* and *Biloculina*. Some forms of calcareous dasyclad algae were also observed. This total range zone is correlated with the SBZ12 of [35] that allowed assigning a late Ypresian (early Eocene) age to the Naqb Formation [34].

6.1.2. Nummulites praelorioli Total Range Zone

The *Nummulites praelorioli* zone is defined by the total range of the *Nummulites praelorioli* Herb & Schaub, 1963. This zone is recognized within the chalky limestone beds of the Qazzun Formation at Gebel El-Garra El-Hamra and El-Bahr sections with thicknesses ranging from 18 to 30 m, respectively. Other associated benthic foraminiferal species identified from this zone are *Nummulites syrticus*, *Nummulites cailliaudi* and *Nummulites variolaria*. The identified *Nummulites praelorioli* Total Range Zone corresponds to the SBZ12 and SBZ13 of [35] that allowed assigning an early Lutetian age to the Qazzun Formation.

6.1.3. Nummulites gizehensis–Nummulites beaumonti Interval Zone

The lower boundary of this zone is determined by the first occurrence (Fo) of the *Nummulites gizehensis* (Forskål, 1795) at the base of the Lower Hamra Member and its upper boundary is defined by the last occurrence (Lo) of the *Nummulites beaumonti* d'Archiac & Haime. The thickness of this zone ranges between 32 m-thick of the Lower Hamra Member at the Gebel El-Garra El-Hamra section, and 14 m-thick at the El-Bahr section to the northeastward. In addition to the two marker species, the zone includes other Nummulites species; *Nummulites migiurtinus Nummulites discorbinus* (Schlotheim) and *Nummulites lyelli* d'Archiac & Haime. The identified *Nummulites gizehensis–Nummulites beaumonti* Interval Zone corresponds to the SBZ14, SBZ15, SBZ16 and SBZ17 of [35], which allowed assigning a middle Lutetian–early Bartonian age to the Lower Hamra Member.

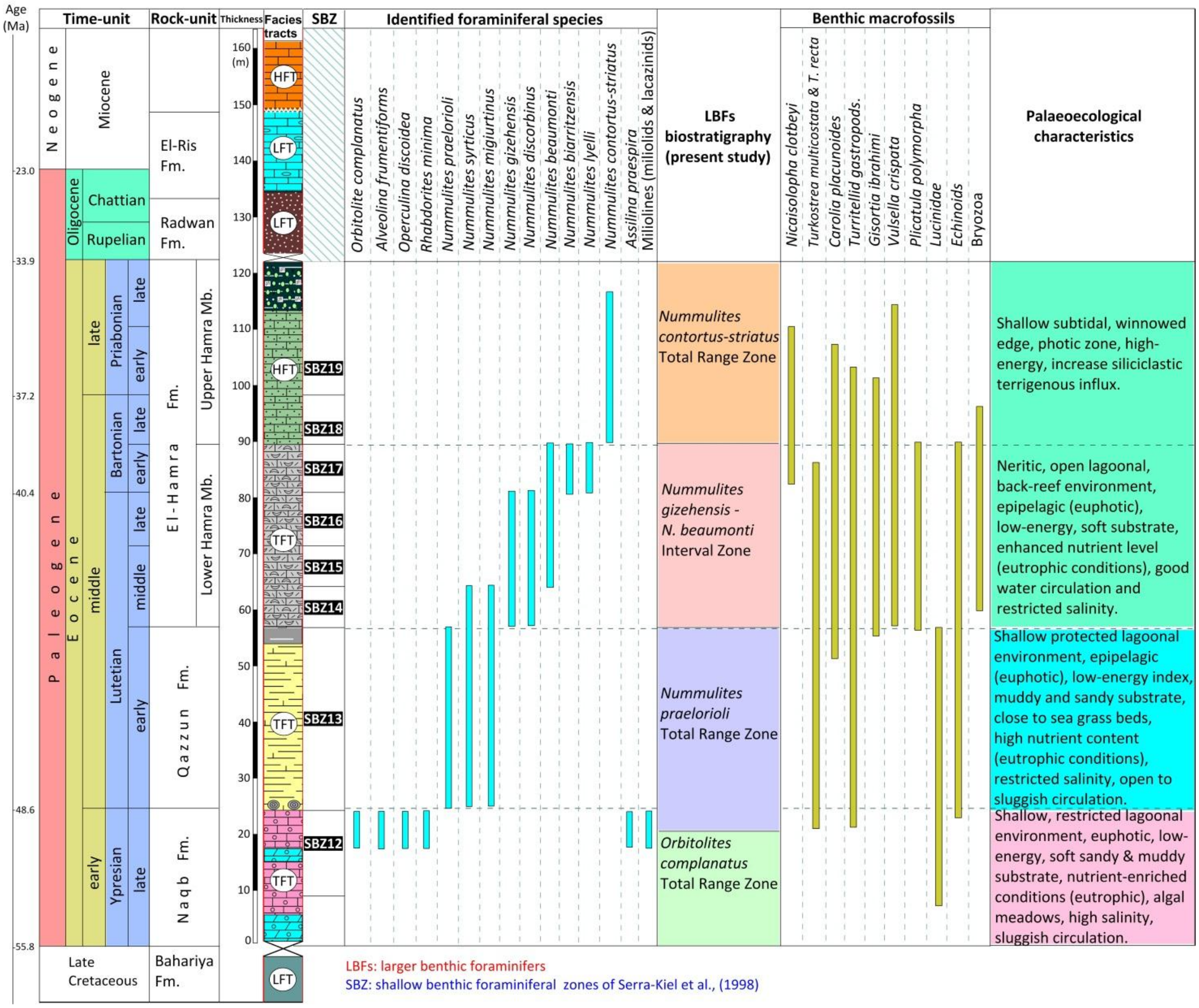

Fig. 5. Biostratigraphic chart demonstrating the larger benthic foraminiferal zones with respect to the shallow larger benthic foraminiferal zones (SBZ) of [35] and other benthic macrofossils identified from the Eocene rock units exposed in the studied area, with their palaeoecological characteristics.

6.1.4. *Nummulites contortus-striatus* Total Range Zone

The *Nummulites contortus-striatus* Total Range Zone is marked by the total range of the *Nummulites contortus-striatus* identified from the middle and upper parts of the Upper Hamra Member. It attains a thickness of about 14 m in the Upper Hamra Member in the Gebel El-Garra El-Hamra section, and about 8 m at El-Bahr section. This zone can be correlated with the SBZ18 and SBZ19 of [35] that allowed assigning late Bartonian–Priabonian age to the Upper Hamra Member.

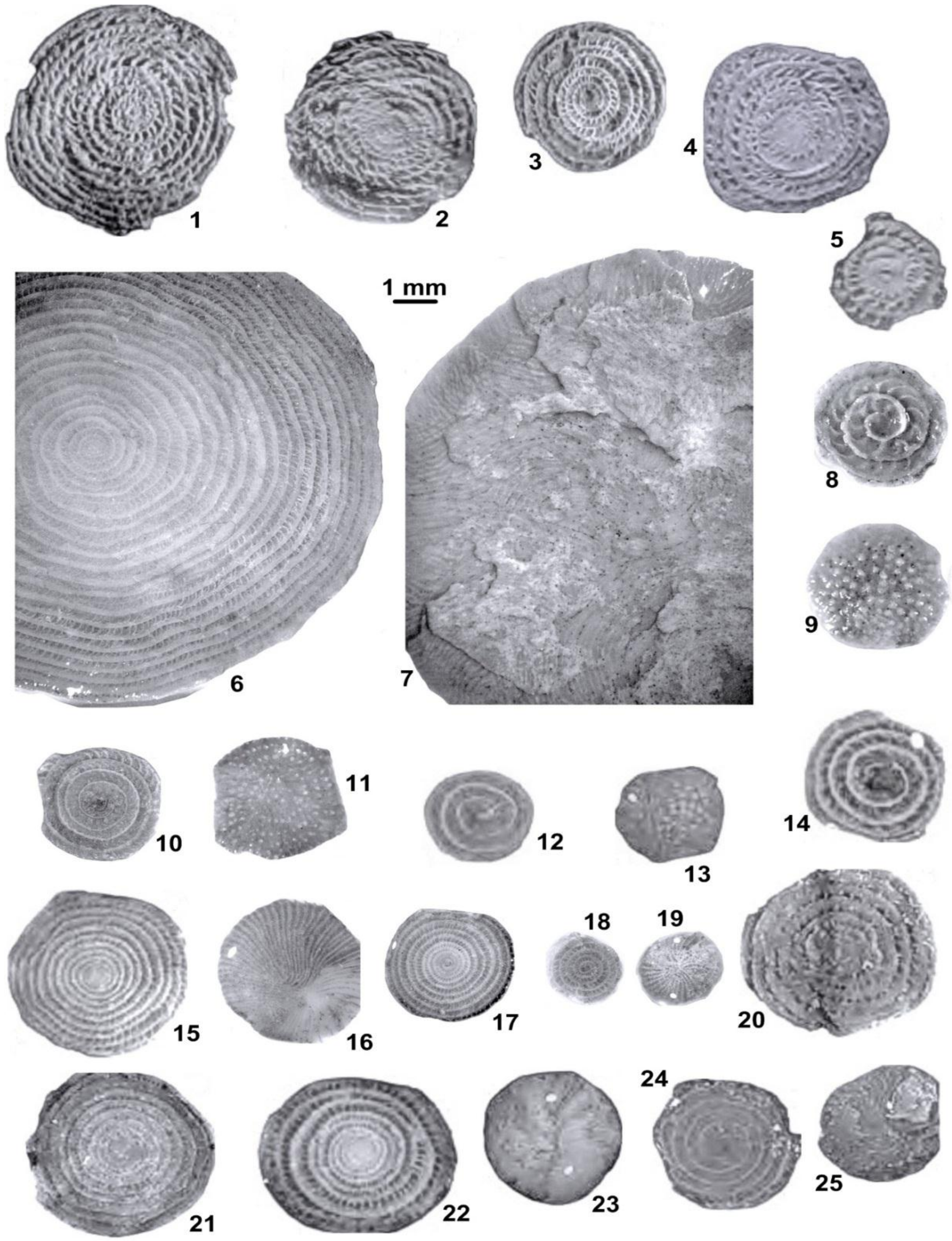

Fig. 6. Larger benthic foraminifera photographs showing: **1–5** ***Nummulites praelorioli*** Herb & Schaub, 1963; **1–4** microspheric forms; **5** megalospheric form. All specimens are equatorial sections. **6–14** ***Nummulites gizehensis*** (Forskål, 1795); **6, 7** microspheric forms; **8–14** megalospheric forms; **6, 8, 10, 12, 14** equatorial sections; **7, 9, 11, 13** external view. **15–19** ***Nummulites beaumonti*** D'archiac & Haime, 1853; **15, 16, 17** microspheric forms; **18, 19** megalospheric forms; **15, 17, 18** equatorial sections; **16, 19** external view. **20** ***Nummulites syrticus*** Schaub, 1981; microspheric form; equatorial section. **21** ***Nummulites biarritzensis*** D'archiac & Haime, 1853; microspheric form; equatorial section. **22–23** ***Nummulites discorbinus*** (Schlotheim, 1820); microspheric forms, **22** equatorial section; **23** external view. **24–25** ***Nummulites lyelli***

D'archiac & Haime, 1853; megalospheric forms; **24** equatorial section; **25** external view. The scale bar is 1 mm.

6.2. Benthic macrofaunal assemblages

Benthic macrofossils (e.g., bivalves, gastropods, bryozoans and echinoids) collected from the studied Eocene rocks provide significant information about the palaeoecological and palaeoenvironmental conditions prevailed during their deposition [36]. Five distinctive macrofaunal assemblages have been identified from the studied lower–upper Eocene exposures in the northern limestone plateau of the Bahariya Depression. These faunal assemblages are described and interpreted in terms of palaeoecological conditions, and are shown in (Fig. 7, 8).

6.2.1. *Lucinidae*–dominated assemblage

This faunal assemblage occurs dominantly in the carbonate strata of the Naqb Formation exposed at Naqb El-Bahariya and the uppermost part of Gebel El-Dist in the floor of the Bahariya Depression. This fossil assmbelage is commonly represented by *Lucina thebaica* and *Lucina polythele*. Other macrofossils associated with this assemblage include *Spondylus aegyptiacus*, *Cassis nilotica*, *Cardium* sp., and *Natica* sp. Palaeoecologically, the Lucinidae are mobile, shallow-marine, filter-feeding bivalves that live infaunally, in deeply buried soft sediments that are often reduced and contain high concentrations of sulfides. Lucinidae significantly contributed to shallow-marine carbonate platforms, specifically since the Paleozoic following the decline of brachiopods [36].

6.2.2. *Turkostrea multicostata*-dominated assemblage

The *Turkostrea multicostata*-dominated assemblage is recorded from the lower and middle parts of the Qazzun Formation and the Lower Hamra Member exposed at the El-Bahr and Gebel El-Garra El-Hamra sections. This fossil assemblage is rich in epifaunal suspension-feeding organisms indicating a shallow-marine environment, with inner neritic, nutrient-rich (eutrophic conditions) and low sedimentation rates [38]. *Turkostrea multicostata* is reef-like building oysters thriving in shallow warm waters. It forms several lags of shell concentrations formed by multiple reworking associated with winnowing of fine-grained sediment and corrosion. Other macrofossils identified from this assemblage include the oyster *Turkostrea recta*, the gastropods *Gisortia ibrahimi*, *Gisortia gigantica* and *Heligmotoma* sp., Thenautiloid *Deltoidonautilus* sp., and the irregular echinoid *Conoclypus delanouei*.

6.2.3. *Turritelline*-dominated assemblage

This assemblage constitutes several turritelline-dominated concentrations in the Qazzun and Lower Hamra rock units in the El-Bahr and Gebel El-Garra El-Hamra sections. The most common turritelline gastropod species identified from this assemblage are *Turritella zetteli*, *Turritella lessepi* and *Turritella* sp., often associated with the bivalve *Carolia placunoides*. Palaeoecologically, gastropods are ubiquitous all over shallow-marine environments, and they are able to tolerate variabilty and excesses of water salinity [36]. Turritelline gastropods are often the most abundant species in the shallow subtidal habitates and benthic communities in which they exist, forming turritelline-dominated assemblages [39]. They tend to live in soft-bottom communities associated with high levels of nutrients (eutrophic conditions) and primary productivity [40, 41]. Turritelline gastropods are widely distributed in temperate, subtropical to tropical waters, and generally inhabit depths of more or less 10–100 m [42]. They essentially flourish in normal marine salinities [43]. The frequently high abundance of such sessile, semi-infaunal, deposit/suspension-feeding turritelline gastropods suggests moderate rates of sedimentation in neritic–subtidal palaeoenvironments [37, 38].

6.2.4. *Carolia placunoides* assemblage

The *Carolia placunoides* assemblage is recorded from both the Qazzun and the Hamra formations. It forms several shell concentrations within these formations. Palaeoecologically, *Carolia placunoides* is attached, epifaunal suspension-feeding bivalve living in monospecific communities. The presence of *Corolia placunoides* indicates a firm substrate, slow sedimentation rates and nutrient-rich community, with low-salinity conditions during regressed shoreline and sea-level fall [44]. Therefore, the frequently high abundance of the *Carolia placunoides* fossil assemblage within the studied Eocene rocks indicates deposition in a nearshore, lagoonal environment across a marginal-marine setting. A comprehensive palaeoecological study of a similar *Carolia*-dominated assemblage in the nearby Faiyum Depression indicated that the predation and parasitic elements, as well as changing environmental conditions were the main factors that caused the extinction of the genus *Carolia* in the latest Eocene in Egypt [45]. Increased water turbidity during post-middle Eocene might also create stressful conditions for such autotrophic taxa causing decrease of their frequency and abundance, and ultimately led to their entire extinction [46].

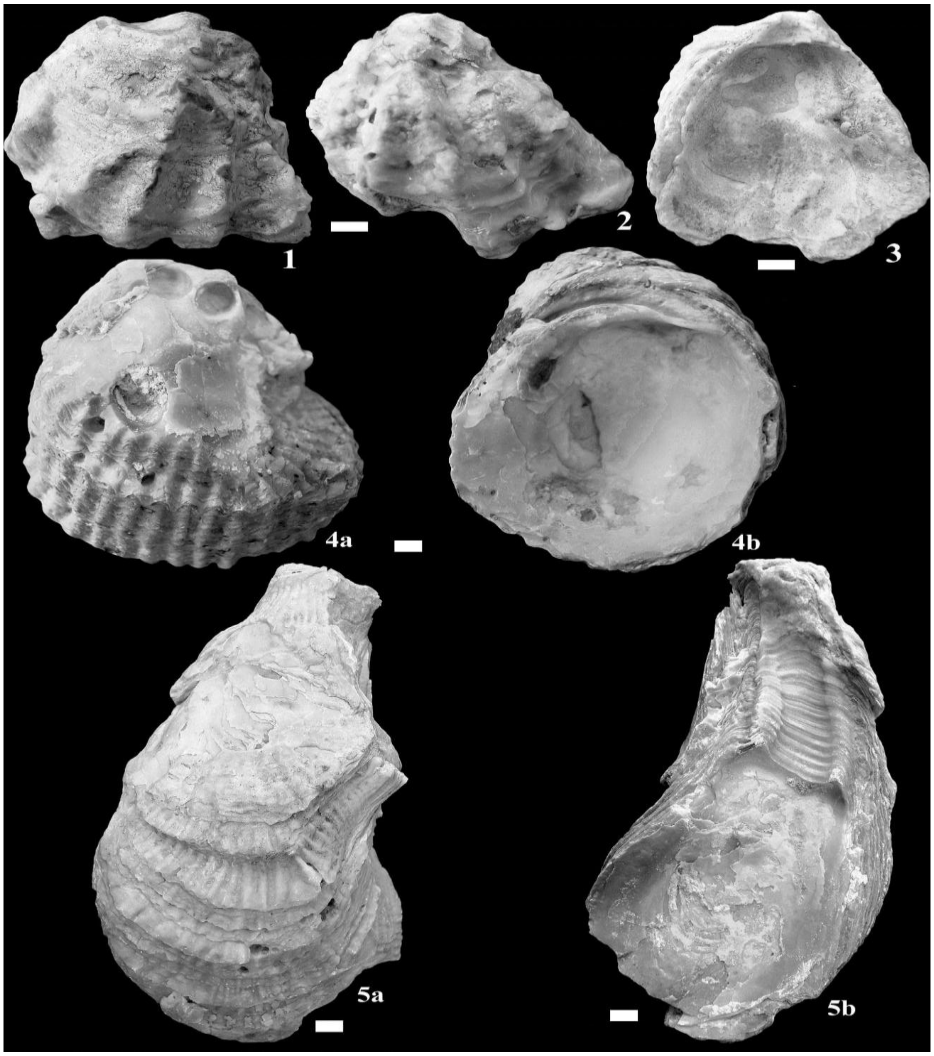

Fig. 7. Benthic macrofossil photographs showing: **1–3** ***Nicaisolopha clotbeyi*** (Bellardi, 1854); **1, 2** external views of the left valves, **3** internal view of left valve. **4** ***Turkostrea multicostata*** (Deshayes, 1818); **4a** external view of left valve, **4b** internal view of left valve. **5** ***Turkostrea recta*** (Oppenheim, 1903); **5a** external view of left valve, **5b** internal view of left valve. The bar scale is 10 mm.

6.2.5. *Nicaisolopha clotbeyi*-dominated assemblage

This fossil assemblage is recorded from the limestone beds of the El-Hamra Formation in the El-Gara El-Hamra, El-Bahr and Teetotum Hill sections. They form several lags of oyster shell concentrations, produced mainly by multiple reworking associated with winnowing of fine-grained sediment. This faunal assemblage includes high diversity of other epipelagic, euphotic, shallow warm water organisms such as *Carolia placunoides*, *Masalia locardi*, *Masalia blanchenhorni*, *Cerithium* sp., and *Vulsella crispat*a, indicating inner neritic, eutrophic conditions of high nutrient levels and slow sedimentation rates.

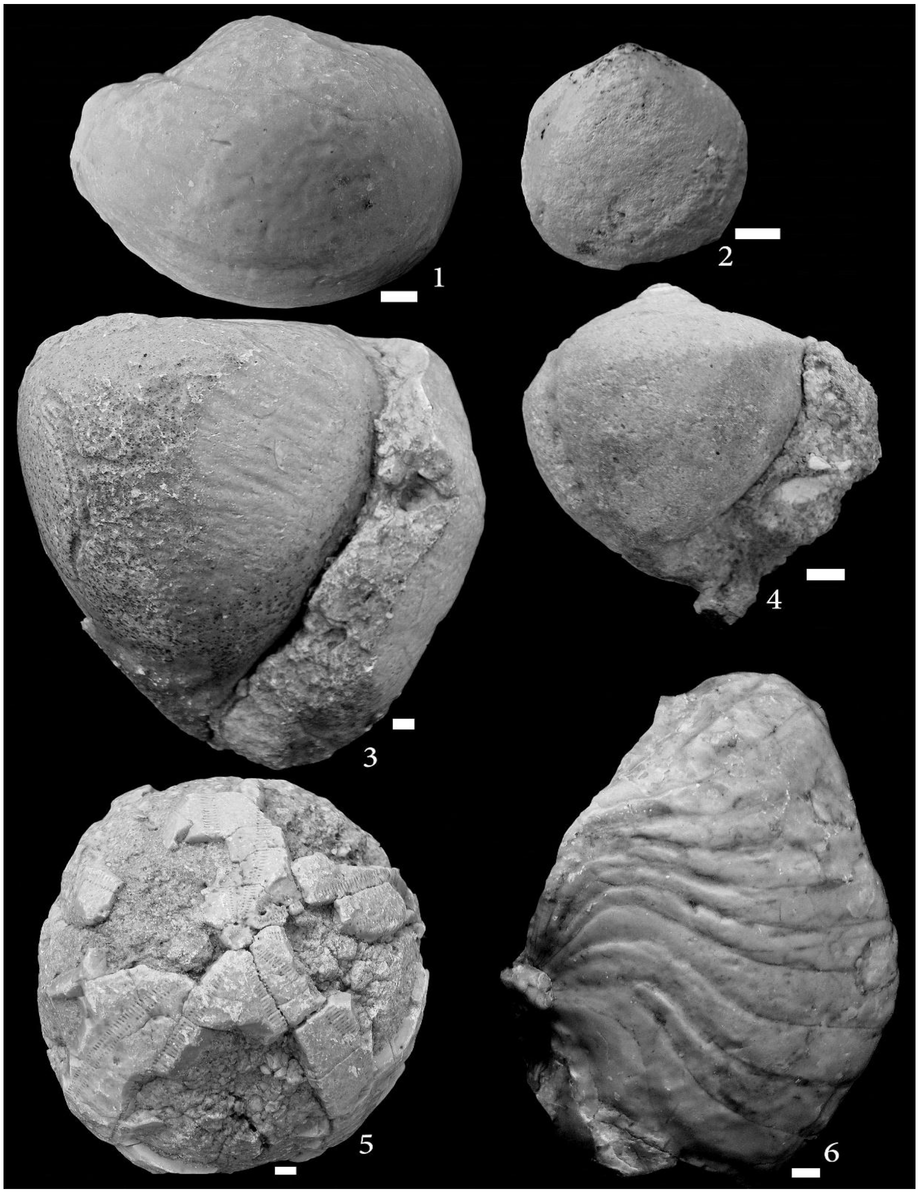

Fig. 8. Benthic macrofossil photographs showing: **1** ***Lucina thebaica*** (Oppenheim, 1903), external view. **2** ***Lucina polythele*** (Oppenheim, 1903), external view. **3** ***Gisortia ibrahimi*** (Abbass, 1967). **4** ***Heligmotoma* sp.,** apertural view. **5** ***Conoclypus delanouei*** (De Loriol, 1880), adapical view. **6** ***Deltoidonautilus* sp.,** side view. The bar scale is 10 mm.

6.3. Regional palaeobiogeographic distribution

Inner to mid-ramp foraminiferal accumulations occur abundantly along the continental margins of the Tethys. They are dominated by larger benthic foraminifera (LBFs) including nummulitids, alveolinids, orbitolitids, assilinids and orthophragminids [47, 48, 49]. The detailed petrographic study of LBFs biofacies is essential to elucidate the paleodepositional settings of such shallow carbonate ramps. In the study area, the faunal assemblages, either the benthic larger foraminifera or benthic macrofossils identified from the studied Eocene successions have a dominantly Tethyan affinity. Both faunal assemblages reflect shallow subtidal, restricted and open lagoonal to reefal palaeoenvironments of marginal-marine carbonate ramps. Similar assemblages of larger benthic foraminifers (LBFs) particularly those of orbitolites, nummulites and alveolines were recorded from different Eocene successions in the African, Arabian, Indian, Middle East and southern Europe shallow carbonate platforms (Fig. 9). In northern Africa, for example, these foraminiferal assembalges were registered from the Eocene rocks exposed in different localities in Egypt e.g., Bahariya, Siwa and Faiyum depressions, Gebel Mokattam, Helwan area, Gebel Ataqa-Northern Galala blocks and along the Cairo–Suez district [50, 51]. Similar Eocene foraminiferal species were also recorded from the subsurface Gialo Limestone in the Sirt Basin in Libya [52], the Halk El-Menzel and El-Garia formations of the Pelagonian shelf along offshore Tunisia [53], and the Karkar Formation in Somalia [54]. The Paleocene–Eocene foraminiferal limestone facies form significant hydrocarbon reservoirs in offshore Tunisia and Libya [55]. In the Arabian–Iranian–Indian carbonate platforms, these foraminiferal taxa were described from the Dammam Formation in Dhofar of Oman [56], the Naopurdan Shaly Series in Iraq [57] the Jahrum Formation in the Zagros of Iran [58] and the middle Eocene Fulra Limestone and Oligocene Maniyara Fort Formation at the north-western margin of India [59] In southern Europe, similar foraminiferal assemblages were also recorded from the Eastern Taurides in southern Turkey [14, 60], the Bartonian Capo Mortola Calcarenite Formation from Olivetta San Michele in NW Italy [46], the middle/upper Eocene boundary in the Veneto area in northern Italy [61] the Ebro basin in Spain [62] and many other countries in the northern bank of the Mediterranean basin.

Likewise, many benthic macrofauna such as *Turkostrea multicostata*, *Carolia placunoides, Vulsella crispata* and Turritellid gastropods identified from the studied Eocene successions display a widespread palaeobigeographic distribution in the northern, southern and western Neo-Tethyan regions (Fig. 9). For example, *Turkostrea multicostata* was recorded from the the Paleocene sediments in Tunisia [63] and Algeria [64] in northern Africa, as well as from the Paleocene sediments formed in the trans-Saharan seaway in Mali [65]. By the advent of the Eocene, *Turkostrea multicostata* widely spread into India, northwestern Europe and covered the whole northern African regions in the southern Neo-Tethys [45]. For instance, it is recorded from the lower Eocene sediments in Mauritania and Senegal [66]. in north-western Africa, and from lower Eocene sediments in north Sudan in north-eastern Africa [67] The fossil *Turkostrea multicostata* is also recorded from the middle and late Eocene rocks in Senegal, Morocco, Libya and Egypt [37, 68, 69].

The fossil *Carolia placunoides* Cantraine, 1838 was recorded from the lower Eocene sediments in Senegal in north-western Africa [70] as well as from the lower Eocene rocks in Egypt and Indian-Pakistani region, and spread out all over the Neo-Tethyan domain. In the middle and late Eocene, *Carolia placunoides* exhibited a wider geographic distribution, since it is recorded from the middle Eocene rocks in Senegal [70] Mali [71] in north-western Africa, Tunisia [72] and Algeria [73] in northern Africa. The fossil *Carolia placunoides* was also recorded from the upper Eocene rocks in the south-eastern Tethys provinces in Libya [74] and Egypt [45, 75, 76].

The fossil *Vulsella crispata* was recorded from the middle and upper Eocene sediments in Libya and Egypt in north-eastern Africa [77, 78].

From the foregoing discussion, it can be summarized that many of the identified early–late Eocene benthic foraminiferal and macrofaunal assembalges in the Bahariya study area have a broad geographic distribution covering large tracts throughout the African, Arabian, Middle East and southern Europe marginal-marine carbonate platforms.

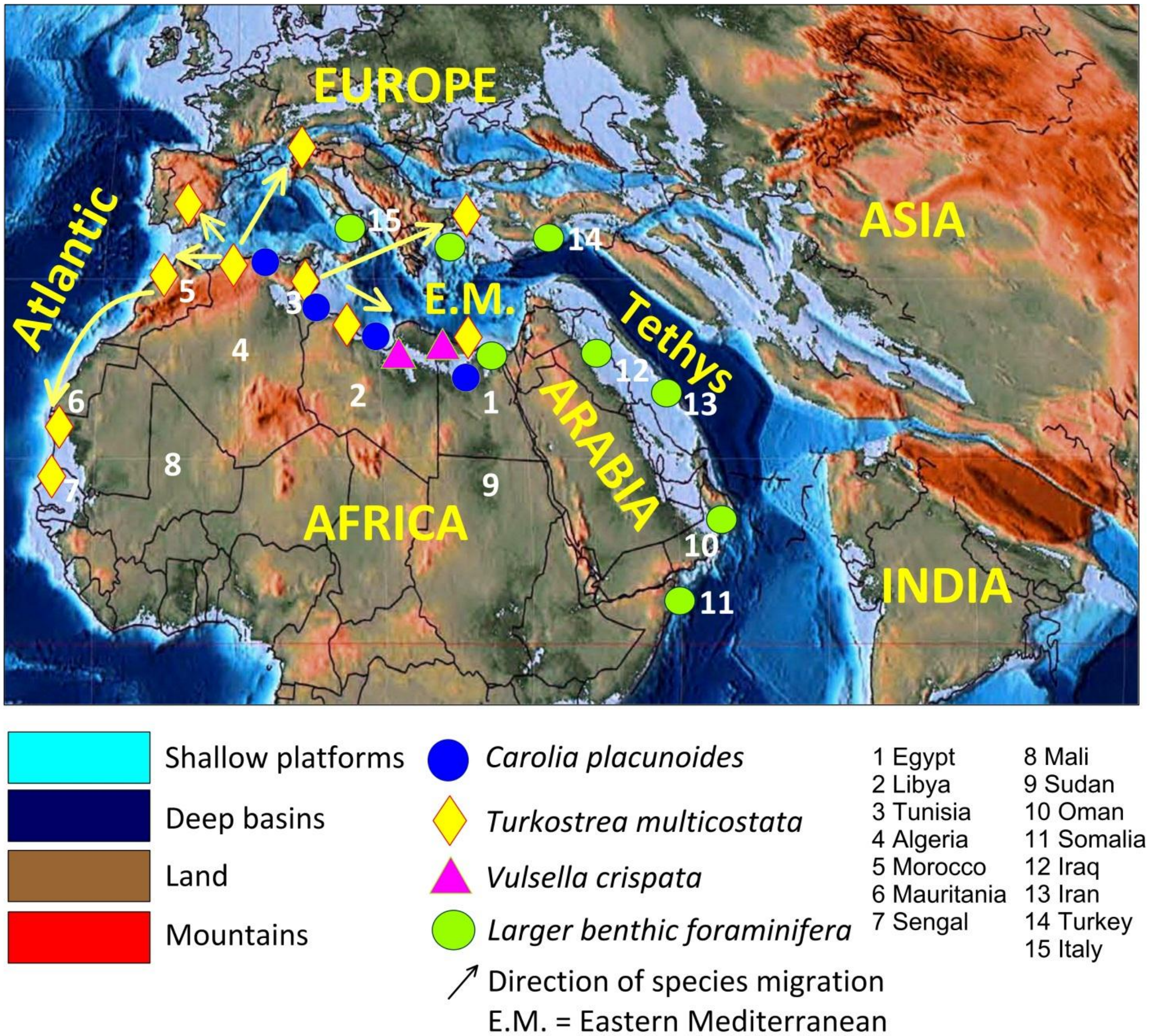

Fig. 9. Palaeogeographic map illustrating the distribution of some Eocene larger benthic foraminifera and macrofauna across northern African, Mediterranean and Tethyan (remnant) territories (the palaeogeographic map is sourced from [79].

7. Conclusions

The Eocene rocks cropping out in the northern Bahariya Depression constitute from base to top, the Naqb, Qazzun and El-Hamra formations deposited in shallow-marine, neritic (littoral and sublittoral), tide-dominated environments positioned on a gently dipping inner to very proximal mid-ramp settings. Four local larger benthic foraminiferal zones, corresponding to the regional larger benthic foraminiferal zones (SBZ12 to SBZ19) of the Tethyan shallow carbonate platforms, were identified. These zones allowed assigning a late Ypresian age to the Naqb Formation, an early Lutetian age to the Qazzun Formation, and a middle Lutetian–Priabonian age to the El-Hamra Formation. Five distinctive macrofossil assemblages were also identified. These benthic fauna were predominantely inhabited in the inner neritic-epipelagic, near-coast tide-dominated zone (<100 m depth), which is characterized by warm water with normal to restricted salinity, and sluggish to open water circulation necessary for carrying nutrients to the lagoons and reefs. Apparently, there was a significant upward change of paleoecological attributes across the lower–upper Eocene succession triggered by variation in neritic siliciclastic inflow due to tectonic and climatic instability. Paleobiogeographically, the identified foraminiferal and macrofaunal assemblages have a dominantly Tethyan character, displaying strong affinity to the African, Arabian, Indian-Iranian and southern Europe marginal-marine carbonate platforms.

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