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ORIGINAL PAPER

Stratigraphy, facies, and depositional environments of the Paleogene sediments in Cairo–Suez district, Egypt

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Abstract The study of eight stratigraphic sections along Cairo–Suez district, between Gebel Ataqa and Gebel Mokattam, reveals a thick Lower Eocene Ypresian carbonate section, approximately 210 m thick, at Gebel Abu Treifiya just to the west of Gebel Ataqa. It is represented by the Minia Formation rich in *Nummulites praecursor*, *Orbitolites pharaonum* Schwager, *Alveolina frumentiformis* Schwager, and one of the precursors of *Nummulites gizehensis* group. The Minia Formation is a fairly clear, warm, and shallow marine facies. The Middle Eocene Lutetian sediments are totally missing in all studied sections probably reflecting instability in deposition echoed in the active block movements the area witnessed since the Paleozoic. The Bartonian sea transgressed over the area depositing Gebel Hof Formation at the base, Observatory Formation in the middle, and Qurn Formation at the top. The Gebel Hof Formation was deposited in an open-marine environment, passed upward into shallow marine, neritic to reefal facies; for the Observatory and Qurn formations, the former changed laterally into a sheltered lagoon facies, Sannor Formation, rich in *Somalina stefaninii* Silvestri, *Dictyoconus aegyptiensis* Chapman, and *Idalina cuvillieri* Bignot and Strougo. The Upper Eocene sediments, Maadi Formation, are mainly represented by a carbonate–clastic section showing shallowing-upward cycles resulted by the retreating of the sea shoreline northward during the Late Eocene, with high supply of terrigenous sediments. The lower carbonate cycle of the Maadi Formation was deposited in a restricted platform and tidal flats, whereas the upper siliciclastic cycle containing *Carolia placunoides* banks was probably deposited in a winnowed platform edge. These depositional environments were developed in grabens, ramps, and footslopes of the down-faulted Middle Eocene blocks, i.e., syn-tectonic deposition. The fluviatile Oligocene sediments were highly controlled by the structural and topographic lows, where a substantial thickness was deposited, Gebel Ahmer Formation, occupying several grabens and gently sloping areas between many synthetic faults.

Keywords Stratigraphy · Eocene · Oligocene · Correlation · Microfacies analysis · Depositional environments · Geologic history · Cairo–Suez district, Egypt

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Introduction

The study area along Cairo–Suez district between Gebel Ataqa in the east and Gebel Mokattam in the west (Fig. 1) exposes a relatively thick sequence of Paleogene sediments. These sediments were greatly influenced by the events which prevailed over the Red Sea and Gulf of Suez regions during the early stages of the Eocene and continued to the Late Miocene (Patton et al. 1994). The most common event was the Gulf of Suez rifting, which resulted in the displacement of many blocks relatively to each other giving rise to a complex stratigraphic setting on both sides of the Gulf (Steckler et al. 1988; Issawi 2002, 2005; Osman 2003; Issawi et al. 2009).

The stratigraphy of the Paleogene sediments in Cairo–Suez district has been dealt with by many authors since Barron (1907) who first classified the Eocene strata in this district into different rock units. Some authors e.g., Barakat and Abou Khadrah (1971), Abdel Shafy and Ismail (1988), and Awad et al. (2002) used the formational names of the Greater Cairo Area facies: Minia, Mokattam, and Maadi formations to describe the Eocene rock units exposed in the area studied (Geological Map of Greater Cairo Area, scale 1: 100.000, 1983). Others, e.g., Strougo and Abdallah (1990), Morsi

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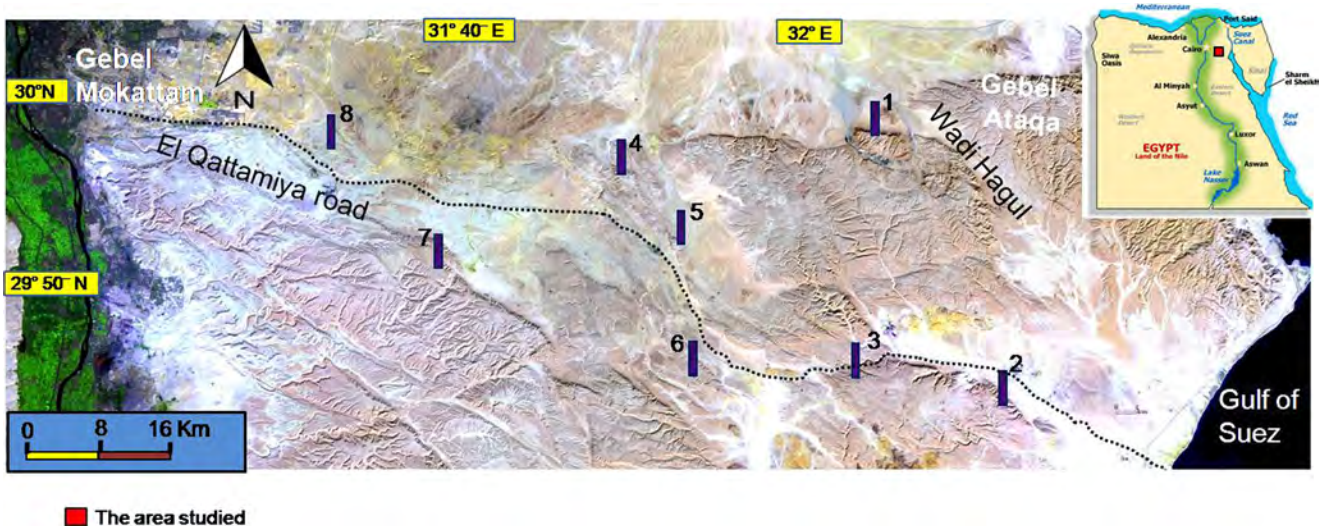

Fig. 1 ETM+ image of the study area showing the location of the studied sections: *1* Gebel Abu Treifiya, *2* Gebel Akheider, *3* Gebel El Ramliya, *4* Gebel El Qattamiya, *5* Gebel Umm Reheiat, *6* Wadi Gharaba, *7* Gebel Abu Shama, and *8* Bir Gindaly

(1991), Strougo et al. (1992), Abul Nasr et al. (1993), and El Safori et al. (1997) followed those of Helwan facies: Gebel Hof, Observatory, Qurn, Wadi Garawi, and Wadi Hof formations. El Akkad and Abdallah (1971) introduced two other formational names in Gebel Ataqa namely Suez Formation at base and Ramiya Formation at top. The two formations were considered of Middle Eocene age (Lutetian) by these authors following Sadek (1926) on the assumption of the identification of *Nummulites gizehensis* Lamark. Later, Osman (2003) redefined this fossil as *Orbitolites* sp. cf. *complanatus* Lamark of Early Eocene age (Ypresian); therefore, he assigned the age of the Suez Formation containing this index fossil to the Ypresian coeval with the Minia Formation in the Nile Valley. On the other hand, Osman (op. cit) relegates the Ramiya Formation including *Somalina stefaninii* Silvestri, *Dictyoconus aegyptiensis* Chapman, and *Idalina cuvillieri* Bignot and Strougo to the Bartonian. Barakat and Abou Khadrah (1971) studied the Eocene section of Gebel Abu Treifiya where they recognized the Minia Formation at the lowermost part of the section, 21 m thick, assigning its age to the early Lutetian, whereas the remaining 183 m thick of the section was assigned to the late Lutetian. They (op. cit) did not record any of the Lower Eocene rocks in Gebel Abu Treifiya. However, Osman (2003) at the nearby Ataqa block recorded the Lower Eocene Suez Formation, *ca*. 224.2 m thick, overlying unconformably the Maastrichtian Maghra El Bahari Formation. Moustafa (1980) recognized the Minia Formation, *ca*. 79.8 m thick, at the base of Gebel Abu Treifiya, assigned its age to the early Lutetian, whereas he (op. cit) introduced a new formational name (Abu Treifiya Formation) for the overlying rock unit, assigned its age to the late Lutetian. In this context, the Abu Treifiya Formation is a misnomer since it is coeval to the Mokattam Formation, a name which is important in the Eocene stratigraphy in Egypt (Said 1962).

The facies changes the units suffer in the study area within the Eocene sections have a great impact on the confusion among the workers in the area. Added to this dilemma, the problem is even complicated by the non accurate fossil identification hence building an erroneous stratigraphic sequence. The main target of the present work is to revise the stratigraphy of the Paleogene sediments in Cairo–Suez district between Gebel Ataqa in the east and Gebel Mokattam in the west helped by detailed field and paleontologic studies. The exposed rock units in the study area fall within a span of time beginning with the late Early Eocene in the east followed westward by other different rock units of Eocene and Oligocene time units. The Paleocene sediments are totally missing or not exposed in the study area. The present work aims also to fix the stratigraphic limits between the many stages of the exposed sediments. Unconformities, lateral and vertical facies changes will be identified, leading to the understanding of the geological history of the area. Microfacies analysis of the proposed rock units is carried out to estimate their depositional environments. The interpretation of local conditions within the frame of global and regional events will be dealt with, enriching the geological picture of the area studied.

Material and methods

The present study includes data gathered during the field work augmented with laboratory analyses. Eight stratigraphic sections along Cairo–Suez district have been logged, sampled, and described with respect to the sedimentary structures, textures, and biotic content. These sections are the following: Gebel Abu Treifiya, Gebel Akheider, Gebel El Ramliya, Gebel El Qattamiya, Gebel Umm Reheiat, Wadi Gharaba, Gebel Abu Shama, and Bir Gindaly sections (Fig. 1). All these sections exhibit diversity in the sedimentary facies, thickness, and extension. Some of limestone samples were crushed and washed, and the different forams were picked-up. The larger benthic foraminifera and ostracods were precisely identified thus assigning exact age for the concerned strata. About 150 rock samples were petrographically studied to define the depositional environments of the concerned formations.

Stratigraphy

The stratigraphic succession in the study area ranges in age from the late Early Eocene to the Oligocene. The Neogene sediments are exposed outside the study area at Wadi Ghoweiba, Wadi Hagul, and to the north at Gebel Iweibed, Gebel Homeiyra, and Gebel Gharra. Quaternary sediments constitute alluvial terraces and cover the wadis floors. The central part of the Cairo–Suez district consists of a nearly parallel, high mountain ridges trending in an E–W and NW–SE directions with lowlands in-between. The Middle Eocene rocks mainly build the mountains and high scarps overlooking both sides of the Qattamiya–Ain Sukhna road, while both the Upper Eocene and Oligocene sediments fill the low topographic areas (grabens). Detailed field studies have proved that the Paleogene succession in the study area consists stratigraphically of seven different rock units arranged from base to top: Minia Fm., (TelMn), Gebel Hof Fm., (TemHo), Observatory Fm., (TemOb) coeval with Sannor Fm., (TemSn) in the eastern part of the study area, Qurn Fm., (TemQn), Maadi Fm., (TeuMd), and Gebel Ahmer (ToAh) Formation. In general, the first six lithostratigraphic units represent the different stages of the Eocene, while the last belongs to the Oligocene. A simplified geologic map of the study area is given (Fig. 2), whereas Fig. 3 is a chronostratigraphic correlation chart of the studied sections. In addition to the sedimentary rocks, some volcanic sheets mostly basalts, were recorded from several places along Cairo–Suez district. They were recorded at Gebel Abu Treifiya, surrounding it from all sides except the northern face and also recorded to the south of Gebel Umm Reheiat along the Qattamiya–Ain Sukhna road, constituting prominent hillocks. The basalts were extruded as a result of the rejuvenation of the E–W and NW–SE normal faults during late Oligocene and Early Miocene (Said 1962). These basalts were assigned by Meneisy and Abdel Aal (1984), using K/Ar method, to the late Oligocene—early Miocene (Aquitanian; 22±2 Ma.).

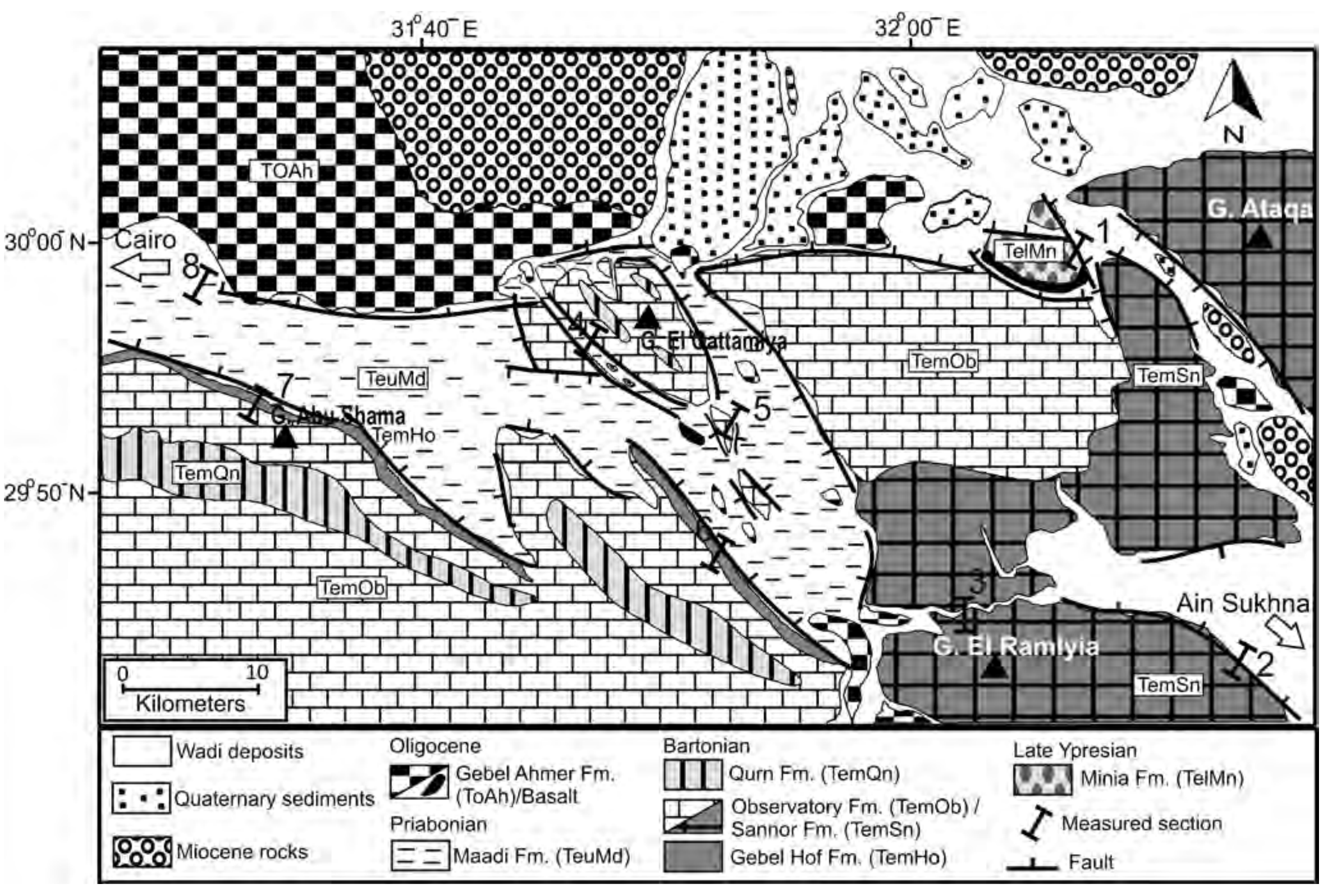

Fig. 2 Geologic map of the studied area (modified from Said 1962). Map labels: *T* tertiary, *e* Eocene, *l* lower, *m* middle, *u* upper, *o* Oligocene, *Mn* Minia, *Ho* Gebel Hof, *Ob* Observatory, *Qn* Qurn, *Sn* Sannor, *Md* Maadi, and *Ah* Gebel Ahmer

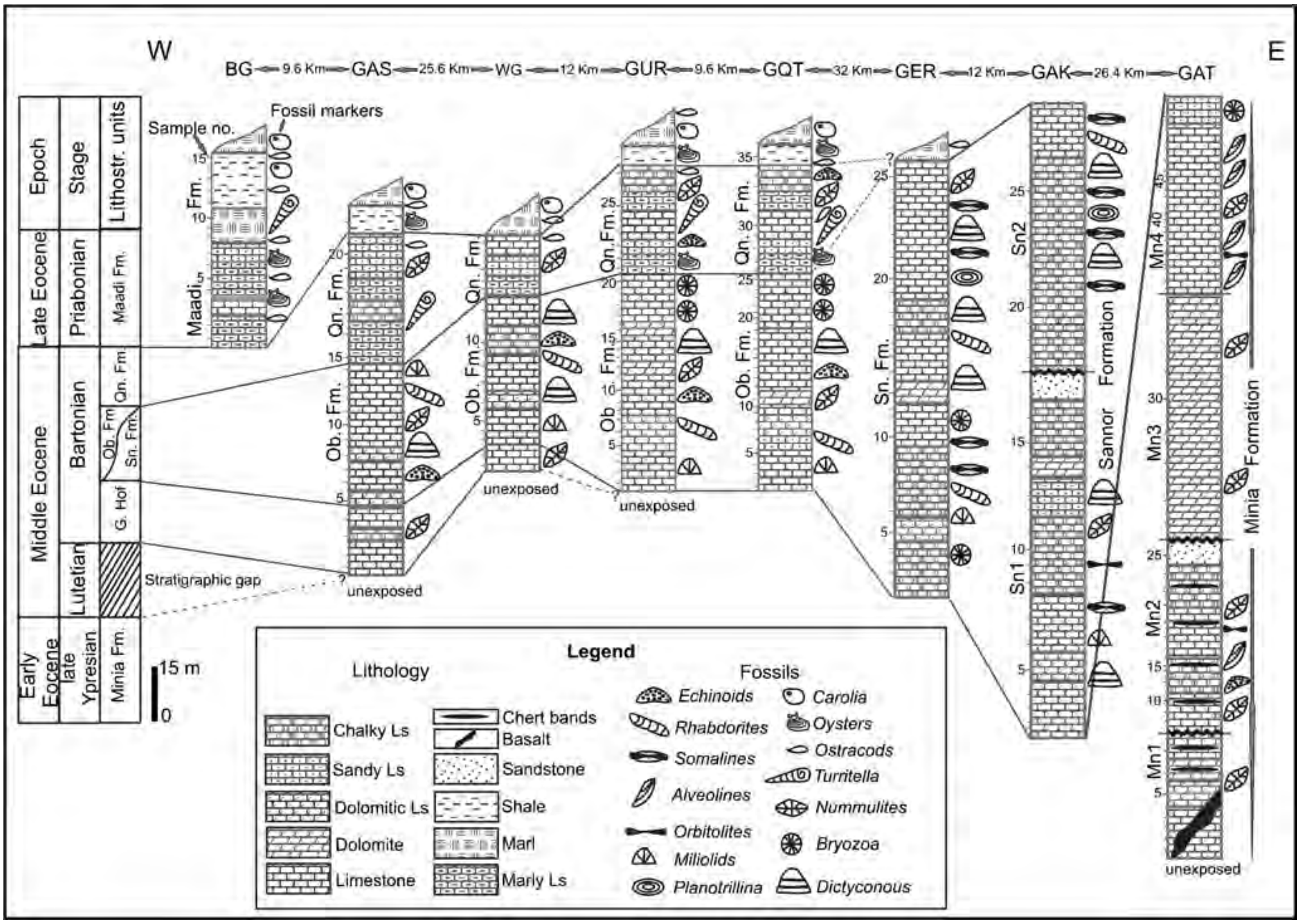

Fig. 3 Chronostratigraphic correlation of the Eocene rock units exposed in the study area. Section labels: *GAT* Gebel Abu Treifiya, *GAK* Akheider, *GER* Gebel El Ramlyia, *GEQ* Gebel El Qattamiya, *GUR* Gebel Umm Reheiat, *WG* Wadi Gharba, *GAS* Gebel Abu Shama, and *BG* Bir Gindaly

A detailed description of the different rock units exposed in the study area is given below, from oldest to youngest.

Minia Formation (TelMn)

The term Minia Formation was introduced by Said (1960) to replace Zittel's upper Libyan (1983) including about 35 m section of thick-bedded, white, alveolinid limestone including *Alveolina frumentiformis* Schwager and *Orbitolites* sp. cf. *complanatus* Lamarck at its type locality: Zawiet Saada, opposite Minia City. In the Nile Valley, it conformably overlies the Ypresian Thebes Formation and underlies the white milky limestone of the Samalut Formation (Bishay 1961).

Based on larger benthic foraminifera, the present authors recognized the Lower Eocene Minia Formation only at Gebel Abu Treifiya, whereas it is missing in other sections. It represents the oldest Eocene rock unit exposed in the study area. However, Barakat and Abou Khadrah (1971) though they recorded the Minia Formation at the base of Gebel Abu Treifiya, however, they assigned its age to the Middle Eocene (Lutetian). The thickness of the Minia Formation at Gebel Abu Treifiya attains approximately 210 m, mainly composed of thick-bedded limestone, gray to whitish gray, white to snow-white, dolomitized in places, and chalky in others. The Minia Formation is poor in foraminiferal content at the lowermost beds, including well-marked chert bands and nodules, enriched in nummulites and alveolines upward.

The Minia Formation exposed at Gebel Abu Treifiya can be lithologically subdivided into four different members (Fig. 4a), occupying small areas, hard to map to a reasonable scale.

The first basal member (Mn_1) of the Minia Formation assumes a thickness of about 35 m, decreases westwards due to the tilting of Abu Treifiya block to the west and southwest directions, and sinking below the second member (Mn_2) of the Minia Formation. The first member (Mn_1) mainly consists of poorly fossiliferous limestone, gray to whitish gray, very hard, dolomitized in places, thin bedded, and highly pitted at the lower beds including well-marked chert bands (30–40 cm thick) resulted by the replacement diagenesis of the limestones and dolomites of this member. The base of the first member is not exposed where thick basalt dykes and sills were intruded (Fig. 4b).

The second member (Mn_2) of the Minia Formation assumes a thickness of about 55 m, mainly composed of nummulitic limestone (Fig. 4c), snow-white, thick bedded,

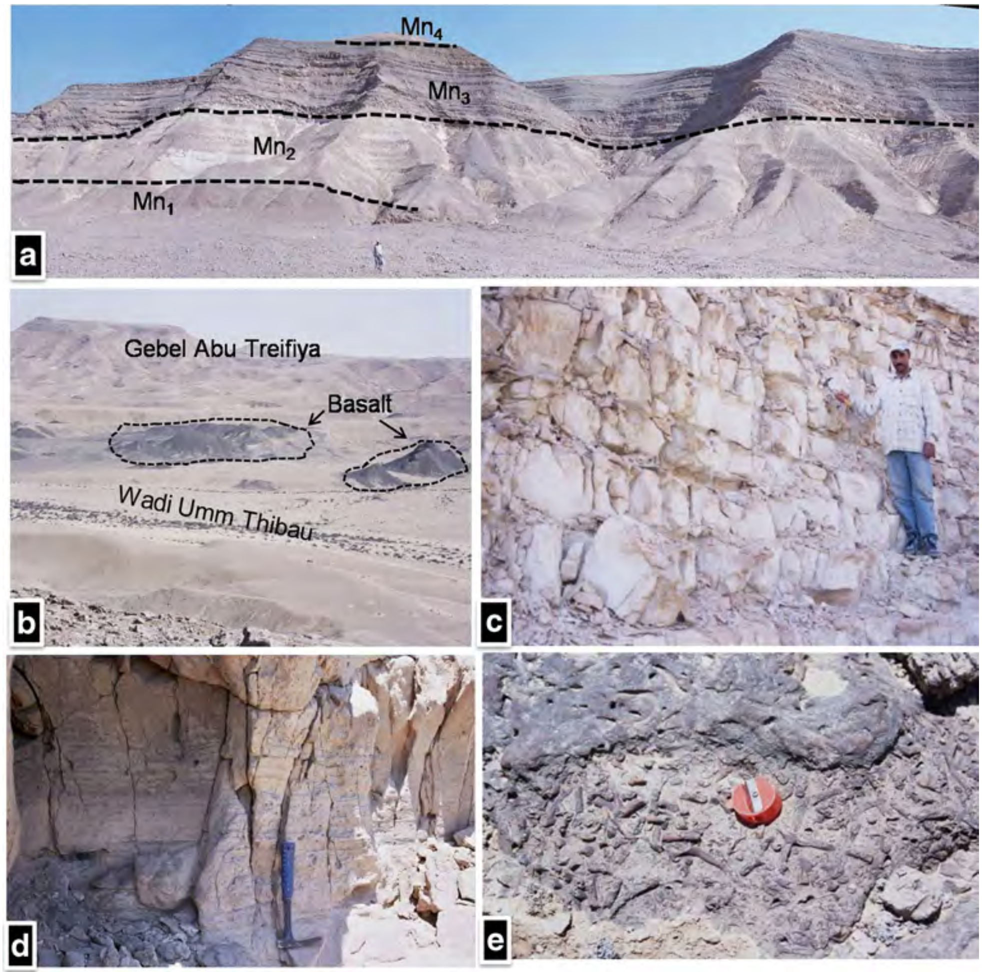

Fig. 4 The Minia Formation exposed at Gebel Abu Treifiya. **a** Panorama showing the different members of the Minia Formation (Mn_1–Mn_4) at the northern face of Gebel Abu Treifiya. **b** Basalt flows intruded in the base of the first member (Mn_1) of the Minia Fm. **c** Thickly bedded nummulitic limestone of the second member (Mn_2) of Minia Formation rich in *Nummulites praecursor* and *Orbitolites pharaonum* Schwager, alternating with thin chert bands. **d** Sandstone bed (paleosol) in-between the second and third members (Mn_2, Mn_3) of the Minia Formation. **e** Siliceous bryozoan limestone bed covering the fourth member (Mn_4) of the Minia Formation

chalky in some places and crystalline in others, and rich in larger benthic foraminifera and echinoids. Chert bands and nodules are also common. An angular unconformity is detected between the first and the overlying second member of the Minia Formation, where the beds of the first member (Mn_1) is steeply dipping (40–50°) due southwest, whereas the overlying beds of the second member (Mn_2) are dipping (20°) toward the west and southwest directions. The second member is unconformably overlain by the beds of the third member (Mn_3) with an erosional surface represented by 2.5-m-thick paleosol horizon, pinkish and earthy gray, hard, and coarse to medium-grained sandstone (Fig. 4d). Paleontologically, the second member (Mn_2) of the Minia Formation yields some benthic foraminiferal species as *Nummulites praecursor* (Fig. 5a, b), *Orbitolites pharaonum* Schwager (Fig. 5c), one of the precursors of *Nummulites gizehensis* group (Fig. 6a–f), and *Nummulites* spp., the occurrence of which indicates the late Ypresian age for this member, a result that matches well with the conclusion of Boukhary and Abdelmalik (1983) that the age of the Minia Formation is late Early Eocene (Cuisien).

The third member (Mn_3) of the Minia Formation is mainly composed of a cliff-forming, thick-bedded, gray, dark gray to brown very hard, dolomitic limestone, assuming a thickness of approximately 65 m. The nummulites in this unit are common, but they are completely dolomitized leaving voids in situ. This member is conformably overlain by the fourth member (Mn_4) of the Minia Formation with a gradational contact in-between. The stratigraphic position of the (Mn_3) in-between the late Ypresian (Mn_2) and (Mn_4) suggests the same age for this member.

The fourth member (Mn_4) of the Minia Formation consists of alveolinid limestone, grayish white to yellowish, thin bedded, hard, bioturbated in places, chalky in others, and rich in larger benthic foraminifers, alveolines, serpulids, and bryozoan remains. This member forms a vertical wall, attaining approximately 55 m thick, and capped by 0.5-m reddish brown, hard, siliceous bryozoan limestone crust reflecting shallowing-upward sequence (Fig. 4e). Paleontologically, the fourth member (Mn_4) of the Minia Formation is very rich in *Alveolina frumentiformis* Schwager (Fig. 5d–f) indicating also late Ypresian age.

The relationships between the different members of the Minia Formation show a highly seismic, uneven precipitation of these units. The unconformity in-between the two lower members, (Mn_1) and (Mn_2), and also the paleosol layer in-between (Mn_2) and (Mn_3) ascertain this approach.

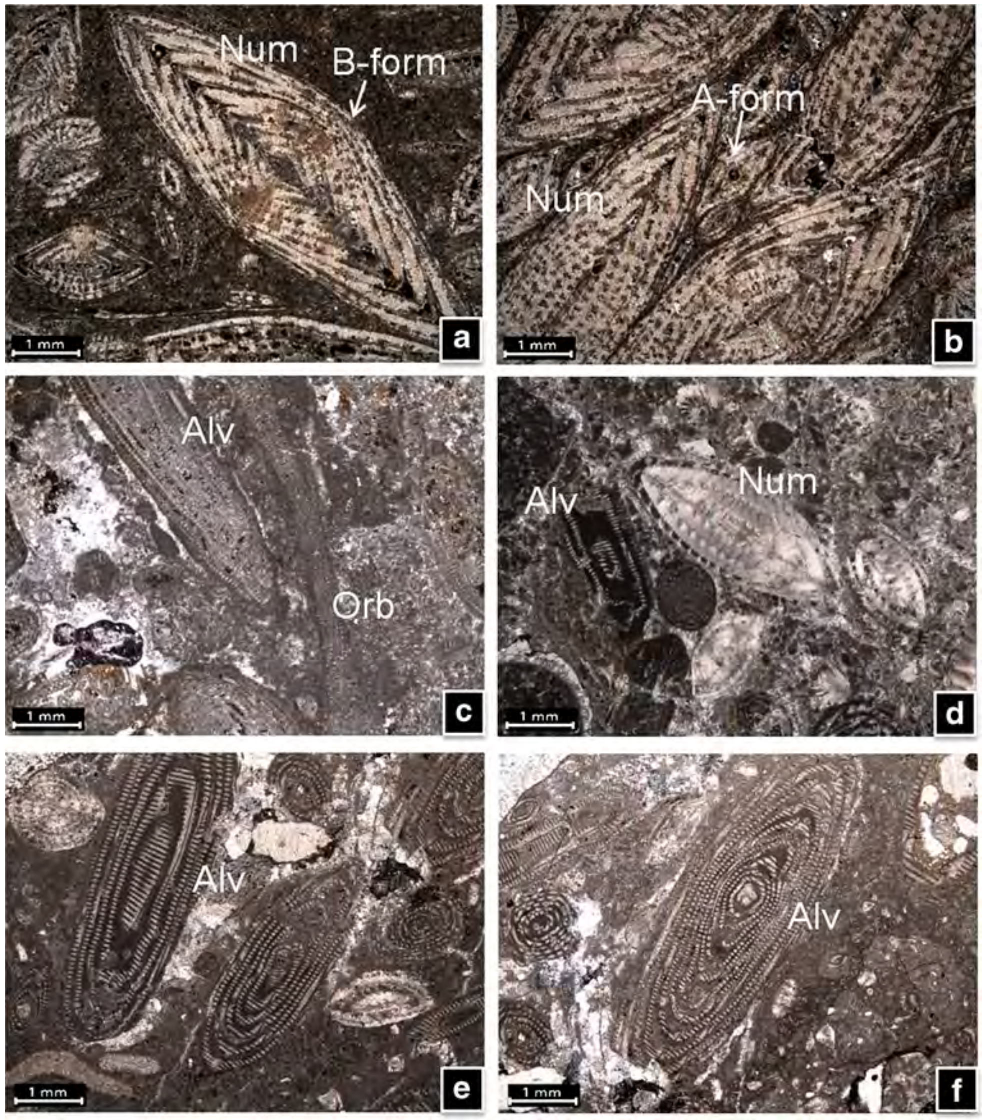

Fig. 5 Larger benthic foraminifera of the late Ypresian Minia Formation, Gebel Abu Treifiya **a**, **b** *Nummulites praecursor* (*Num*), Mn_2, samples 8–10 **c** *Orbitolites pharaonum* Schwager (*Orb*), axial section and *Alveolina frumentiformis* Schwager (*Alv*), Mn_2, samples 18, 36. **d**–**f** *Alveolina frumentiformis* Schwager (*Alv*) and *Nummulites* spp. (*Num*), Mn_4, samples 34–49

Gebel Hof Formation (TemHo)

This rock unit was proposed by Farag and Ismail (1959) to describe about 120-m-thick section of white limestone, chalky at base, alternated with thin bands of hard dolomitic limestone at its type locality in Gebel Hof (Helwan area).

The Gebel Hof Formation has a limited distribution throughout the study area. It is exposed at the base of two sections: Gebel Abu Shama and Wadi Gharaba. The exposed thickness of Gebel Hof Formation at Gebel Abu Shama ranges from 15–18 m, which considerably decreases eastward to about 8.0 m at Wadi Gharaba. In both sections, the basal contact between Gebel Hof Formation and the underlying rock unit is not exposed; therefore, the 18 m should be considered here a minimum thickness. The Gebel Hof Formation is conformably overlain by the Observatory Formation with a gradational contact in-between. Lithologically, the Gebel Hof Formation at Gebel Abu Shama is mainly composed of nummulitic limestone, gray to grayish white, hard, thin bedded, sandy in places, and slope forming. At Wadi Gharaba section, the Gebel Hof Formation is mainly composed of thin-bedded, white to yellowish white, hard, sandy, bioturbated, and nummulitic limestone including dolomitic limestone bands.

Paleontologically, the Gebel Hof Formation at Gebel Abu Shama and Wadi Gharaba sections yields the following foraminiferal species: *Nummulites bartovigatus* Boukhary and Hussein (Boukhary et al. 2002) (Fig. 6g–j) and *Nummulites migiurtinus* Azzaroli. These foraminiferal species suggest Bartonian age for Gebel Hof Formation.

Observatory Formation (TemOb)

This formation was introduced by Farag and Ismail (1959) describing about 80 m, white to golden-tan, marly, and nodular limestone section from the Observatory Plateau, east of Helwan. It was considered of Lutetian age by these authors.

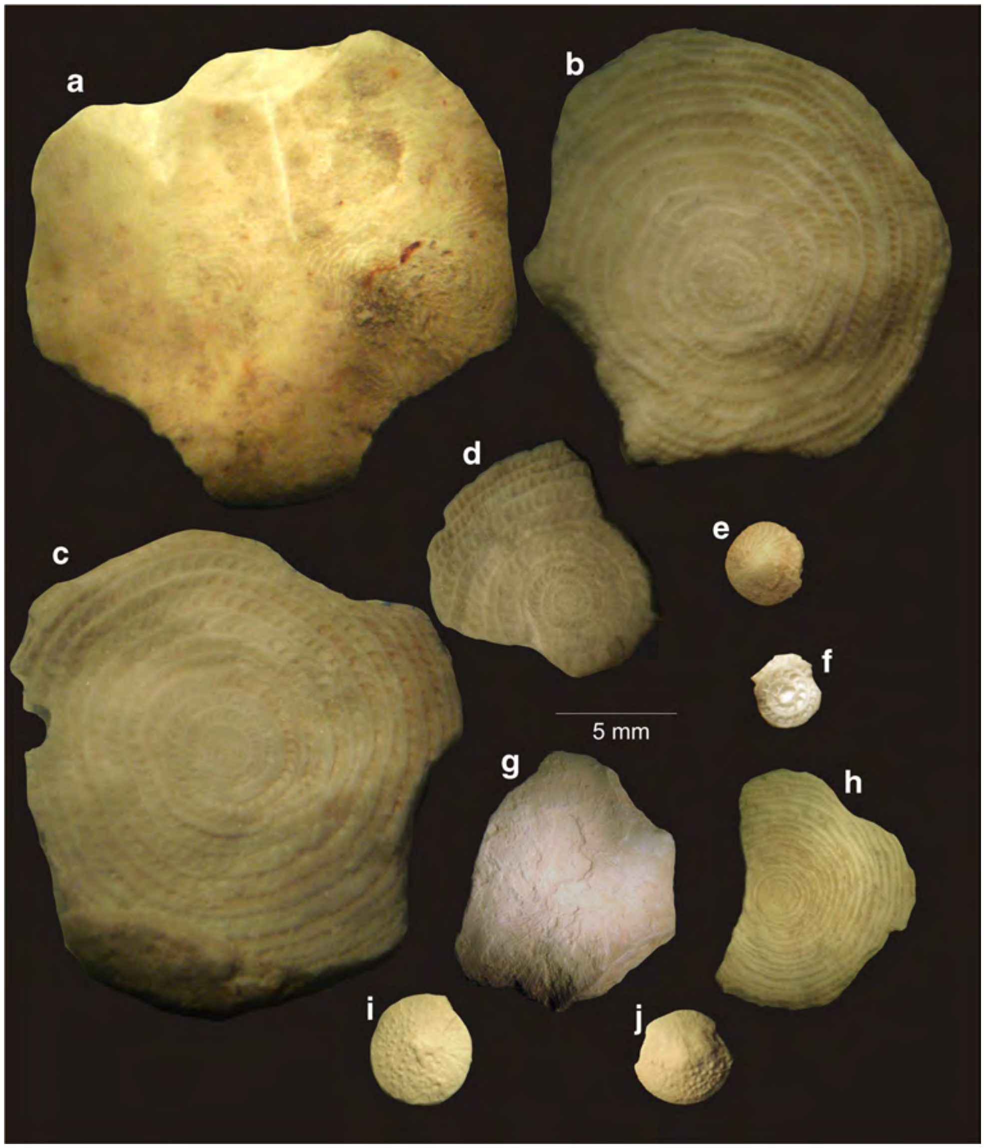

Fig. 6 **a**–**f** *Nummulites* sp. cf. *gizehensis* (precursor of *Nummulites gizehensis* group), Minia Fm., Gebel Abu Treifiya: **a**–**d**, microspheric form: **a** external and **b**–**d** equatorial section; **e**, **f** megalospheric form: **e** external and **f** equatorial section. **g**–**j** *Numnmlites bartovigatus* Boukhary et al. 2002, Gebel Hof Fm., Gebel Abu Shama: **g, h**, microspheric form: **a** external and **b** equatorial section; **i, j** megalospheric form, both are external

In the study area, the Observatory Formation partly constitutes the main bulk of the high scarps overlooking both sides of the Qattamiya–Ain Sukhna road, also found at Gebel Abu Shama, Gebel Sad El Naam, Wadi Gharaba, Gebel Nasuri, Gebel Anqabiya, Gebel El Qattamiya, and Gebel Umm Reheiat.

Lithologically, the Observatory Formation is mainly composed of nodular nummulitic limestone, white to whitish gray, moderately hard, thin bedded, bioturbated, chalky at the lower part, while it includes hard, dark gray, bioturbated, dolomite beds in the middle and upper parts. The nodular limestone characterizing the lower part of the Observatory Formation indicates an unstable area during deposition, probably related to highly pulsating seismicity in the area. Well-marked chert bands (12 cm each) and concretions are most common in the middle part. Iron pockets were also recorded at the sites of fault planes between the Observatory Formation and the Upper Eocene Maadi Formation. The upper part of the Observatory Formation is characterized by a great abundance of coralline and bryozoan colonies-forming. The growth of the bryozoa and corals probably indicates deposition in warm, high salinity water, and soft substrate (Cheethman 1963; El Safori et al. 1997). Echinoid tests, pelecypods, and large gastropod molds are also common.

Both Gebel El Qattamiya and Gebel Umm Reheiat sections expose the Observatory Formation at their lowermost parts, with nearly the same lithological characteristics and the same thickness (approximately 60 m thick for each). The Observatory Formation in the two sections begins at the base with a carbonate unit, composed mainly of nodular, thin-bedded, chalky, nummulitic limestone (45–50 m thick), followed upward by a distinct horizon (10–15 m thick) of bryozoan limestone (Fig. 7d). The Bryozoan remains are embedded in a coarse-grained sparry calcite groundmass exhibiting

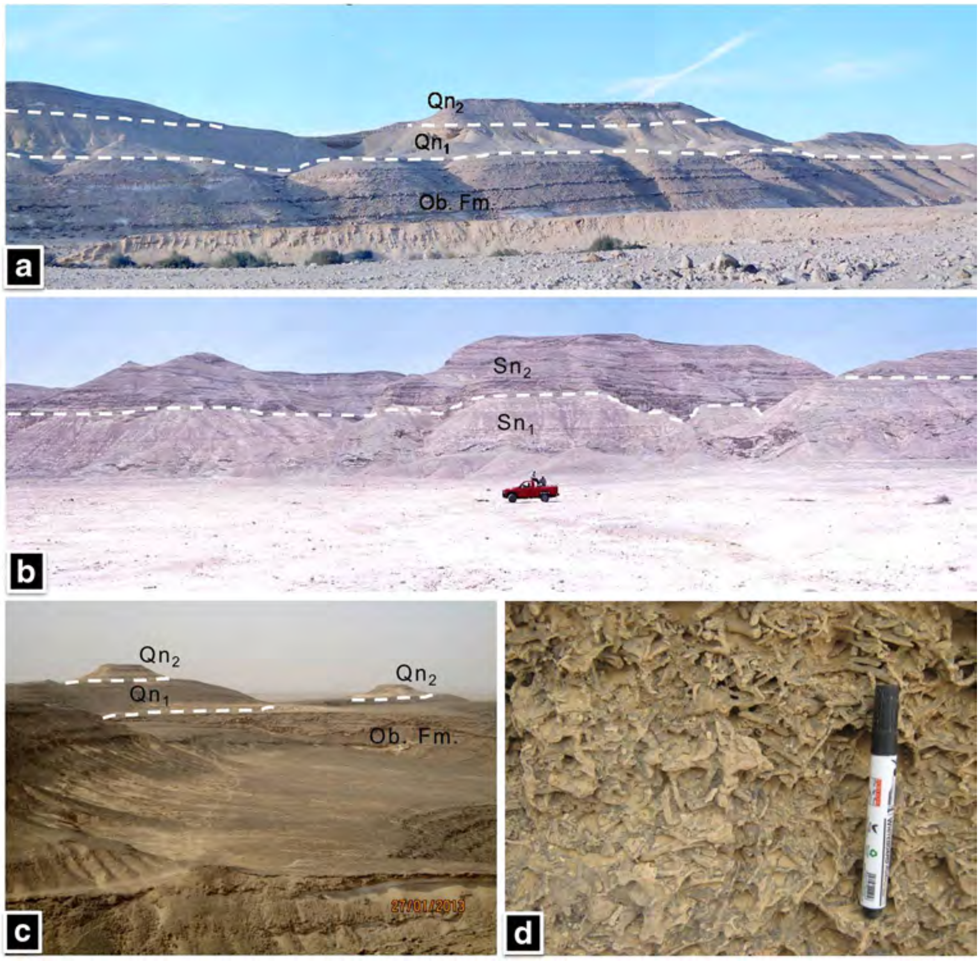

Fig. 7 The Observatory Formation exposed at the area studied. **a**, **c** The Observatory Formation (Ob. Fm.) underlies conformably the Qurn Formation (Qn. Fm.) at Gebel Abu Shama and Gebel El Qattamiya (Qn_1 & Qn_2), respectively. **b** The two members of the Bartonian Sannor Formation (Sn_1 & Sn_2) exposed at Gebel Akheider. **d** Bryozoan bank at the upper part of the Observatory Formation at Gebel El Qattamiya

recrystallization in parts. The noticeable difference between the two sections is a marked increase in the dolomite beds at Gebel Umm Reheiat section than in Gebel El Qattamiya, probably reflecting the increasing of dolomitization in the former section. Also, the Observatory Formation at Gebel Umm Reheiat section includes two well-marked horizons of oval and rounded concretionary chert nodules, sometimes elongated, which are dissemenated in the country carbonate rocks. The first horizon of nodular chert is located at the middle part of the formation associated with the dolomite beds, while the second horizon lies just below the bryozoan limestone banks. The chert nodule is dull-colored, hard, and compact and splinter when struck with a hammer. The chert nodule ranges from 8–15 cm in width (Fig. 15c), probably produced by the secondary replacement of the carbonate minerals and fossils within shallow marine shelf. The Observatory Formation at Gebel El Qattamiya and Gebel Umm Reheiat is conformably overlain by the Qurn Formation.

At Gebel Abu Shama and Wadi Gharaba, the Observatory section is nummulitic, coralline limestone; white to gray, hard, thin bedded, cavernous, bioturbated at the top. Pelecypods, gastropods, and echinoid tests are common. The Observatory Formation assumes a thickness of about 40 m at Gebel Abu Shama and nearly the same thickness at Wadi Gharaba section. It conformably overlies the Gebel Hof Formation and conformably underlies the Qurn Formation (Fig. 7a).

Paleontologically, the Observatory Formation yielded rich benthic larger foraminiferal assemblages suggesting the Bartonian age for this formation: *Dictyoconus aegyptiensis* Chapman (Fig. 8a, b), *Rhabdorites minima* Henson (Fig. 8c, d), *Idalina cuvillieri* Bignot and Strougo (Fig. 8e, f), *Pseudolacazina schwagerinoides* (Blanckenhorn) (Fig. 8g, h), *Nummulites migiurtinus* Azzaroli, *Nummulites* spp., *Orbitolites* spp. Other allochems are mainly represented by several species belonging to the family Miliolidae, e.g., *Sphaerogypsina globula*, *Denderitina* sp., *Quinqueloculina*, *Triloculina*, *Biloculina*, and *Pyrgo*. Rare ostracod species present as *Bairdia* sp. and echinoids as *Echinolampus africanus*, *Echinocyamus blanckenhorni*, and *Echinolampus perrieri*. Bryozoan and coral remains are abundant.

Sannor Formation (TemSn)≡Observatory Formation

The term Sannor Formation (coeval with the Observatory Formation in the western part of the study area) was first

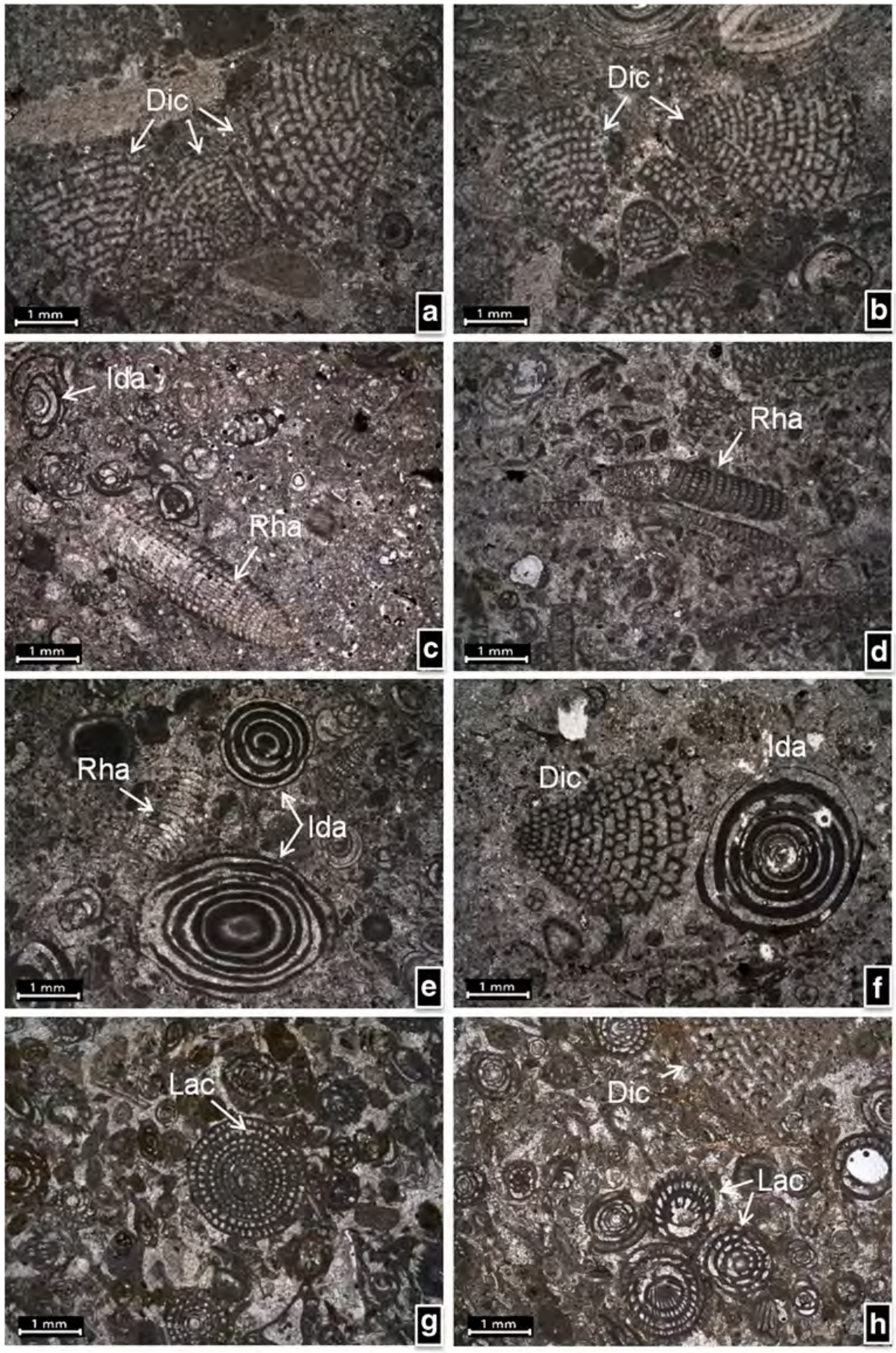

Fig. 8 Larger benthic foraminifera of the Bartonian Observatory Formation. **a**, **b** *Dictyoconus aegyptiensis* Chapman (*Dic*), Gebel El Qattamyia, samples 15–20. **c**, **d** *Rhabdorites minima* Henson (*Rha*) and *Idalina cuvillieri* Bignot and Strougo (*Ida*), Gebel Umm Reheiat, samples 3, 6, 7. **e**, **f** *Idalina cuvillieri* Bignot and Strougo (*Ida*), *Rhabdorites minima* Henson (*Rha*), and *Dictyoconus egyptiensis* Chapman (*Dic*), Gebel El Qattamyia, samples 4, 14, 19. **g**, **h** *Pseudolacazina schwagerinoides* (Blanckenhorn) (*Lac*) and *Dictyoconus egyptiensis* Chapman (*Dic*), Gebel Abu Shama and Wadi Gharba sections, samples 8, 13

proposed by Boukhary and Abdelmalik (1983) to describe about 48.4-m-thick shallow reefal carbonate section in the Nile Valley at the latitude of Beni Suef. Osman (2003) described the Sannor Formation, *ca*. 40 m thick, from Gebel Ataqa, increases westward to about 310 m at Gebel Kehilia.

The Sannor Formation is well represented at two sections located in the eastern part of the studied area namely Gebel Akheider and Gebel El Ramliya. At Gebel Akheider, the Sannor Formation assumes a total thickness of about 175 m, consists mainly of nummulitic bryozoan limestone at base and chalky limestone rich in *Somalina stefaninii* Silvestri at top, which represents an index fossil to the Bartonian age. Lithologically, the Sannor Formation at Gebel Akheider can be subdivided into two members (Fig. 7b). The first member

(Sn_1), 92 m thick, is mainly composed of nummulitic bryozoan limestone, earthy gray to grayish white, hard, thick bedded, dolomitic, rich in *Nummulites bullatus* at base, chalky at middle, and sandy and bioturbated, including chert nodules at top, which may reflect a shallowing-upward sequence. Pelecypod and gastropod molds are common. The second member (Sn_2), 83 m thick, consists mainly of chalky limestone, white, hard, thick bedded, wall forming, bioturbated, and cavernous at the top part rich in *Somalina stefaninii* Silvestri and *Dictyoconus aegyptiensis* Chapman. Algae and bryozoan remains increase upward. Chert nodules are very rare. The contact between the two members is characterized by the presence of a planation surface composed of 2.0 m glauconitic greenish sandstone bed (unconformity surface).

At Gebel El Ramliya, the Sannor Formation, *ca*. 120 m thick, consists mainly of chalky bryozoan nummulitic limestone, white to earthy gray, hard, banded, cross bedded, cavernous, dolomitic in parts, including chert bands and nodules at the lower part of the section, whereas the section is chalky upward. Algae are most common in the upper part of this section. Among benthic foraminifera, the most valuable for biostratigraphical purpose are *Somalina stefaninii* Silvestri (Fig. 9a), *Dictyoconus aegyptiensis* Chapman (Fig. 9b), *Rhabdorites minima* Henson (Fig. 9c), *Planotrillina deserti* Bignot and Strougo (Fig. 9d), *Orbitolites* sp. cf. *complanatus* Lamarck (Fig. 9e), *Idalina cuvillieri* Bignot and Strougo (Fig. 9a – f), *Nummulites* sp. cf. *beaumonti*, *Gypsina carteri*, *Linderina* cf. *brugesi*, and Miliolidae (Fig. 9f). These fossils indicate the Bartonian age for the Sannor Formation.

Qurn Formation (TemQn)

The Qurn Formation was originally proposed by Farag and Ismail (1959) in the Qurn high area, east of Helwan, including about 97-m-thick section of chalky and marly limestone alternating with sandy marls and assigned its age to the Late

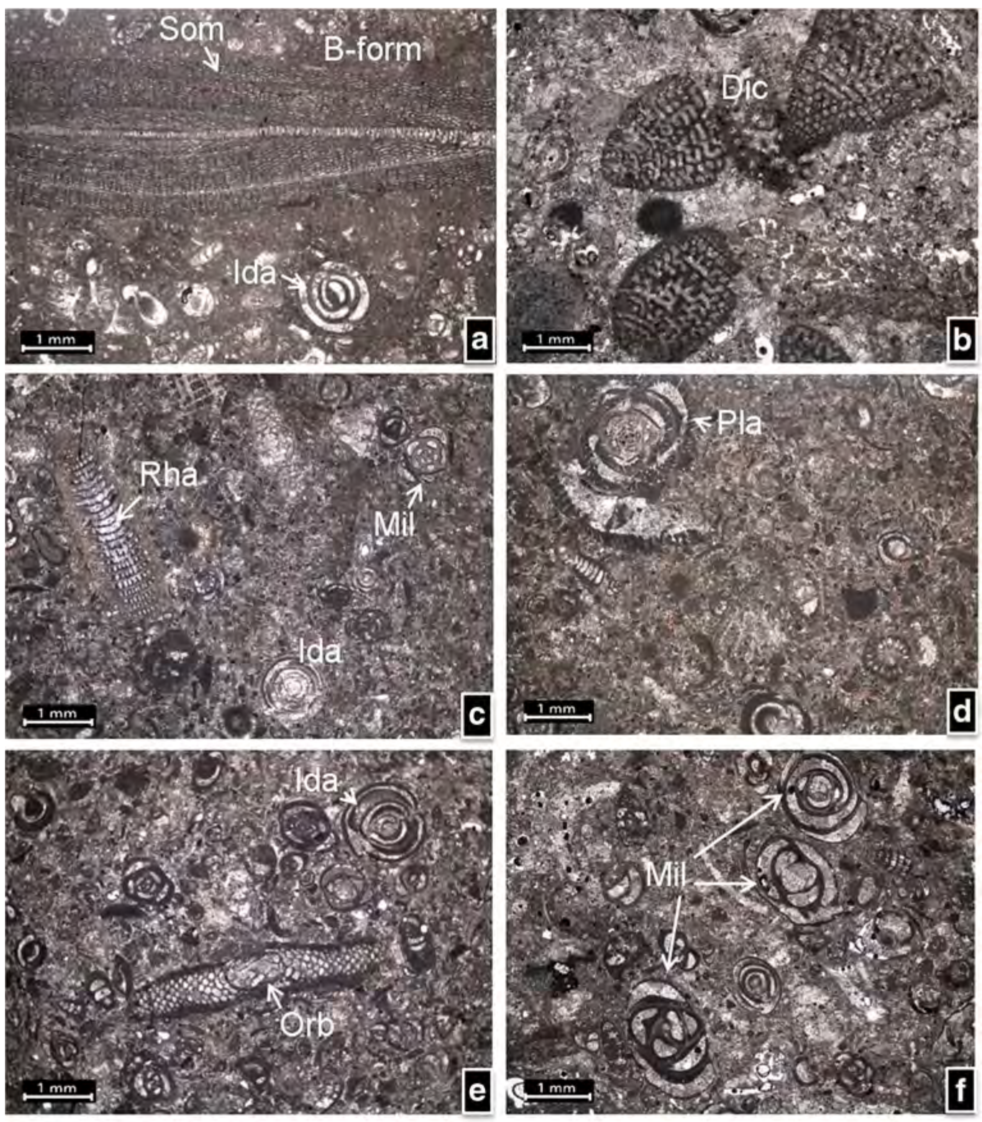

Fig. 9 Larger benthic foraminifera of the Bartonian Sannor Formation. **a** *Somalina stefaninii* Silvestri (*Som*) and *Idalina cuvillieri* Bignot and Strougo (*Ida*), Gebel Akheider, samples 6, 21, 23, 25. **b** *Dictyoconus aegyptiensis* Chapman (*Dic*), Gebel Akheider, samples 5, 13, 22, 25. **c** *Rhabdorites minima* Henson (*Rha*) and Miliolids (*Mil*), Gebel El Ramlyia, samples 6, 7, 15. **d** *Planotrillina deserti* Bignot and Strougo (*Pla*), Gebel El Ramlyia, samples 20, 21. **e** *Orbitolites* sp. cf. *complanatus* Lamarck (*Orb*), axial section, and *Idalina cuvillieri* Bignot and Strougo (*Ida*), Gebel Akheider, sample 9. **f** Miliolids (*Quinqueloculina* and *Idalina* sp.) Gebel El Ramlyia, samples 6, 7, 11, 17, 20

Eocene. Based on foraminiferal assemblages, Strougo (1985) and Strougo and Boukhary (1987) suggested a Middle Eocene age to this formation.

In the area studied, the Qurn Formation is easily recognizable due to its lighter colors in contrast with the darker colors of the underlying Observatory Formation. Lithologically, the Qurn Formation is mainly composed of marly limestone, soft marls at the base alternating with fossiliferous sandy marl beds. Upward, the Qurn Formation is dominated by chalky limestones very rich in nummulites, echinoid spines, oysters, and rare bryozoa. The moderately hard lithology of the Qurn rocks with respect to the hard nature of the underlying Observatory rocks has resulted into retreating hillocks of the Qurn Formation capping the Observatory Formation with wide benches in-between. At Gebel El Qattamiya, the Qurn Formation can be subdivided lithologically into two members (Fig. 7c). The lower member (Qn_1; 15–20 m thick) is composed of marly limestone and marl interbeds, yellowish white to faint yellow, moderately hard, thin bedded, sandy, chalky in places, bioturbated, fossiliferous rich in *Ostrea reili*, *Vulsella crispata*, *Lucina pharaons*, and *Lucina egyptiaca* with a notable decrease in the foraminiferal content reflecting a more shallow marine depositional environment. The upper member (Qn_2; *ca*. 15 m thick) of the Qurn Formation consists of white chalky limestone with few interbeds of sandy marl. This member (Qn_2) is characterized by abrupt increase in nummulites than that in the lower member (Qn_1). Echinoid spines, *Turritella* sp., and oyster shells are also very common. The Qurn Formation attains a thickness of about 35 m at Gebel Abu Shama, 15 m at north Wadi Gharba, 30 m at Gebel El Qattamiya, and about 25 m at Gebel Umm Reheiat section. The Qurn Formation conformably overlies the Bartonian Observatory Formation and underlies unconformably the Upper Eocene Maadi Formation.

Paleontologically, the Qurn Formation in the studied sections is characterized by the following foraminiferal species: *Nummulites* aff. *pulchellus*, *Nummulites* sp. cf. *beaumonti*, *Nummulites bullatus*, and *Nummulites* cf. *incrassatus*. The formation yielded rich ostracod species: *Cativella qurnensis*, *Trachyleberis nodosus*, *Costa humboldti*, and *Ruggieria* (*Keijella*) *glabella*. These species whether larger benthic foraminifers or ostracods relegate the Qurn Formation to the Bartonian.

Maadi Formation (TeuMd)

The Maadi Formation was introduced by Said (1962) to describe a clastic section with minor carbonate beds rich in oysters and *Carolia placunoides* Cantraine, overlying the Lutetian Mokattam Formation at Gebel Mokattam, east of Cairo. The Maadi Formation was assigned by Said (op. cit) to the Late Eocene age, coeval with Wadi Garawi and Wadi Hof formations described by Farag and Ismail (1959) in Helwan area.

In the study area, the Late Eocene witnessed a dramatic change in the sedimentary facies from pure carbonates (Observatory and Qurn formations; Bartonian time) to clastics with minor carbonate facies (Maadi Formation; Priabonian) indicating the change of the depositional regime during the Bartonian and the Priabonian. The Priabonian Maadi Formation has a wide areal distribution in the area studied covering a large stretch extending from Gebel Mokattam east of Cairo to Gebel Ataqa along the Qattamiya–Ain Sukhna road. This formation is a fossiliferous subtidal to tidal shallow marine carbonate–clastic section attaining a total thickness of about 60 m (Fig. 10a). The lower 40 m thick of the formation consists mainly of marly limestone, shales, ochreous grits and yellowish brown, gypseous marls intercalated with sandy marl beds crowded with *Ostrea clotbeyi* and *Ostrea multicostata* forming a marked oyster bank. Above this bank, a thin bed, (ca. 85 cm thick) of ferruginous sandstones including fossils was recorded. This section is followed upward by about 15 m thick fissile, laminated, greenish gray gypseous shales including ferrigenous pockets and alternated with small scale cross-bedded sandstone and siltstone, capped by hard bed (5.0 m thick) yellow marly limestone overcrowded with *Carolia placunoides* Cantraine forming another oyster bank (Fig. 10b).

The thickness of the Maadi Formation varies from about 60 m at Bir Gindaly section opposite the Qattamiya Cement Factory, 30–40 m southwest of Gebel El Qattamiya, 20 m at Gebel Abu Shama, and 8.0 m thick in some residual hills at Wadi Gharaba. The deposition and distribution of the Maadi Formation were mainly controlled by the predominant structural setting of the area prior to its deposition in grabens, half-grabens, and footslopes of the down-faulted blocks, hence the variation in thickness.

At many places, especially at graben and half-graben areas, e.g., Bir Gindaly, a thick section of the Maadi Formation was developed, where the maximum thickness reaches more than 60 m, while in other places, e.g., northeast side of Gebel El Qattamiya and Wadi Gharaba sections, the lower 40 m thick of the Maadi Formation is totally missing, where the *Carolia placunoides* Cantraine banks characterize the upper part of the Maadi Formation are directly overlying the Middle Eocene rocks with wavy contact in-between indicating a surface of unconformity (Fig. 10c, d). Besides, at some places in Gebel El Qattamiya, the Maadi sediments are rich in oysters and *Carolia placunoides* Cantraine making tongues-like and filling the small gullies down from the upthrown Bartonian Observatory and Qurn formations. The lithologic characteristics of the Maadi Formation with marked increasing of sand and clay ratio reflect the continuous shallowing and gradual retreation of the Priabonian shoreline northwards together with the emergence of the Middle Eocene blocks. The faulting movement was most probably associated with a period of erosion indicated by the presence of 1.5 m reddish,

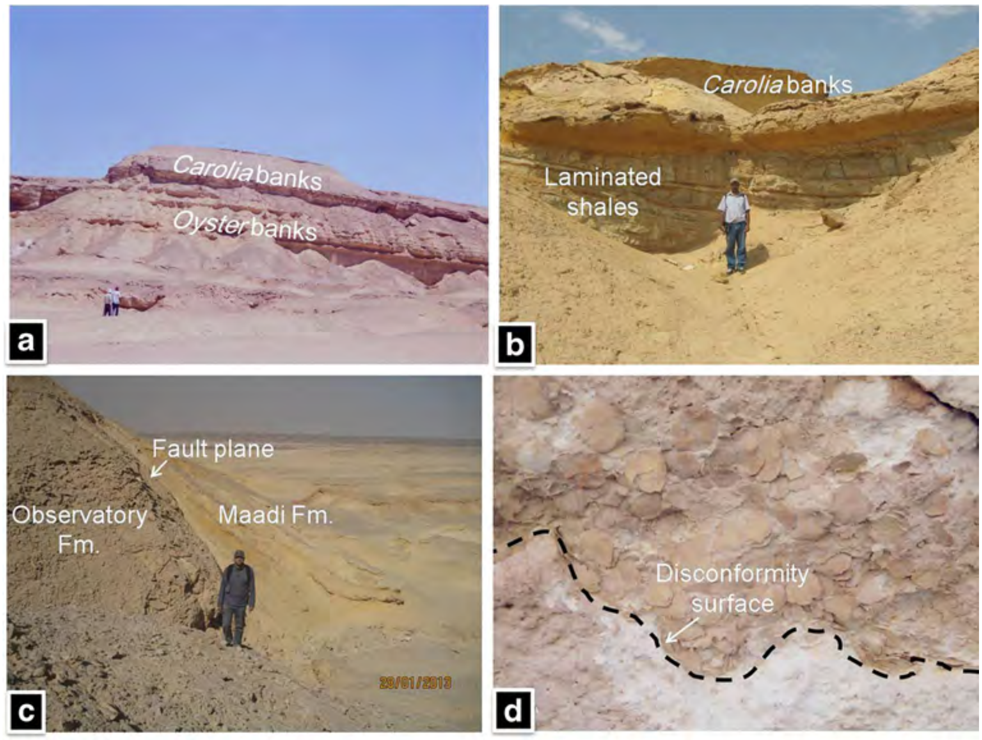

Fig. 10 The Upper Eocene Maadi Formation exposed in the study area. **a** Thick bedded clastic–carbonate section of the Maadi Formation including oyster banks, at Bir Gindaly. **b** Laminated shales and siltstones capped by marly limestone overcrowded with *Carolia placunoides* Cantraine at Bir Gindaly. **c** The Maadi Formation unconformably overlies the Middle Eocene Observatory Formation at Gebel El Qattamiya. **d** *Carolia placunoides* Cantraine bank characterizes the upper part of the Maadi Formation, northwest of Gebel El Qattamiya

fossiliferous limestone bed usually caps the down-faulted blocks. The Priabonian Maadi Formation unconformably overlies the Bartonian Qurn Formation and unconformably underlies the Oligocene Gebel Ahmer Formation.

Several ostracod species of Priabonian age were identified from the Maadi Formation: *Uromuellerina saidi* Bassiouni, *Trachyleberis* gr. *nodosus* Bassiouni, *Reticulina heluanensis* Bassiouni, *Asymmetricythere asymmetrella* Bassiouni, and *Achanthocythereis maadiensis* Bassiouni.

Gebel Ahmer Formation (ToAh)

The name of this formation was originally derived from El Gebel El-Ahmar (i.e., Red Mountain), which is located east of Cairo, near the suburb of Heliopolis. It is mainly composed of varicolored (yellow, red, reddish brown), cross bedded, friable, coarse to fine-grained, ochreous sands including bands of gravels, dark brown to black, disc-shaped, sometimes elongated, pebble to cobble size (more than 4.0 cm in diameter), and capped by a dark gray to brown, very hard, quartzitic sandstone bed (1.0–2.0 m thick) (Fig. 11a). Silicified wood and root casts are very common at the topmost part of the Gebel Ahmer Formation. Snails of fresh water are found. The Oligocene Gebel Ahmer Formation is widespread covering a large stretch east and northeast of Gebel Mokattam e.g., Gebel El-Ahmer (type locality), Gebel Yahmoum El-Asmar, Gebel Nasuri, El Anqabia, Gebel Ikhshein and Bir Gindaly area, where its thickness ranges from 40 to 100 m. The Oligocene sands and gravels are sporadically occurring eastward of the Gulf of Suez, forming several small exposures. In the first area south and northeast of Gebel El Qattamiya, the Oligocene sediments (20–30 m thick) abut against the Middle Eocene beds filling many low topographic areas (grabens) easily recognized from a distance owing to their vivid colors (i.e., red, yellow, brownish yellow, and whitish gray) which contrast with the surrounding earthy gray colors of the Eocene rocks. Silicified tree trunks are common in this section. South of Gebel Akheider along Qattamiya–Ain Sukhna road, the Oligocene section is approximately 40-m-thick sands and gravels (quarried), brownish yellow to reddish brown to pale red, including many conglomerate lenses and beds (Fig. 12). A basalt dyke was injected in the same sands and gravels southwest of Gebel El Qattamiya along the Qattamiya–Ain Sukhna road. This basalt is a continuation of the basalt eruptions injected into the Gebel Ahmer Formation near its top, at Gebel Nasuri and Gebel Anqabiya at Cairo–Suez road. The age of basalt was determined by Meneisy and Abdel Aal (1984) using K/Ar method as Aquitanian (22±2 Ma).

The Gebel Ahmer Formation is of a fluviatile origin deposited from westerly and northerly flowing meandering fluvial system filling local topographic depressions in the stretch between Gebel Ataqa in the east and Gebel Mokattam in the west. The Oligocene sediments were highly controlled by the structural and topographic lows, where a substantial thickness of these sediments was deposited occupying several grabens and gently sloping areas between many synthetic faults. The Oligocene sediments can thus be observed in some places at lower levels than the higher upthrown Eocene rocks, whereas in other

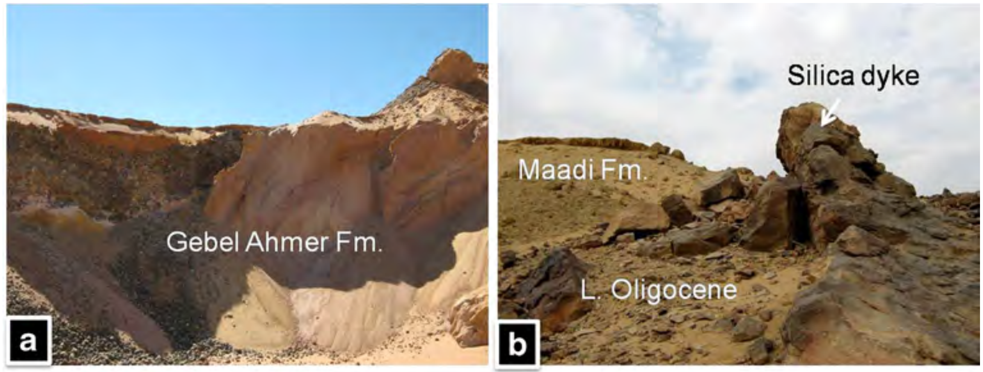

Fig. 11 The fluviatile Oligocene sediments. **a** Gebel Ahmer sands and gravels capped by a hard quartizitic bed at the southern side of Gebel El Qattamiya. **b** The lower Oligocene sediments injected by silica thermal springs forming a dyke-like body along the NW oriented major fault at Wadi Gindaly

places they are abutting against either the Middle or the Upper Eocene beds. The thickness of the Gebel Ahmer Formation is variable due to structural setting, since it varies from 40 to 100 m at Gebel Ahmer, 20 m thick at Gebel El Qattamiya and Wadi Gindaly, and decreases to 5.0 m thick south of Gebel Umm Reheiyat. A subsequent phase of thermal silica springs, geyser and basalt eruptions took place after the deposition of the Early Oligocene sands and gravels, due to the rejuvenation of the E–W and NW–SE faults during the late Oligocene (Shukri 1953; Shukri and Akmal 1953; Al Ahwani 1982). This has resulted into a dyke-like body of silicified sandstones (Fig. 11b), castle-like forms of red and brown silicified tubes cutting through the early Oligocene sands and gravels and basalt sheets covering the early Oligocene sediments. Stratigraphically, the Gebel Ahmer Formation unconformably overlies the Upper Eocene Maadi Formation and unconformably underlies the Miocene sediments or basalt sheets.

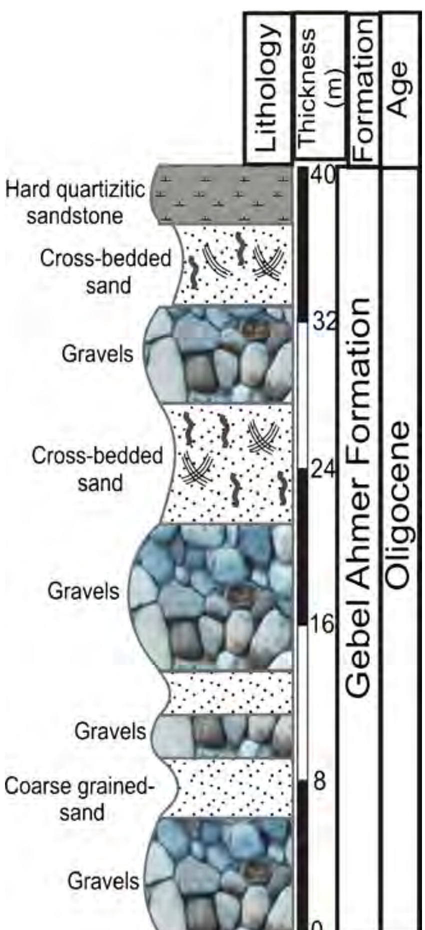

Fig. 12 Stratigraphic columnar section of the Oligocene Gebel Ahmer Formation, south of Gebel Akheider along Qattamiya–Ain Sukhna road

Facies analysis and depositional environments

The depositional environments of the rock units exposed in the study area are based on thin-section analysis for about 150 rock samples, supplemented by field observations, biotic components, and textural and sedimentological features. Twenty-three microfacies types have been recognized in the different rock units exposed in the study area. The textural descriptions of carbonate rocks follow Dunham's classification scheme (1962) and refined by Embry and Kolvan (1971). Data for microfacies analysis and interpretation are based on the Standard Microfacies Types (SMF) and Standard Facies Zone (FZ) of the modified Wilson model (Wilson 1975; Flugel 1982, 2004). The microfacies types and depositional environments of the different rock units are summarized in Table 1 and Fig. 13. In the following paragraphs, a brief description and interpretation of the different microfacies types is given, with an emphasis on their depositional environments.

Microfacies types of the Minia Formation: description and interpretaion

Six microfacies types were recognized in the rocks of the Ypresian Minia Formation in Gebel Abu Treifiya section, arranged from base to top.

Lime mudstone

This microfacies association was recognized in the lowermost member (Mn_1) of the Minia Formation, *ca*. 15 m thick. In the

Table 1 The relationship of the stratigraphic setting, microfacies types, and depositional environments of the studied rock units

Age	Rock units	Lithofacies	Benthic foraminifera	Other biota	Microfacies types	SMF/FZ	Depositional Environments
Upper Eocene (Priabonian)	Maadi Fm. (TeuMd)	Marls, marly limestones at base, while sandy, gypseous shales and siltstones at top		Ostracods. *Carolia placunoides, Ostrea multicostata, Ostrea clotbeyi*	-Silicicalstic lithofacies -Carbonate lithofacies	-SMF11/FZ6 -SMF12/FZ7 and FZ8	-Winnowed platform edge -Restricted platform -Tidal flats
Middle Eocene (Bartonian)	Qurn Fm. (TemQn)	Marly limestone, chalky at the upper part	*Nummulites* aff. *pulchellus, Nummulites* sp. cf. *beaumonti, Nummulites bullatus*, and *Nummulites* cf. *incrassatus*	Ostracods, *Ostrea reili, Vulsella crispata, Lucina pharaons, Turritella* sp., echinoid spines	-Shelly nummulitic grainstone -Nummulitic/miliolidae packstone to grainstone -Sandy shelly wackestone	-SMF8, SMF9, SMF10, SMF11/FZ2, FZ5 and FZ7	-Shallow marine -Shelf lagoons -Reefs
	Sannor Fm. (TemSn)	Nummulitic bryozoan limestone at base, while chalky *Somalina* limestone	*Somalina stefaninii, Dictyoconus egyptiensis, Rhabdorites minima, Nummulites* sp. cf. *beaumonti* -Miliolids	Algae, corals and echinoids	-Somalina/ miliolidae packstone to grainstone -Dictyoconus/miliolidae packstone to grainstone -Nummulitic dolostone -Miliolidae/algae packstone -Shelly oyster packstone -Recrystallized bryozoan packstone -Nummulitic wackestone -Lime mudstone	-SMF 9 / FZ 8	-Shallow and erratic sea, most probably sheltered lagoon environment
	Observatory Fm. (TemOb)	Nodular nummulitic limestones at base including chert nodules, while bryozoan nummulitic limestone at top. Dolomites	-*Dictyoconus egyptiensis, Rhabdorites minima, Nummulites migiurtinus, Nummulites* spp., *Orbitolites* spp. -Miliolids	Bryozoa, corals and echinoids	-Recrystallized bryozoan/ coralline grainstone -Dolostone -*Pseudolacazina* schwageri-noides/*Dictyoconus egyptiensis* grainstone -*Dictyoconus egyptiensis* packstone to grainstone -Miliolidae packstone to grainstone	-SMF9, SMF11, SMF18/FZ7 and FZ8	-Shallow marine platform, neritic to reefal environment -Intertidal to supratidal zone
	Gebel Hof Fm. (TemHo)	Limestones; dolomitic in parts	*Nummulites bartovigatus, Nummulites migiurtinus*	Echinoids	-Sandy nummulitic wackestone	-SMF18/FZ7	-Open-marine plarform
Late Ypresian (Cuisien)	Minia Fm. (TelMn)	Carbonate rocks; mainly limestones and dolomites including chert bands at the lower parts.	*Nummulites praecursor, Orbitolites pharaonum, Alveolines* spp.	Bryozoa, Echinoids, gastropods and bivalves	-Recrystallized bryozoan packstone -Alveolina/nummulites packstone to grainstone -Dolostone -Nummulites/alveolina packstone to grainstone -Nummulitic wackestone -Lime mudstone	-SMF5, SMF8, SMF9, SMF18/ FZ2, FZ3, FZ4, FZ5, FZ7 and FZ8	-Platform-margin reefs -Reef slope and restricted-shallow marine platform -Deep shelf margin and open-marine platform

SMF—Standard Microfacies Type, and FZ—Facies Zone

field, the member consists of thin-bedded non-fossiliferous limestone, gray to whitish gray alternating with chert bands. The microfacies consists mainly of micritic matrix (less than 5 μm in size) including planktonic foraminifera. This microfacies type can be correlated with SMF 3 which was deposited in an open-marine platform (FZ 7) and in deep shelf margin (Toe-of-slope and slope; FZ 3), within euphotic zone, normally above wave base.

Nummulitic wackestone (Fig. 14a)

This microfacies type overlies the lime mudstone microfacies reflecting a shallowing-upward cycle in the first member (Mn_1) of the Minia Formation. It assumes a thickness of about 20 m. The rock is composed of poorly foraminiferal limestone, thin bedded, gray to grayish white, perforated, hard, including chert bands. The microfacies consists of about 10–15 % allochems represented by well-preserved *Nummulites* spp. scattered throughout a micritic matrix, microsparitic in parts. The thick walls of these nummulites have a radial fibrous microstructure, most probably aragonite crystals. The fibers are aligned at right angles to the test wall. It matches with the SMF 8, deposited in the deep shelf of low-energy conditions below wave base (FZ 2 and FZ 7), within or just below the euphotic zone.

Nummulites/alveolines pack to grainstone (Fig. 14b)

This microfacies type was described from the second member (Mn_2) of the Minia Formation overlying the nummulitic wackestone microfacies. In the field, the limestones are thick bedded, snow-white, chalky in places, crystalline in others including thin bands of chert as a diagenetic replacement of the carbonates. Petrographically, this microfacies is composed of grain-supported *Nummulites praecursor* (50–60 %), *Alveolina frumentiformis* Schwager (15–20 %), *Orbitolites pharaonum* (less than 5 %), and other allochems (less than 4 %) of the rock. The allochemical components are cemented by sparry calcite with some patches of micrite. The majority of nummulites are well preserved, exhibiting radial fibrous microstructure of aragonite crystals. Some of nummulites and

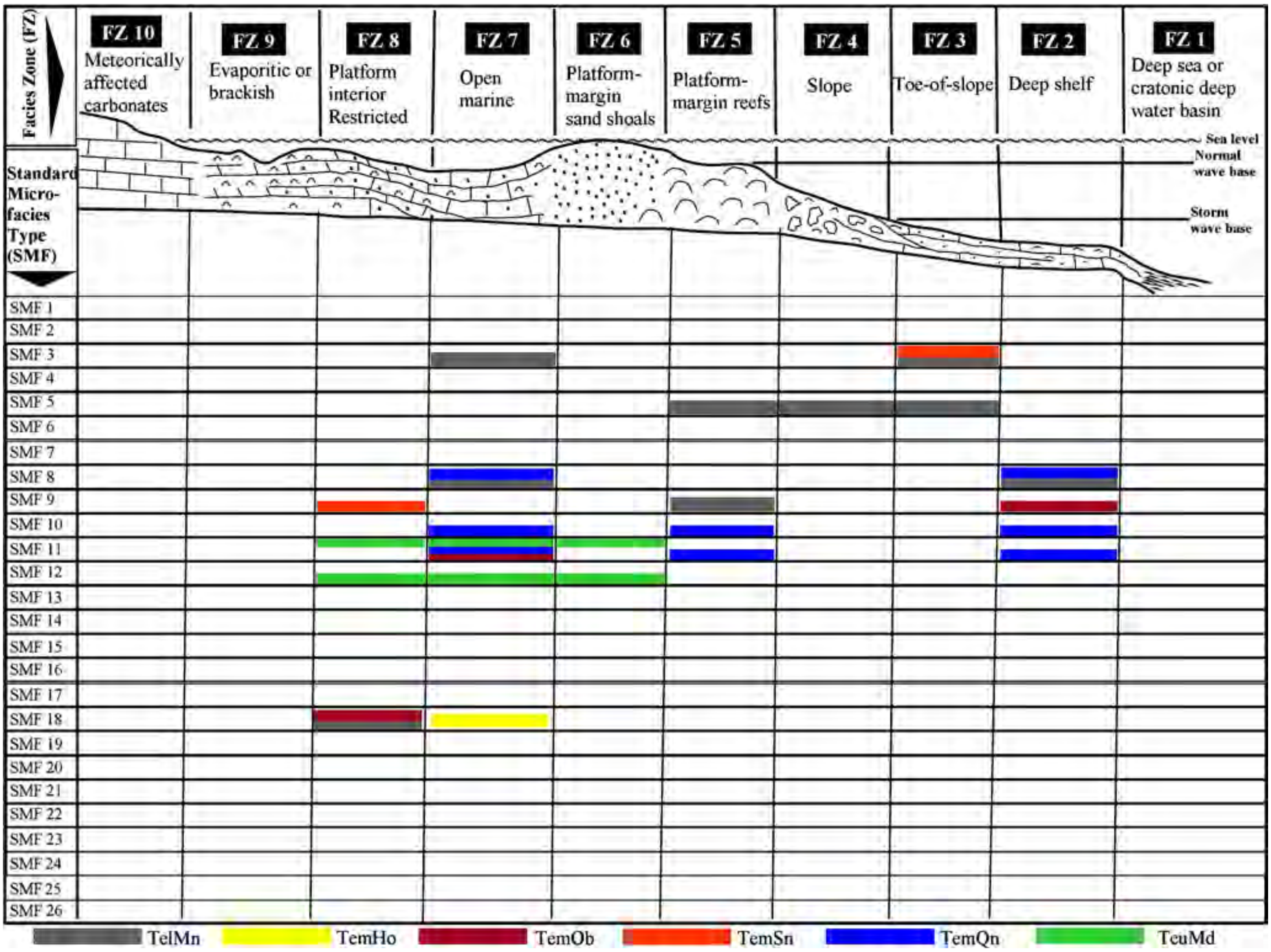

Fig. 13 The differnet microfacies types described in the studied formations and their distribution in the Standard Facies Zones (FZ) of the modified Wilson model (1975). Standard Microfacies Types of Wilson model: (SMF 1) spiculitic wackestone or packstone; (SMF 2) microbioclastic peloidal calcisiltite; (SMF 3) pelagic lime mudstone and wackestones; (SMF 4) microbreccia; (SMF 5) allochthonous bioclastic grainstone, rudstone, packstone, floatstone; (SMF 6) reef rudstone; (SMF 7) organic buondstone; (SMF 8) wackestones and floatstones; (SMF 9) burrowed bioclastic wackestone; (SMF 10) bioclastic packstone and wackestone; (SMF 11) coated bioclastic grainstone; (SMF 12) limestones with shell concentrations; (SMF 13) oncoid rudstone and grainstone; (SMF 14) lag deposit; (SMF 15) oolite, grainstones; (SMF 16) peloid grainstone and packstone; (SMF 17) grainstone with aggregate grains; (SMF 18) bioclastic grainstone and packstone; (SMF 19) densely laminated bindstone; (SMF 20) laminated stromatolitic bindstone/boundstone; (SMF 21) fenestral packstone and bindstone; (SMF 22) oncoid floatstone and wackestone; (SMF 23) non-laminated homogenous micrite; (SMF 24) lithoclastic floatstone, rudstone or breccias; (SMF 25) laminated evaporate-carbonate mudstone and (SMF 26) pisoid cementstone, rudstone or packstone

alveolines are partly exhibiting a micritization in the outer rims. This microfacies type matches with the SMF 5, indicates deposition in shelf margin (FZ 3) or reef slope (FZ 4) with water depth ranging from 200 to 300 m.

Dolostone

The dolostone lithofacies was recognized in the rocks of the third member (Mn_3) of the Minia Formation, attaining a thickness of about 65 m. It consists of thick bedded, gray, dark gray to brown, very hard, vuggy dolomite, and dolomitic limestone. Microscopically, the rock is composed mainly of euhedral and subhedral rhombs of dolomite forming about 90 % of the rock. The texture is unzoned dolomite crystals of equigranular and xenotopic fabric. The allochems, mainly nummulites, are generally replaced by dolomite crystals. The vuggy dolostone most probably deposited in the upper intertidal zone in a restricted-marine platform (FZ 8) indicating upward-shallowing. Dolomitization is thought to occur when the sea water was enriched with meteoric water percolating through the porous and permeable limestone within a few meters of the surface.

Alveolines/nummulites pack to grainstone (Fig. 14c)

This microfacies was recorded from the upper fourth member (Mn_4) of the Minia Formation overlying the dolostone

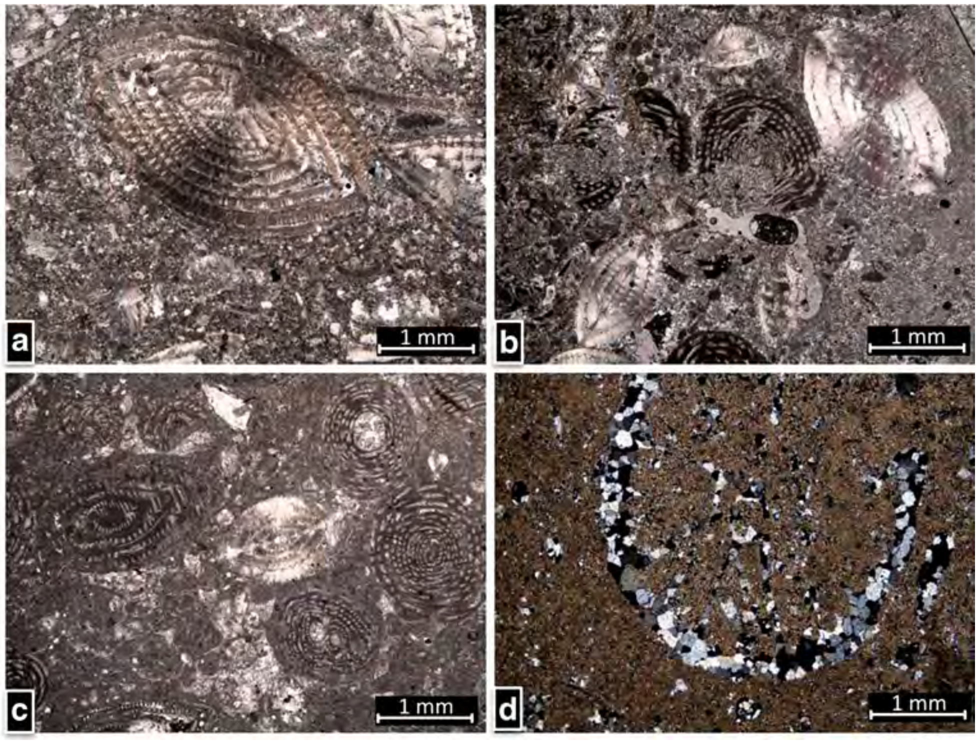

Fig. 14 Microfacies types described in the late Ypresian Minia Formation. **a** Nummulitic wackestone, where the nummulites are well prserved with radial fibrous microstructures. **b** Nummulites/alveolines pack to grainstone, where alveolines are partly exhibiting a micritization. **c** Alveolines/nummulites pack to grainstone. **d** Recrystallized bryozoan packstone, since the walls of zooids are recrystallized and replaced by medium to coarse quartz, while chambers are filled with micrite

lithfacies, attaining a thickness of about 55 m. The rock consists of alveolinid limestone, grayish white to yellowish, thin bedded, hard, sandy, and bioturbated in places. Petrographically, this microfacies type consists mainly of allochems and sparry calcite cement with some patches of micrite and microcrystalline quartz grains. *Alveolina frumentiformis* Schwager are the main allochemical components present. They form about 80–90 % of the rock, whereas the other *Nummulites* spp. form about 5 %. Most of the allochemical particles are well preserved. The binding material between the allochemical grains is sparry calcite, filling the intergranular spaces and most chambers of the skeletal particles. The original micrite was washed away due to the action of currents and waves in a shallow marine environment. Based on the Standard Facies Type of Wilson (1975, this microfacies type can be matched with the SMF 18, deposited in a restricted-marine platform (FZ 8), within the euphotic zone.

Recrystallized bryozoan packstone (Fig. 14d)

The bryozoan microfacies was described from the uppermost bed (0.5 m thick) of the fourth member (Mn_4) of the Minia Formation, overlying the alveolina/nummulites pack to grainstone microfacies. The rock itself is composed of reddish brown, hard, and siliceous bryozoan limestone. Petrographically, this microfacies type consists mainly of bryozoan remains forming about 95 % of the rock. The walls of zooids are recrystallized and replaced by medium to coarse quartz, while chambers are filled with micrite. The microfacies also includes quartz grains and iron oxide pellets. Ferrugination and siliceous fillings are the main diagenetic features recorded in this microfacies. It can be correlated with the SMF 5 and SMF 9 indicating its deposition in platform-margin reefs in forereef position (FZ 5) with open circulation at or just below the fair-weather wave base. Water depth is generally some meters.

Facies interpretation

The different microfacies types and foraminiferal assemblages recorded in the rocks of the Minia Formation indicate a shallowing-upward cycles in carbonate rocks. These cycles are well observed where the lime mudstone and wackestone microfacies types at base (deposited in deep shelf margin and open-marine platform; FZ 2, FZ 3, and FZ 7) followed upward by packstone to grainstone and dolostones microfacies, reef slope and restricted-shallow marine platform (FZ 4 and FZ 8), and covered by bryozoan reefs reflecting deposition in platform-margin reefs (FZ 5) in a warm, low-energy environment within the euphotic zone.

Microfacies types of Gebel Hof Formation: description and interpretaion

One microfacies type was recognized in the rocks of the Bartonian Gebel Hof Formation: sandy nummulitic wackestone microfacies. In the field, the rock is limestone, gray to grayish white, hard, thin bedded and sandy, assumes a thickness range from 8.0 m at the base of Wadi Gharaba to about 18 m at the lowermost beds of Gebel Abu Shama. This microfacies type is composed mainly of allochems represented by *Nummulites bartovigatus* and *Nummulites migiurtinus* and fine angular quartz grains embedded in a micritic matrix, microsparitic in parts. This type probably corresponds to (SMF 18) that indicates deposition in an open-marine plarform, (FZ 7), with open current circulation and receiving small amount of detrital sand grains. Water depth is tens of meters within the euphotic zone.

Microfacies types of the Observatory Formation: description and interpretaion

Five microfacies types were recognized in the rocks of the Bartonian Observatory Formation, arranged from base to top.

Miliolidae pack to grainstone (Fig. 15a)

This microfacies occurs in the lowermost part of the Observatory Formation at Gebel El Qattamiya, Gebel Umm Reheiat, and Gebel Abu Shama sections, attaining a thickness of about 15 m. In the field, the rock consists of nodular foraminiferal limestones, thin bedded, white to gray, hard, and bioturbated including echinoids, small gastropods, and pelecypods. Petrographically, this microfacies type is composed of allochems represented by many species of family Miliolidae as *Pseudolacazina schwagerinoides*, *Idalina*, *Quiqueloculina*, *Triloculina*, *Biloculina*, and *Pyrgo*. Other allochemical particles are algae, *Dictyoconus aegyptiensis*, and echinoid spines. These allochemical components are embedded in sparry calcite groundmass, micritic in parts. The shells of most allochems are filled with sparitic calcite as a result of aggrading neomorphism. The great abundance of miliolids

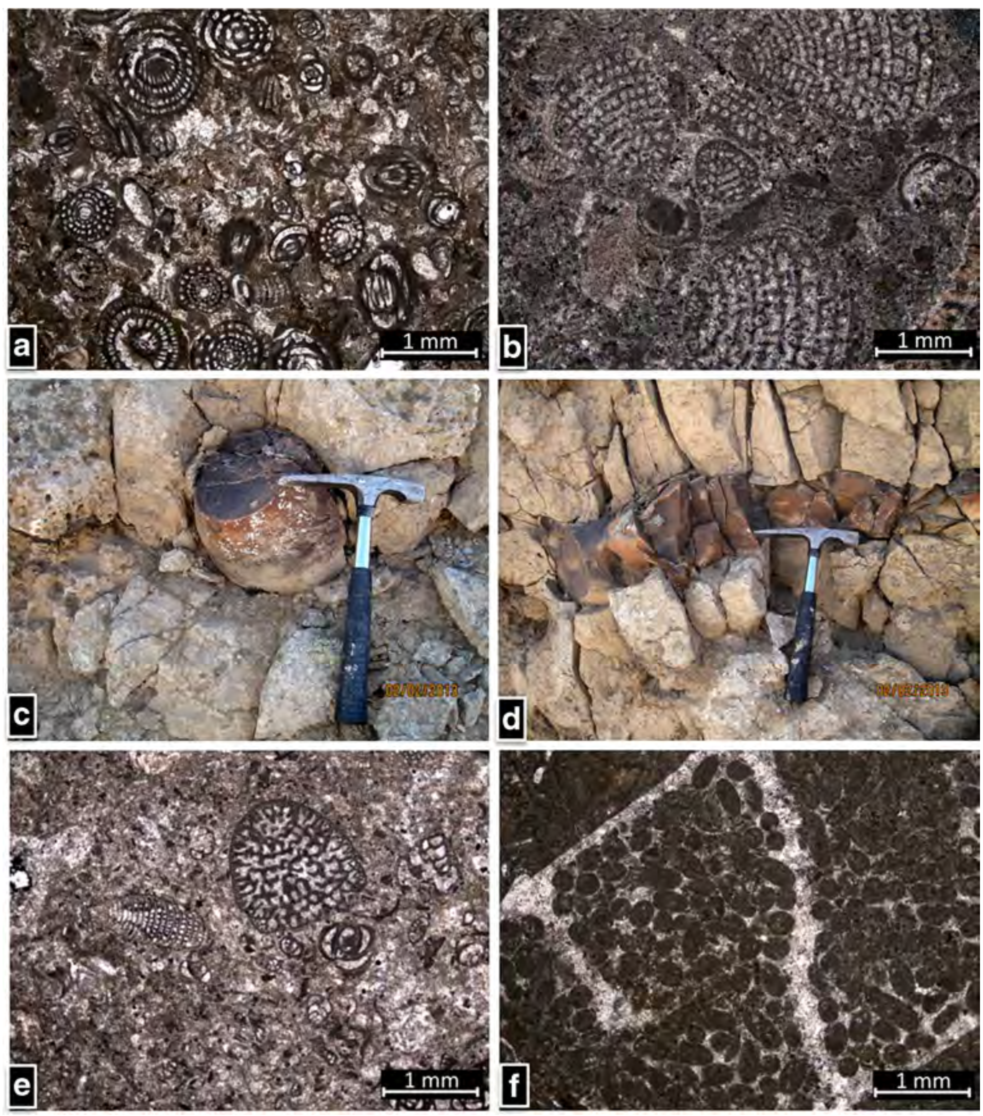

Fig. 15 Microfacies types described in the Bartonian Observatory Formation. **a** Miliolidae pack to grainstone, embedded in sparry calcite groundmass, micritic in parts, Ob. Fm., GUR section. **b** *Dictyoconus aegyptiensis* pack to grainstone, embedded in micritic matrix, Ob. Fm., GQT section. **c** A rounded concretionary chert nodule disseminated in the nummulitic limestones, Ob. Fm., GUR section. **d** Elongated chert nodule in dolomitic limestones, Ob. Fm., GUR section. **e** *Dictyoconus aegyptiensis*/*Rhabdorites minima* packstone, the bioclasts are embedded in microsparitic matrix, Ob. Fm., GUR section. **f** Bryozoan grainstone, the walls of bryozoa are neomorphosed into microsparite, Ob. Fm., GQT section

in this microfacies supports deposition in a slightly restricted environment (Flugel 1982).

Dictyoconus aegyptiensis pack to grainstone

This microfacies association is very common in the Bartonian Observatory Formation. It overlies the previous miliolidae microfacies, assuming a thickness of about 20 m. In the field, the rock is thick bedded fossiliferous limestone, gray to grayish white and hard, including dolomite bands and chert nodules. Petrographically, this microfacies is composed of benthic foraminifera represented by *Dictyoconus aegyptiensis* (Fig. 15b), miliolids, nummulites, echinoids, and rare algae. All allochems are well preserved, embedded in microcrystalline calcite reflecting deposition in a shallow marine, calm, and neritic to reefal environment of low energy within light-penetrated photosynthetic zone. Chert occurs as oval, elongated, and irregular nodules in limestone (Fig. 15c, d) as a secondary replacement of the carbonate minerals and fossils within shallow marine shelf.

Dictyoconus aegyptiensis/Rhabdorites minima packstone (Fig. 15e)

This microfacies type is also common in the rocks of the Observatory Formation, attains a thickness of about 5 m. The rock is gray to whitish gray fossiliferous limestone, thin bedded, hard, and dolomitic in parts. This microfacies consists mainly of allochemical particles represented by *Dictyoconus aegyptiensis* (15 %), *Rhabdorites minima* (10 %), algae (5 %), and miliolids (2 %). The allochems are well preserved maintaining their internal microstructure. They are embedded in microsparitic matrix. The chambers of some miliolids are filled with micrite. This microfacies indicates deposition in a shallow to reefal marine environment.

Dolostone

The dolostone was described in the middle part of the Observatory Formation, attaining a thickness of about 2.0 m. The rock is a very hard, dark gray, and massive dolomite. It consists of unzoned dolomite rhombic-shaped crystals, usually euhedral to subhedral grains having equigranular and xenotopic texture. This microfacies type was probably deposited in intertidal to supratidal environment.

Bryozoan grainstone (Fig. 15f)

The bryozoan microfacies was recognized from the upper beds of the Observatory Formation, attaining a thickness of about 10–15 m. The rock itself is composed of dark gray to brownish, hard, and siliceous bryozoan limestone. Petrographically, this microfacies type consists mainly of bryozoa forming about 95 % of the rock. The bryozoa are well preserved, and the walls of zooids are neomorphosed into microcrystalline calcite. The microfacies includes few quartz grains and some iron oxide pellets. Ferrugination and siliceous fillings are the main diagenetic features recorded in this microfacies.

Facies interpretation

According to the Standard Microfacies Type (SMF), the above described six microfacies types recognized in the beds of the Bartonian Observatory Formation can be correlated with the SMF 9, SMF 11, and SMF 18 indicating deposition in a shallow marine platform, neritic to reefal environment within euphotic zone (FZ 7 and FZ 8), normally above fair-weather wave base. Water depths are a few meters to tens of meters with open circulation.

Microfacies types of the Sannor Formation: description and interpretation

The Bartonian Sannor Formation represents a transitional unit from the shallow marine, neritic to reefal facies; Observatory Formation, to a more restricted-marine, sheltered lagoon facies; Sannor Formation. Eight microfacies types were recognized in the rocks of the Sannor Formation in both Gebel Akheider and Gebel El Ramliya sections located in the eastern part of the study area.

Lime mudstone

The lime mudstone microfacies type was recorded in the lowermost beds of the Sannor Formation in Gebel Akheider section, assumes a thickness of about 3.0 m. The rock is a gray to grayish white limestone, thin bedded, laminated, hard, and non-fossiliferous. The microfacies is mainly composed of micritic matrix containing scattered small bioclasts of pelagic microfossils (foraminifera) and few scattered thin molluscan shell fragments. This microfacies association can be correlated with the SMF 3-For (pelagic foraminifera), deposited in Toe-of-slope (open deep shelf; FZ 3) below wave base. Water depth perhaps is 200–300 m.

Nummulitic wackestone (Fig. 16a)

The nummulitic wackestone microfacies was described in the lower member (Sn_1) of the Sannor Formation in both Gebel Akheider and Gebel El Ramliya sections, attaining a thickness of about 25 and 15 m, respectively. In the field, the rock consists of nummulitic limestone, earthy gray to grayish white, hard, thick bedded, sandy, bioturbated, and including chert nodules at top. This microfacies is mainly composed of allochemical constituents represented by *Nummulites* spp.

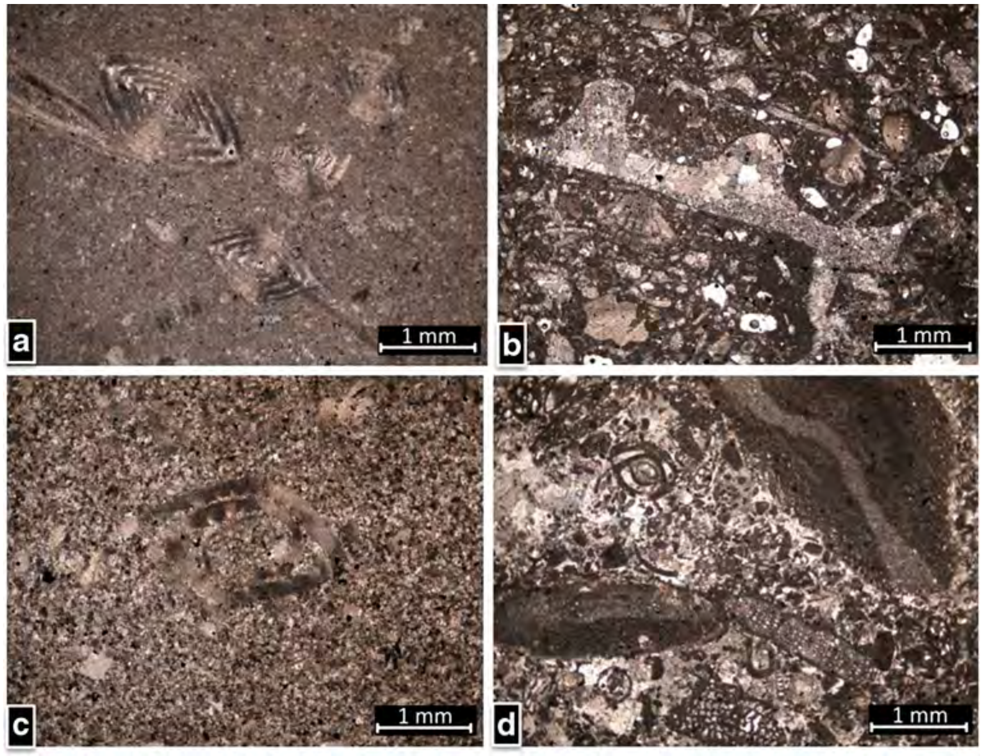

Fig. 16 Microfacies types described in the Bartonian Sannor Formation. **a** Nummulitic wackestone, the nummulites are well preserved maintaining their original radial textures and embedded in a micritic matrix. **b** Shelly oyster packstone, showing aggrading neomorphism, and embedded in a dark dense micrite. **c** Nummulitic dolostone, where the dolomite fills and cut across the boundaries of nummulites. **d** Somalina/miliolidae pack to grainstone, cemented by a sparry calcite

(15 %) of the rock volume, bryozoan remains (3 %), and recrystallized shell fragments (1 %). These allochems are well preserved maintaining their original radial textures and embedded in a micritic matrix.

Recrystallized bryozoan packstone

This microfacies type was recorded in the middle part of the first member (Sn_1) of the Sannor Formation, assumes about 20 m thick at Gebel Akheider section and about 25 m at Gebel El Ramliya section. In the field, the rock consists mainly of bryozoan limestone, gray, hard, thick bedded, bioturbated, and sandy. This microfacies is petrographically composed of bryozoa (70 %) of the rock and small miliolids (10 %) embedded in a dense micritic matrix, sparitic in parts. The bryozoa is affected by aggrading neomorphism, where the micrite is neomorphosed into sparry calcite. Some miliolidae are filled with microsparite.

Shelly oyster packstone (Fig. 16b)

The oyster microfacies type was recognized in the middle part of the Sannor Formation in Gebel El Ramliya section, attaining a thickness of about 4.0 m. The rock is lithologically composed of fossiliferous limestone, gray to yellowish white, massive, and moderately hard. This microfacies consists mainly of oyster shell fragments (85 %), gastropods (4 %), nummulites (3 %), and echinoids (2 %) showing aggrading neomorphism in which the micrite is replaced by sparitic calcite. These particles are embedded in a dark dense micrite.

Miliolidae/algae packstone

This microfacies association is common in the Sannor Formation in both its two members. It characterizes the upper beds of the first member (Sn_1) and the lower part of the second member (Sn_2), attaining a thickness of about 40 m. Lithologically, the rock consists of fossiliferous limestone, gray, hard, thin bedded, bioturbated, and sandy. Petrographically, this microfacies is mainly composed of allochemical particles embedded in a sparry calcite matrix, micritic in parts. The allochems are mainly represented by different species of family Miliolidae (65 %) (Fig. 9f), e.g. *Idalina cuvillieri*, *Pseudolacazina*, *Quiqueloculina*, *Triloculina* and *Pyrgo. Dictyoconus aegyptiensis*, *Orbitolites* sp. cf. *complanatus*. Algal fragments are also found constituting about (15 %) of the rock volume. Most of these bioclasts are filled with macrocrystalline calcite due to aggrading neomorphism maintaining their original microstructure and enveloped with micrite, whereas few others are completely dissolved.

Nummulitic dolostone (Fig. 16c)

The nummulitc dolostone lithofacies was described in the rocks of the lower member (Sn_1) of the Sannor Formation, attaining a thickness of about 5.0 m. It consists of massive, dark gray, and very hard dolomite including *Nummulites* spp.

Petrographically, the rock is composed mainly of euhedral to subhedral rhombs of dolomite forming about 90 % of the rock and about 10 % of *Nummulites* spp. The nummulites are partly recrystallized to dolomite, and rhombs of dolomite can be seen to fill and cut across the boundaries of nummulites. The dolomite is unzoned crystals having equigranular, xenotopic fabric. Dolomitization was caused by the mixing of surface fresh water with saline water in the porous and permeable limestone within a few meters of the surface. The nummulitic dolostone was probably deposited in intertidal to supratidal environment.

Dictyoconus/miliolidae pack to grainstone

This microfacies association is the most common in the Bartonian Sannor Formation. It was recognized in both members of the Sannor, attaining about 70 m thick. The rock is lithologically composed of fossiliferous limestone, gray to whitish gray, thick bedded, bioturbated, dolomitic in parts, and chalky in others. Petrographically, it is composed mainly of benthic foraminifera represented by *Dictyoconus egyptiensis* (70 %) (Fig. 9b), miliolids (10 %) represented by *Idalina*, *Pseudolacazina*, *Quiqueloculina*, *Triloculina*, *Biloculina*, and *Pyrgo*), bryozoa (3 %), echinoids (2 %), and rare algal fragments (1 %) of the rock. All allochems are well preserved, embedded in coarse-grained sparry calcite cement, and some miliolidae are filled with sparite reflecting deposition in a shallow marine, more restricted sheltered lagoon environment.

Somalina/miliolidae pack to grainstone (Fig. 16d)

The Somalina/miliolidae packstone to grainstone microfacies is very common in the Sannor Formation, characterizes its upper member (Sn_2), and assumes about 58 m thick. The rock in the field consists mainly of chalky limestone, grayish white and white, thick bedded, bioturbated, and including coralline algae near the top. This microfacies is petrographically composed of allochems represented mainly by *Somalina stefaninii* (40 %), Miliolidae (8 %), *Orbitolites* sp. cf. *complanatus* (6 %), *Rhabdorites minima* (5 %), algae (3 %), and *Dictyoconus aegyptiensis* (2 %). The bioclasts are well preserved, and the miliolidae are filled with sparry calcite. They are cemented by a sparry calcite reflecting deposition in quiet water shallow marine environment in a shelf lagoon with somewhat low energy.

Facies interpretation

The Sannor Formation in both Gebel Akheider and Gebel El Ramliya sections was deposited in a very shallow and erratic sea, most probably sheltered lagoon environment with restricted circulation and hypersaline water (SMF 9 and FZ 8). Intercalations of backages of skeletal wacke and packstones with oysters, gastropods, echinoids, and algae ascertain intermittent shallow-water deposition, with smooth transition between deeper and shallower facies. Water depth is below one meter and few meters. The high content of algae in the upper beds of the Sannor Formation suggests deposition in a light-penetrated photosynthetic zone on a restricted-marine platform.

Microfacies types of the Qurn Formation: description and interpretation

Three microfacies types were recognized in the beds of the Bartonian Qurn Formation, arranged from base to top.

Sandy shelly wackestone (Fig. 17a)

This microfacies association is common in the lower member (Qn_1) of the Qurn Formation at Gebel El Qattamiya, Umm Reheiat, and Gebel Abu Shama sections, assuming a thickness of about 20, 15, and 25 m, respectively. Lithologically, the rock is marly limestone alternating with marl thin beds, yellowish white to faint yellow, moderately hard, thin bedded, sandy, and bioturbated, including *Ostrea reili*, *Vulsella crispata*, *Lucina pharaons*, *Lucina egyptiaca*, and very rare foraminifera and ostracods. The microfacies consists petrographically of bioclasts represented by oyster shell fragments (12 %), well preserved having foliated microstructure and long-curved shape. Echinoids and bryozoan fragments are also recorded together with quartz grains (Fig. 17b). These components are embedded in a micritic matrix (75 %) of the rock. Some of this micrite are partly neomorphosed into microspars filling the intergranular spaces. This microfacies type can be compared to the SMF 8 and SMF 9 deposited in the shelf lagoon of low-energy environment in quiet water below wave base (FZ 2 and FZ 7) with normal salinity, oxygenated water conditions, and good current circulation. Water depth is tens of meters.

Nummulitic/miliolidae pack to grainstone (Fig. 17c, d)

The nummulitic/miliolidae pack to grainstone microfacies is very common in the lowermost beds of the upper member (Qn_2) of the Qurn Formation. In the field, the rock is composed of white nummulitic chalky limestone, assumes a thickness of about 4.0 m. Microscopically, this microfacies consists of allochems (up to 65 %) mostly larger benthic foraminifera, miliolids (10 %) as *Sphaerogypsina globula*, *Quinqueloculina*, *Triloculina*, *Biloculina*, *Pyrgo*, and few ostracods (4 %) These bioclasts are embedded in a sparry calcite groundmass containing few scattered, fine-grained quartz grains (2 %) reflecting shallow marine environment. Most

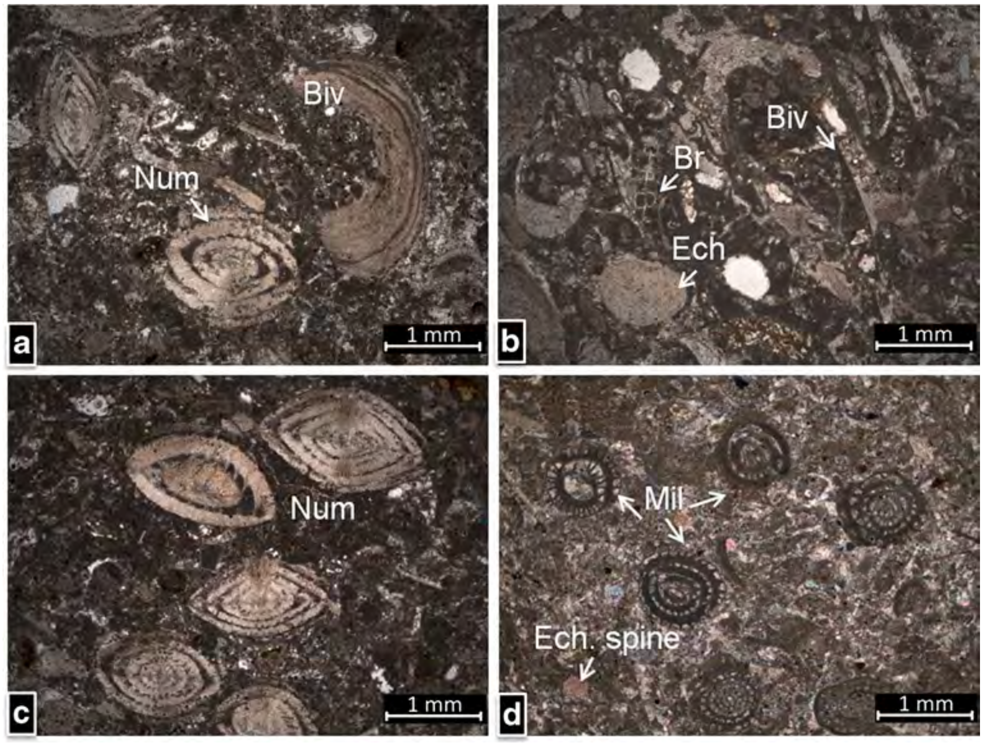

Fig. 17 Microfacies types recognized in the Bartonian Qurn Formation. **a**, **b** Sandy shelly wackestone, the oyster shells are well preserved having foliated microstructure. **c**, **d** Nummulitic/miliolidae pack to grainstone, embedded in sparry calcite groundmass

bioclasts are well preserved and filled with microcrystalline calcite as a result of aggrading neomorphism.

Shelly nummulitic grainstone

This microfacies is well known in the upper beds of the upper member (Qn_2) of the Qurn Formation, attaining a thickness of about 6.0 m. It consists of marly limestone, chalky in parts rich in *Nummulites* spp., echinoid spines, *Turritella* sp., and oyster shells. This microfacies is composed of coated bioclasts represented by *Nummulites* spp. (55 %), echinoid spines (20 %), and oyster shell fragments (15 %) embedded in a micritic matrix. The oyster shells are well preserved, with foliated internal microstructure. The nummulites exhibit micrite envelops indicating micritization process occurs in a very shallow environment. Therefore, this microfacies type can be correletaed with the SMF 10 and SMF 11, indicating deposition in open sea shelf (FZ 7) and in reefs (FZ 5) with normal marine salinity.

Facies interpretation

The microfacies types and the wide occurrence of various ostracod species in the Qurn Formation indicate its deposition in a high energy, shallow marine environment (Whatley 1983, 1988a, 1988b; Brouwers 1988). The formation was deposited in shallowing-upward cycle starting at base with the wackestone microfacies and ends by shelly nummulitic grainstone. These facies can be correlated with the SMF 8, SMF 9, SMF 10, and SMF 11 of the Standard Facies Types of Wilson model (1975) reflecting deposition in a very shallow marine most probably in shelf lagoon and reef environments (FZ 2, FZ 5, and FZ 7). Water depths are some meters.

Facies and depositional environments of the Maadi Formation

The Late Eocene, as mentioned earlier, has witnessed a marked change in the sedimentary facies from carbonate sediments which constitute the main bulk of both Observatory and Qurn formations, into clastic sediments with less carbonates (Maadi Formation) indicating a severe change of the depositional regime by the advent of the Late Eocene time, from shallow marine platform into littoral, tidal, and subtidal environment.

The Maadi Formation is a carbonate–siliciclastic facies showing shallowing-upward cycles. It can be subdivided into two main facies types, from base to top: (1) carbonate facies and (2) siliciclastic facies. The basal carbonate facies, about 40 m thick, consists mainly of marly limestone, ochreous grits, and yellowish brown, gypseous marls intercalated with sandy marl beds crowded with *Ostrea clotbeyi*, *Ostrea multicostata*, and gastropods forming marked banks. This facies represents a transitional unit between the underlying nummulitic carbonate facies (Qurn Formation) and the overlying siliciclastic facies. It can be correlated with the SMF 12 indicating its deposition in restricted platform and tidal flats (FZ 8) and open platform (FZ 7) within euphotic zone, normally above wave base. Water depths are a few meters.

The siliciclastic facies, about 15 m thick, consists of fissile, laminated, greenish gray, and gypseous shales alternated with cross-bedded sandstone, claystone, and siltstone lamina, capped by hard bed, 5.0 m thick, yellow marly limestone overcrowded with *Carolia placunoides* Cantraine forming a well-marked bank. Sandstone intercalations probably indicate the presence of an emergent source area. The cross-bedded sandstone and siltstones indicate deposition close to the shore. The claystone beds and gypsum veinlets may reflect sedimentation in shelf lagoon environment under quiet water and severe evaporation conditions. The accumulation of *Carolia* shells reflects deposition in shelf edges under brackish water conditions (Carbonel and Pujos 1981). It can be compared with the SMF 11 deposited in a winnowed platform edge (FZ 6) above wave base, within the euphotic zone, and highly affected by tidal currents.

Summary and geologic history

The stratigraphic and paleogeographic setting of Cairo–Suez district was affected to some extent by the collision between both Africa and Europe plates and its related impacts on the development and distribution of the different stratigraphic units in this district (Issawi et al. 2009). The collision between the two plates took place most probably at the Lutetian (*ca*. 40 million years) known in the literature as the Pyrenean–Atlasic Compressive event (Guiraud 1986; Guiraud and Bellion 1995). This event resulted into the development of a belt of domal structures between Taba in the east and Cairo in the west and dissected by many faults. This belt was named the Trans North Egypt Fracture Zone (TNEFZ, Issawi et al. 2009). Synchronous with the Pyrenean–Atlasic Compressive event was the continuous continental rifting of the Gulf of Suez that initiated in the Jurassic and continued to the Late Miocene (cf. Mckenzie et al. 1970; Le Pichon and Francheteau 1978; Cochran 1983; Girdler and Southren 1987; Hempton 1987; Joffe and Garfunkel 1987; Steckler et al. 1988; Coleman 1993; Khalil and McClay 2001; Bignot and Strougo 2002; Issawi and Osman 2002; Bosworth et al. 2005; Tueckmantel et al. 2010; Selim 2011). The Cairo–Suez district represents the western shoulder of the Gulf of Suez rift, dominated by normal faults with sinuous trends that strike roughly parallel to the rift creating many tilted blocks (Said 1962). The stresses originated by the Pyrenean–Atlasic Compressive event together with the Suez Gulf rifting resulted into break-up of the different stratigraphic successions on both sides of the Gulf of Suez creating many grabens, half grabens, and horst blocks of variable sizes and amplitudes (Issawi and Osman 2002). These blocks were covered subsequently by stratigraphic units including many unconformities and gaps in the sections. The rifting was often associated with periods of erosional disconformity indicated by the presence of 1.5 m red carbonate bed at Gebel El Qattamiya, reddish sandstone bed (paleosol; 2.5 m thick) at Gebel Abu Treifiya, 2.0 m glauconitc greenish sandstone bed at Gebel Akheider, and 5.0 m paleosol horizon at Gebel Ataqa (Osman 2003). These structures caused a variation in the sedimentary facies and stratigraphic sequences deposited on and around the faulted blocks. The output picture of these global and regional events is adjacent tilted fault blocks usually of different stratigraphy and lateral facies changes.

The Paleogene sediments in the study area can be stratigraphically subdivided into seven rock units arranged from base to top: Minia Formation (late Ypresian), Gebel Hof Fm., (Bartonian), Observatory Fm., (Bartonian) coeval with Sannor Fm., in the eastern part of the study area, Qurn Fm., (Bartonian), Maadi Fm., (Priabonian), and Gebel Ahmer Formation (Oligocene). The Paleocene sediments in the area studied are not recorded, and they are totally missing at Ataqa block, where the Ypresian Suez Formation unconformably overlies the Maastrichtian Maghra El Bahari Formation (Osman 2003). To the north of the Southern Galala Plateau, at Wadi El Dakhl, Haggag (1991) recorded many unconformities throughout the Paleocene sequence which increase northward, and the period is totally missing at Gebel Ataqa (Osman 2003). These unconformities together with lateral and vertical facies changes echoed in the active block movements the area witnessed since the Paleozoic became more vigorous as the timing of the great rift was approached.

The Lower Eocene rocks are recognized in the study area for the first time at Gebel Abu Treifiya. They are represented by the Minia Formation, *ca*. 210 m thick, consists mainly of thick-bedded white and earthy gray, hard, and nummulitic limestone at the lower and middle parts including chert bands, dolomite at the upper beds. The Minia Formation, at Gebel Abu Treifiya, can be subdivided lithologically into four different members: (Mn_1), (Mn_2), (Mn_3), and (Mn_4). The relationships between the different members of the Minia Formation show a highly seismic, uneven precipitation of these units. The unconformity in-between the two lower members (Mn_1) and (Mn_2) and also the paleosol layer in-between (Mn_2) and (Mn_3) ascertain this approach. The Minia Formation yielded several benthic foraminiferal species, e.g., *Nummulites praecursor*, *Alveolina frumentiformis* Schwager, and others (*vide supra*), which ascertain the late Early Eocene for this section. The different microfacies types and foraminiferal assemblages recorded in the rocks of the Minia Formation indicate a shallowing-upward cycles in carbonate rocks. These cycles are well observed where the lime mudstone and wackestones microfacies types at base (deposited in deep shelf margin and open-marine platform (FZ 2, FZ 3, and FZ 7) followed upward by packstone to grainstone and dolostones microfacies, reef slope, and restricted-shallow marine platform (FZ 4 and FZ 8) and then followed by bryozoan reefs reflecting deposition in platform-margin reefs (FZ 5) in a warm, low-energy environment within the euphotic zone.

The Minia Formation was originally assigned to the early Lutetian by Said (1960) and was used for many years, e.g., Bishay 1961, 1966; Said and Martin 1964; Boukhary 1970; Hassan et al. 1978 and many others. Later, Boukhary and Abdelmalik (1983) made a revision of the stratigraphy of the Eocene deposits of Egypt, and based on the foraminiferal assemblages, they (op. cit) suggested that the Minia Formation is not younger than the Cuisien (late Early Eocene). The fact that the Early Eocene sea transgression swept over all Egypt and was recorded in North Sudan (Klitzsch 1984), 300 km south of Egypt, substantiates that north Egypt was covered by Early Eocene sea. This conclusion is accepted and followed in the present work. The presence of the Lower Eocene Minia Formation, 210 m thick, in Gebel Abu Treifiya section indicates that the area was lowland, invaded by the Early Eocene sea, also depositing 224.2 and 488.5 m at Gebel Ataqa and Northern Galala plateau, respectively (Osman 2003).

The Lutetian sediments are not recorded in all the studied sections reflecting instability in the deposition echoed in the active block movements the area witnessed since the Paleozoic. A sudden drop in sea level during the Lutetian (Issawi 2002, 2005) was another factor affecting the non-deposition of the Lutetian sediments in the study area.

The absence of the Lutetian rocks in Gebel Abu Treifiya section can be interpreted as due to uplifting and tilting of Abu Treifiya block as a result of the rejuvenation of the E–W and NW–SE faults, running along Wadi Umm Thibau. The uplifting was followed by an erosive phase indicated by red, reddish brown, ferruginous, bryozoan, and sandy carbonate crust (0.5 m thick) capping the Lower Eocene beds. A similar case was also reported at the nearby Ataqa block, since it was high during the Lutetian, recorded at Wadi Gamal in Gebel Ataqa, indicated by about 5.0 m paleosol horizon, overlain by *ca*. 40 m thick Bartonian Sannor Formation (Osman 2003). At Wadi Naaut in the Northern Galala Plateau, the Lutetian Mokattam Formation was recorded by Osman (op. cit), attaining a thickness of about 60 m, conformably overlying the Lower Eocene Thebes and Minia formations. The unstability of the late Ypresian as indicated above heralded for the uplift of many sections in NE Egypt, hence the major unconformity in-between the Ypresian and the Bartonian. Although in the sections, e.g., Northern Galala plateau, the Lutetian was deposited in low areas relative to the other high areas, Gebel Abu Treifiya and Gebel Ataqa, which were not reached by the Lutetian transgression.

The Bartonian sea transgressed over the area studied depositing Gebel Hof Formation at base, Observatory Formation in the middle (coeval with Sannor Formation in the eastern part of the study area), and Qurn Formation at top. These formations were recorded in most of the studied sections; Gebel Abu Shama, Gebel El Qattamiya, Gebel Umm Reheiat, Wadi Gharaba, Gebel El Ramliya, and Gebel Akheider. The lower Bartonian Gebel Hof Formation is a nummulitic limestone including dolomitic limestone bands rich in *Nummulites bartovigatus* Boukhary and Hussein (Boukhary et al. 2002), attaining a thickness ranging from 15–18 m at the base of Gebel Abu Shama, decreases eastward to about 8.0 m at the base of Wadi Gharaba section. The only microfacies type described from the rocks of Gebel Hof Formation, sandy nummulitic wackestone, probably corresponds to (SMF 18) that indicates deposition in an open-marine plarform, (FZ 7), with open current circulation and receiving small amount of detrital sand grains. Water depth is tens of meters within the euphotic zone. The Gebel Hof Formation was deposited under relatively deep marine conditions in contrast to the overlying Observatory Formation; shallow marine, neritic to reefal environment.

The middle Bartonian Observatory Formation consists mainly of nodular nummulitic limestone; white to whitish gray, moderately hard, thin bedded, bioturbated and chalky at the lower part, while dolomitic in the middle and upper parts. The nodular limestone characterizes the lower part of the Observatory Formation indicates an unstable area during deposition, probably related to highly pulsating seismicity in the area. Well-marked chert bands (12 cm each) and concretions are most common in the middle part. The upper part of this formation is characterized by the great abundance of coralline and bryozoan colonies-forming. The growth of the Bryozoa and corals probably indicates deposition in warm, high salinity water, and soft substrate (Cheethman 1963; El Safori et al. 1997). The Observatory Formation attains a thickness of about 40, 60, and 63 m at Gebel Abu Shama, Wadi Gharaba, Gebel El Qattamiya, and Gebel Umm Reheiat, respectively. It conformably overlies the Gebel Hof Formation at Gebel Abu Shama and Wadi Gharaba sections and conformably underlies the Qurn Formation in the western part of the study area at Gebel Abu Shama, Wadi Gharaba, Gebel El Qattamiya, and Gebel Umm Reheiat. Petrographically, six microfacies types were described in the Observatory Formation corresponding to the SMF 9, SMF 11, and SMF 18 reflecting deposition in a shallow marine platform, neritic to reefal environment within euphotic zone (FZ 7 and FZ 8) with open circulation. These conditions changed laterally into a more restricted, sheltered lagoonal facies (Sannor Formation). The Observatory Formation yielded very rich larger benthic foraminifera, e.g., *Dictyoconus aegyptiensis* Chapman, *Rhabdorites minima* Henson, and others (*vide supra*). Few ostracods were also recorded from the Observatory Formation as *Bairdia* sp. and echinoids as *Echinolampus africanus* and *Echinocyamus blanckenhorni*.

The coeval Sannor Formation is well represented in two sections: Gebel Akheider (175 m thick) and Gebel El Ramliya (120 m thick), consists mainly of chalky limestone rich in *Somalina stefaninii* Silvestri, *Dictyoconus aegyptiensis*

Chapman, and others (*vide supra*). These foraminiferal assemblages ascertain the Bartonian age for the Sannor Formation. Based on both lithological and microfacies types, the Sannor Formation in both Gebel Akheider and Gebel El Ramliya sections was deposited in a very shallow and erratic sea, most probably sheltered lagoon environment with restricted circulation and hypersaline water (SMF 9 and FZ 8). Water depth is below 1 m up to few meters. The high content of algae in the upper beds of the Sannor Formation suggests deposition in a light-penetrated photosynthetic zone on a restricted-marine platform.

The upper Bartonian Qurn Formation consists mainly of marly limestone at the lowermost part alternating with fossiliferous sandy marl beds, whereas the uppermost beds are dominated by chalky limestones rich in benthic foraminifera, e.g., *Nummulites* aff. *Pulchellus*, *Nummulites* sp. cf. *beaumonti*, and others (*vide supra*). At Gebel El Qattamiya, the Qurn Formation is subdivided into two members. The lower member (Qn_1; 15–20 m thick) is marly limestone and marl interbeds, whereas the upper member (Qn_2; *ca*. 15 m thick) consists of white chalky nummulitic limestone with few interbeds of sandy marl. The Qurn Formation attains a thickness of 35 m at Gebel Abu Shama, 15 m at Wadi Gharba, 30 m at Gebel El Qattamiya, and about 25 m at Gebel Umm Reheiat section. The microfacies types recognized from the Qurn Formation point to deposition in a very shallow marine most probably in shelf lagoon and reefs environments (FZ 2, FZ 5, and FZ 7) in the form of shallowing-upward cycles. These cycles start at base with the wackestone microfacies and end by shelly nummulitic grainstone (SMF 8, SMF 9, SMF 10, and SMF 11). This section closes the Middle Eocene history in the study area.

By the close of the Middle Eocene and the advent of the Late Eocene, the area was gradually uplifted associated with an extensive phase of erosion, evidenced by the highly eroded Bartonian Qurn Formation, which conformably overlies the Observatory Formation with a wide bench in-between. In this context, the erosion might also reach the upper beds of the Observatory Formation, since a red calcareous bed (1.5 m thick) was observed covering the topmost surface of Observatory Formation and also below the Upper Eocene Maadi Formation in some localities, e.g., Gebel El Qattamiya.

It seems that although apparent conformities distinguish the Bartonian section in the present area, yet the small thicknesses of the many Bartonian units here relative to the nearby sections, Gebel Ataqa and Northern Galala plateau, prove that the study area was constantly and structurally active during this time.

The facies changes, by the close of the Middle Eocene from carbonate facies to clastics with minor carbonate facies, a relatively shallow marine environment which changed vertically and laterally into protected and shallow water character, is related to two major events: the first event was the gradual rising of the Red Sea Hills—a pre-rift movement—which occurred in two main pulses, usually associated with volcanic eruptions, most abundant on the rift shoulders. The first pulse most probably started at Priabonian–Rupelian time span, *ca*. 34 Ma (Omar and Steckler 1995) while the second began at the Chattian and going through the Aquitanian (Early Miocene). These pulses most probably coincided with the second major event, known as the Lutetian Pyrenean–Atlasic Compressive event (Guiraud 1986), which resulted into the development of a new deposition regime in the Eocene history of Egypt.

The rising of the Red Sea Hills together with the gradual retreat of the Mediterranean Sea shoreline northwards has resulted into the continuous shallowing-upward from the late Bartonian till late Oligocene. The deposition and distribution of the Upper Eocene sediments were mainly controlled by the structures and tectonics prevailed in the area studied (Patton et al. 1994). The low stand of sea level during the Priabonian is another factor affecting the type of the Upper Eocene sediments in the area studied. Due to the gradual retreat of the Late Eocene shoreline northwards, the sediments of this time unit is marked by high ratio of sand and shale beds. These sediments were deposited in grabens, half-grabens, ramps, and footslopes of the down-faulted blocks, whereas they are totally missing on the peaks of the horst blocks; the horst Middle Eocene blocks never received Upper Eocene sediments. The model that the Upper Eocene Maadi Formation was faulted down after its complete deposition upon the Middle Eocene rocks, and the area was then subjected to a wide phase of severe erosion resulted into complete removal of the Maadi Formation from the peaks of the horst blocks (Said 1962) is not accepted in the present work. Based on field observations and stratigraphic relationships, the present authors believe that the deposition of the Upper Eocene sediments took place almost during the faulting movements, i.e., syn-tectonic deposition, initiated at the beginning of the Priabonian (probably inherited from previous movements). In other words, the faulting movement was active during the deposition of the Upper Eocene sediments, i.e., syn-sedimentary faulting. This setting gave rise to variable thicknesses of the Upper Eocene sediments throughout the studied area. The thickness of Upper Eocene Maadi Formation varies from about 60 m at Bir Gindaly section, opposite the Qattamiya Cement Factory, 30–40 m southwest of Gebel El Qattamiya, and about 20 m at Gebel Abu Shama. The lithological nature of these sediments reflects a continuous shallowing and regression of the sea northward during the Late Eocene.

The Maadi Formation shows shallowing-upward cycles. The basal carbonate cycle, *ca*. 40 m thick marl and marly limestone, represents a transitional unit between the underlying nummulitic carbonate facies (Qurn Formation) and the overlying siliciclastic cycle. The lithology and fossil assemblages of this cycle support deposition in restricted platform and tidal flats (FZ 8) and open platform (FZ 7) within euphotic zone. On the other hand, the siliciclastic cycle, about 15-m-thick shale, cross-bedded sandstone and calystone, was probably deposited in a winnowed platform edge (FZ 6) affected by tidal currents. The cross-bedded sandstone and siltstones indicate deposition close to the shore. The claystone beds and gypsum veinlets may reflect sedimentation in shelf lagoon environment under quiet water and severe evaporation conditions. The accumulation of *Carolia placunoides* shells may reflect deposition in shelf edges under brackish water conditions (Carbonel and Pujos 1981).

The Oligocene fluviatile sediments were also controlled to a great extent by the structural and topographic lows, where a considerable thickness of vividly colored ocherous sands and blackish gravels was deposited filling several grabens and gently sloping areas between synthetic faults. This is followed by a phase of silica thermal springs and basaltic eruptions, as a result of the rejuvenation of the E–W and NW–SE faults during the late Oligocene. The thickness of Gebel Ahmer Formation varies from 40 to 100 m at Gebel Ahmer, 20 m thick at Gebel El Qattamiya, and 5.0 m thick south of Gebel Umm Reheiyat.

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