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Facies and sequence stratigraphy of some Miocene sediments in the Cairo–Suez District, Egypt

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ABSTRACT

The shallow-water siliciclastics and carbonates of the Miocene sediments in the Cairo–Suez District, Egypt represent an epiric ramp. The facies are characterized by stacked high-frequency cycles with restricted ramp to shoal margin sequences. Based on an extensive micro- and biofacies documentation, six lithofacies associations were defined and their respective depositional environments were interpreted. A sequence-stratigraphic analysis was carried out by integrating lithostratigraphic marker beds, facies relationships, stratigraphic cycles, and biostratigraphy. The investigated sections were subdivided into three third-order sequences, named S1, S2 and S3. S1, is interpreted to correspond to the Late Burdigalian stage (18–16.38 My), S2 corresponds to the Late Burdigalian–Early Langhian stage (16.38–14.78 My), and S3 represents the Late Langhain–Early Serravallian stage (14.78–13.66 My). Each of the three sequences was further subdivided into fourth order cycle sets and fifth-order cycles.

1. Introduction

The overall sedimentary nature of the Miocene sediments in the Cairo–Suez District, Egypt tends to be dominated by epiric ramp deposits. The Cairo–Suez area lays East of Cairo and extends about 120 km to the city of Suez. It lies between Latitudes 29°55′–30°20′N and Longitudes 31°15′–32°35′E (Fig. 1). The topography of the area is largely controlled by its structure and the relief is generally low except for few hills and small mountains. Topographically, the area is subdivided into three ridges crossing the district in a more or less E–W alignment; between these ridges there are two depressions. The Cairo–Suez asphaltic road passes through the southern one, while Gabal Ataqa, Gabal Abou Treifiya, Gabal Qattamiya, Gabal Anqabiaya, Gabal Nasuri and Gabal Mokattam form an elongated ridge running parallel to Cairo–Suez high way depression from East to West and to the South of it (Abou Khadrah et al., 1993). The oldest exposed rocks in the area are of Early Cretaceous age while the youngest rocks are of Quaternary age of sy-nrift sedimentary sequence (Bruce and Hotzl, 1988). The Miocene rocks of the Cairo–Suez area were the subject of many studies since the last quarter of the 19th century.

The regional stratigraphy of the Miocene in the Cairo–Suez area has been studied by different authors (e.g. Fuchs, 1883; Depéret and Fourtau, 1900; Blanckenhorn, 1901; Barron, 1907; Shukri and Akmal, 1953; Sadek, 1959; Said, 1962, 1971, 1990; Said and Metwalli, 1963; Ghorab and Marzouk, 1965; Abdallah and Abd El-Hady, 1966; Barakat and Aboul Ela, 1970; Stratigraphic Sub-Committee, 1974; Abbass, 1977; El-Heiny, 1982; Abdel Wahab and El-Belassy, 1987; Szczechura and Abd-Elshafy, 1988; Abd-Elshafy and Abd-Elmoneim, 1992; Hamza, 1992; Abou Khadrah et al., 1993; El-Sorogy and Ziko, 1999; El-Shazly and Saber, 1999; Abdelghany, 2002; Elattar, 2003; Mowafi, 2006). The lithostratigraphic classification of the Miocene in the Cairo–Suez area is illustrated in Table 1.

The main two aims of the present study are: (1) Identifying facies types of the Miocene sediments in the Cairo–Suez area in Egypt, as well as make an acceptable interpretation by integrates micro- and biofacies analysis to construct a 2D siliciclastic–carbonate model. (2) Estimating the studied successions in the view of sequence stratigraphic analysis by subdividing the studied sections into sequences, cycle sets, and cycles. Three stratigraphic sections have been chosen to fulfill these aims of study. These are Gabal Geneifa, Gabal Gharra and Gabal Homeira sections (Fig. 1).

1.1. Methodology

A standardized logging sheet was developed and used to log the studied sections of the Cairo–Suez District, Egypt. The main

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properties recorded in these sections are: texture, biota, grain type and size, sorting, bedding style, sedimentary features of the rocks and facies. 450 representative samples were collected from the field to produce 162 thin sections, which were examined under polarizing microscope to integrate lithological, paleontological and diagenetic data for facies characterization, and sequence stratigraphy. The nomenclature of limestone in the present study follows that system introduced by Dunham (1962) and Embry and Klovan (1972).

2. Results and discussion

2.1. Facies analysis and interpretation

14 Lithofacies types (LFT) were distinguished in the Miocene studied sections on the Cairo–Suez District (Table 2, Figs. 2 and 3). The description and classification of these lithofacies types depend on the following: textures, mineralogy, rock color, grain size, sorting, components (skeletal or non skeletal), thickness of different rock unit, bedding style, sedimentary features, interpretation of depositional setting and the appearance according to lithofacies code (Fig. 4). In general, the studied sections are divided into two lithostratigraphic units namely, the Gharra Formation and the Genefe Formation in ascending order, according to Ghorab and Marzouk (1965).

The Gharra Formation rests unconformably on sediments of Oligocene age (sands and gravels) with silicified woods in both Gabal Gharra and Gabal Homeira sections, while in Gabal Geneifa one the base of the formation is unexposed. In all the three sections, the Gharra Formation is conformably overlained by the Genefe Formation, and consists mainly of clastics (shale, claystone, marl and sandstone) with sandy limestone interbeds. The limestones are low or moderate fossiliferous to highly fossiliferous, containing rich assemblages of macrofossils.

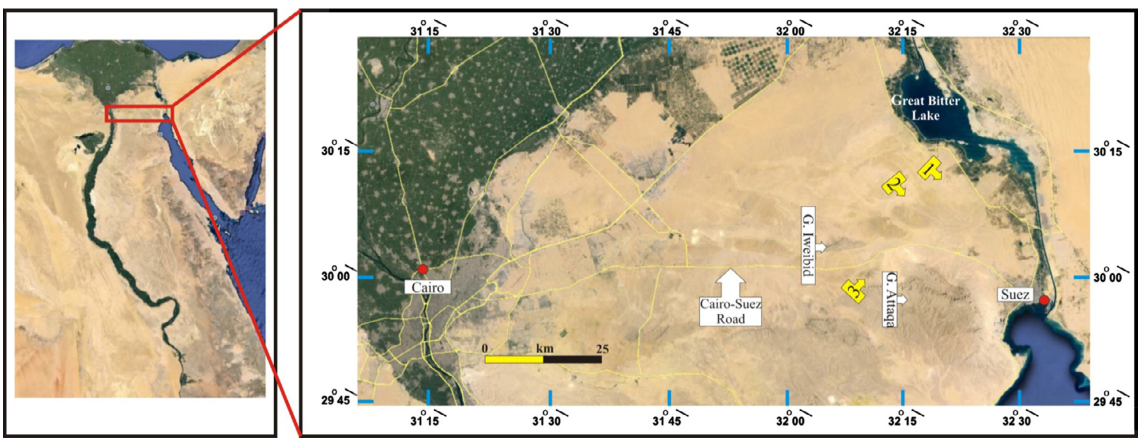

Fig. 1. Location map of the studied sections, 1. Gabal Geneifa section, 2. Gabal Gharra section, 3. Gabal Homeira section.

Table 1
Different rock units proposed by different authors for the Miocene rocks in the Cairo–Suez District.

Shukry & Akmal (1953) Shukri & Ayouti (1956)	Said (1962)	Ghorab & Marzouk (1965)	Farag & Sadek (1966)	Stratigraphic Sub Committee (1974)	Abbass (1977)	El-Heiny (1982)	Said (1990)	El Shazly & Saber (1999)	Elattar (2003)	Mowafi (2006)	Present work
Non marine Miocene	Upper Miocene: Non marine Miocene	Iweibid Fm: El-Bahhara Member; El-Hamza Member	Upper Miocene: Non marine Miocene	Upper Miocene: Hagul Formation		Plioc.: Hamzi Formation Messinian: Hagul Formation	Late Pliocene: Hamzi Formation; Hagul Formation	Late Miocene (?)		Post Middle Miocene	Post Middle Miocene
Marine Miocene	Middle Miocene: Marine Miocene; Calcerous unit	Gharra Formation (Fm): Genefe Member; Gafra Member; Abbasia Member; Reishi Member	Helvetian: Marine Miocene	Middle Miocene: Genefe Member; Hommath Formation: Gafra Member; Abbasia Member; Reishi Member	Gharra Formation: Genefe Chalky Limestone Member; Hommath Sady Limestone Member	Middle Miocene: Genefe Formation; Hommath Formation	Langhian: Genefe Formation	Middle Miocene: Genefe Formation	Middle Miocene	Middle Miocene: Genefe Formation	Serravalian: Sequence 3 Laghiam: Sequence 2
	Lower Miocene: Sandy unit	Sukhna Member	Burdigalian	Lower Miocene: Sadat Formation	Sadat reefal LST Member; Agrud S.s Member	Burdigalian: Sadat Formation	Aquitanian-Burdigalian: Gharra Formation	Early Miocene: Gharra Formation	Sadat Formation Early Miocene	Early Miocene: Gharra Formation	Burdigalian: Sequence 1
Oligocene	Oligocene	Oligocene	Oligocene	Upper Eocene	Oligocene	Oligocene	Oligocene	Oligocene	Eocene	Oligocene	Oligocene

Table 2
Description of the ithofacies types in the studied sections.

Lithofacies types	Lithology and texture	Sedimentary structure and diagenesis	Grain size and sorting	Components	Thickness	Figures
LFT 1a: Sandy silty shale	Shale, siltstone and sandstone	Fine lamination	Subrounded to subangular, poorly sorted	Iron oxides, gypsum.	Meters (m) thick units	2a
LFT 2a: Calcareous quartz arenite	Sandstone, quartz arenite	Lamination	Subrounded to angular, poorly to moderately sorted	Iron oxides, molluscan shells, feldspar grains as plagioclase and microcline	Meters thick units	2b
LFT 2b: Calcareous fossil. quartz arenite	Sandstone, quartz arenite	Lamination	Subrounded to angular, poorly to moderately sorted	Few foraminifera, echinoids, molluscan shells and euhedral and zoned dolomite	Decimeters (Dm) to several (m).	2c
LFT 3a: Sandy bioclas. dolo mudstone	Dolostone, mudstone	Bioturbation	Siltite, poorly sorted.	Few foraminifera, molluscan shells and quartz grains.	Centimeters (cm) to Dm.	2d
LFT 3b: Bioclastic dolomitic wackestone	Limestone, dolostone, wackestone	Fine grained dm thick layers, micritization, recrystallization	Siltite to fine arenite, poorly to moderately sorted	Bioclastic of shell fragments, foraminiferes (Miliolidae), echinoid fragments, dolomite rhombs and quartz grains.	Cm to Dm thick units	2e
LFT3c: Bioclastic algal wackestone	Limestone, wackestone	Micritization, recrystallization, neomorphism	Siltite to fine arenite, poorly sorted	Red algae; frequent forms of bryozoans, molluscs, echinoidal fragments, and scleractinian corals.	Dm to meters thick units.	2f
LFT 4a: Bioclastic wacke- to -packstone	Limestone, wackestone, packstone.	Graded bedding, dm thick layers	Siltite to fine arenite, poorly sorted	Polymictic bryozoans, algae, molluscan fragments, echinoids, foraminifera (*Operculina complanata*, *Amphistegina* sp., *Miogypsina* sp.), quartz grains.	Cm to meters thick units.	2g, 2h
Lithofacies types	Lithology & Texture	Sedimentary structure & diagenesis	Grain size and sorting	Components	Thickness	Figures
LFT 4b: Bioclastic bryozoan packstone	Limestone, packstone	Graded bedding, dog teeth cement, neomorphism	Fine to coarse arenite, moderately sorted	Different types of foraminifera (*Operculina complanata*, *Amphistegina* sp., miliolidae), algae, bryozoa, molluscan fragments, echinoids, algal oncoids and quartz grains.	Cm to Dm thick units	3a
LFT 4c: Bioclastic echinoidal packstone	Limestone, packstone	Graded bedding, bioturbation	Medium to coarse arenite, moderately sorted	Algae, bryozoa and shell fragments of echinoidal plates and spines, quartz grains	Cm to Dm thick units	3b
LFT 5a: Bioclastic pack- to grainstone	Limestone, packstone, grainstone	Graded bedding, recrystallization	Medium to coarse arenite, moderately sorted	Shell fragments, foraminifera (*Heterostegina* sp.), algae, pelecypod fragments, echinoidal plates and spines, quartz grains	Dm thick units	3c
LFT 5b: Molluscan grainstone	Limestone, grainstone	Cross bedding	Medium to coarse arenite, well sorted	Pelecypods, gastropods, foraminifera (*Amphistegina* sp., *Miogypsina* sp., *Operculina* sp.), ostracods, algae, bryozoans,	Dm thick units	3d
LFT 5c: Sandy fossiliferous grainstone	Limestone, grainstone	Cross bedding, neomorphism	Medium to coarse arenite, moderately to well sorted	Foraminifera (*Operculina complanata*, *Amphistegina* sp., *Heterostegina* sp. and other miogypsenoids), some serpulids, algae, ostracods, bryozoa (*Holoporella* sp.), molluscan fragments (pelecypods and gastropods), echinoidal fragments.	Dm thick units	3e
LFT 5d: Sandy algal grainstone	Limestone, grainstone	Cross bedding, micritization	Medium arenite, moderately to well sorted	Algae (*Lithothamnium* sp.), foraminifera, ostracods, pectinides, oysters, gastropods, and echinoidal plates and spines.	Several dm thick units	3f
LFT 6a: Algal coralline framestone	Limestone, framestone	Amalgamated beds	Medium arenite to fine rudite, moderately to well sorted	Organic reef (scleractinian corals and/or algae) with frequent amounts of foraminifera, shell fragments, and echinoid plates.	Several dm thick units	3g, 3h

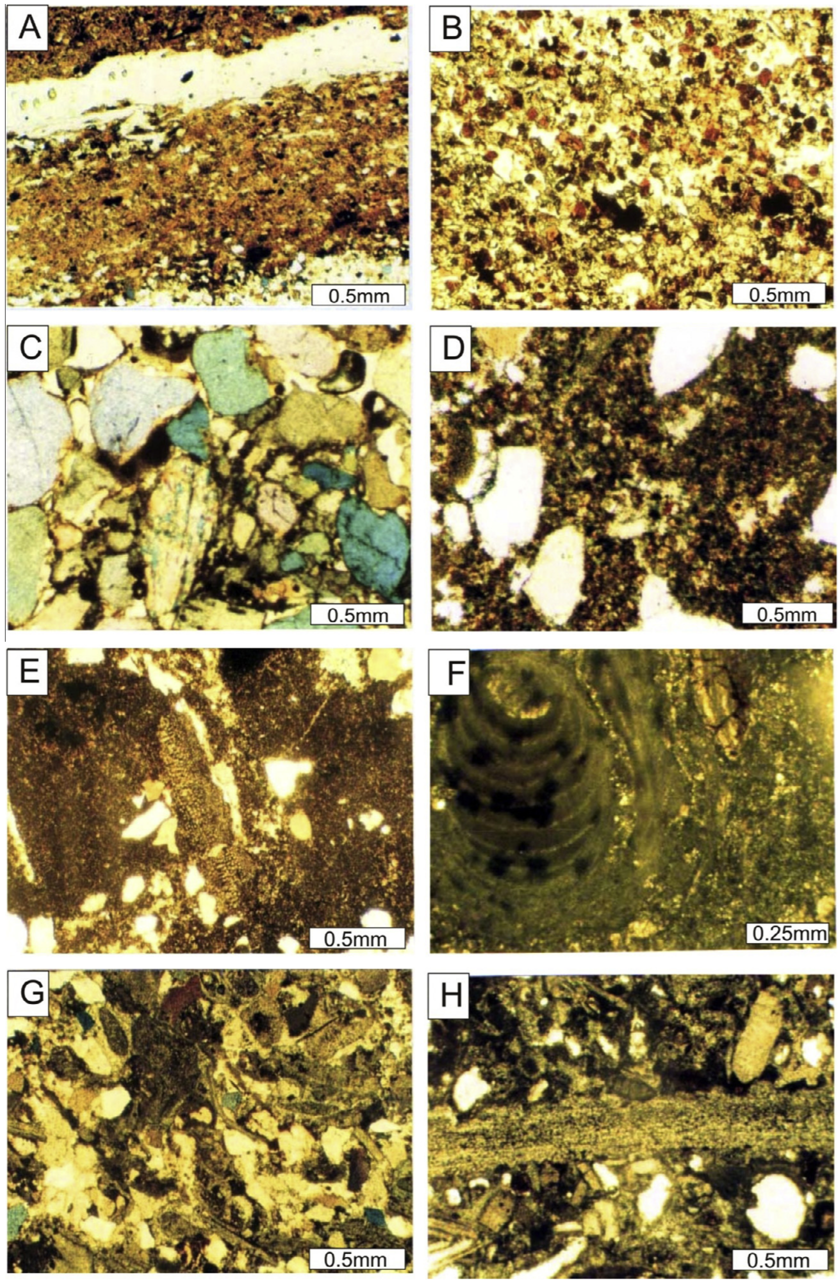

Fig. 2. (A) Sandy silty shale, Gabal Geneifa. (B) Calcareous ferruginous quartz arenite, Gabal Gharra. (C) Calcareous fossiliferous quartz arenite, Gabal Gharra. (D) Sandy Bioclastic dolo mudstone with rhombic zoned, idiotypic dolomite crystals and fine to medium quartz grains, Gabal Homeira. (E) Bioclastic dolomitic wackestone with micritized foraminiferal tests and subangular to subrounded quartz grains embdded in micrite matrix, Gabal Homeira. (F) Algal wackestone with well preserved red algae with *Lithothamnium* sp., Gabal Homeira. (G) Bioclastic wacke/packstone with foraminiferal biomorpha and bioclasts (Amphistiginids and operculinids), echinoid fragments and quartz grains, Gabal Gharra. (H) Bioclastic wacke/packstone with echinoid spine and foraminiferal test, Gabal Geneifa.

The Genefe Formation rests conformably on the sediments of Gharra Formation and its top is not covered in the three sections and it consists mainly of algal, reefal and chalky limestones with oyster banks, mudstone and calcareous shale intercalations. The limestones and calcareous shales are low or moderate fossiliferous to highly fossiliferous with macrofossils assemblages.

2.2. Lithofacies associations (LFA) and depositional model

Facies types were grouped into lithofacies associations (LFA) based on their interpreted depositional environment on the carbonate platform. Table 3 lists the names and characteristics of these lithofacies associations. From the previous data, a 2D depositional model for the inner ramp part of a platform with facies types and related depositional/lithofacies associations for the investigated area of the Miocene outcrop sections was done (Fig. 5).

2.3. Sequence stratigraphy

The interpreted lithofacies types are stacked into facies sequences of multiple hierarchies. Based on the approach of Kerans and Tinker (1997), three orders of cycles were distinguished. Cycles of small-scale order form cycle sets of medium-scale order which finally arranged in sequences (large-scale cycle). The most significant vertical changes within these successions are sedimentary texture, grain size and bio-component. The described

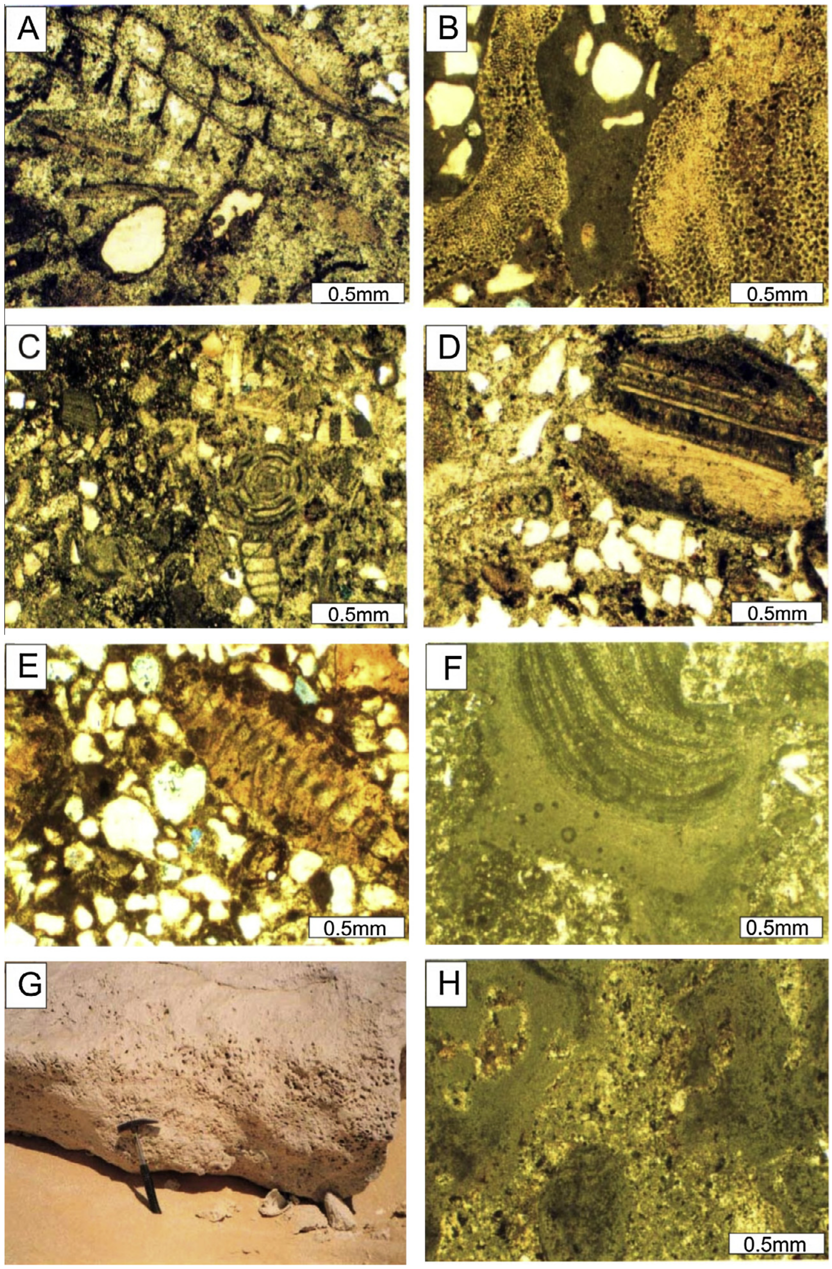

Fig. 3. (A) Bioclastic bryozoan packstone with ideoniform bryozoans, foraminiferal and molluscan shell fragments, Gabal Geneifa. (B) Bioclastic echinoidal packstone with echinoidal plates and quartz grains, Gabal Gharra. (C) Bioclastic pack/grainstone with red algal fragments (*lithophyllum* sp.), foraminiferal, molluscan, bryozoan fragments and fine quartz grains, Gabal Geneifa. (D) Molluscan grainstone with molluscan shell fragments, echinoids and polycrystalline quartz grains, Gabal Homeira. (E) Sandy fosssiliferous grainstone with echinoid fragments, complete operculinid foraminifera and quartz grains, Gabal Geneifa. (F) Sandy algal grainstone with red algal and molluscan fragments, Gabal Homeira. (G) Part of the coral reef bank in the lower part of Genefe Formation, Gabal Gharra section. (H) Algal coralline framestone with well preserved algae (*Lithophyllum* sp. and *Lithothamnium* sp.), Gabal Gharra.

cycles, cycle sets and sequences were subdivided into transgressive and regressive parts. They are separated by turnarounds, i.e. zones of maximum and minimum accommodation (Cross and Lessenger, 1998).

2.3.1. Small-scale cycles

2.3.1.1. Restricted ramp cycle type. The thickness of this rather asymmetrical cycle type ranges in thickness from 3 to 5 m (Fig. 6). The main distribution of this cycle is apparently restricted on S1 and S2 at the three studied sections. The lower part of this cycle varies from 1.25 to 4.5 m thick, consists mainly of brownish gray, moderately compact, thinly laminated, jointed, unfossiliferous, ferruginous, gypsiferous, with gypsum bands and veins (up to 2 cm thick), very slightly calcareous (LFT 1a). The vertical thickness of the upper part ranges in thickness from 0.25 to 0.75 m and consists of yellowish brown, moderately sorted and compact calcareous sandstone, with few feldspar minerals and pelecypod fragments (LFT 2a).

The lower part could be interpreted as low energy proximal peritidal facies types forming a regressive hemi-cycle. The sequence boundary is marked by change in facies from shale sediments to bioclastic sandstone. The transgressive hemi-cycle could be interpreted as a retrogradation of more distal, tidal flat facies association over the peritidal strata.

2.3.1.2. Back shoal cycle type. This cycle type has an average thickness from 6 to 8 m (Fig. 7), it exists in S1 and S2 in all sections. The basal part is several decimeters thick, begins with calcareous

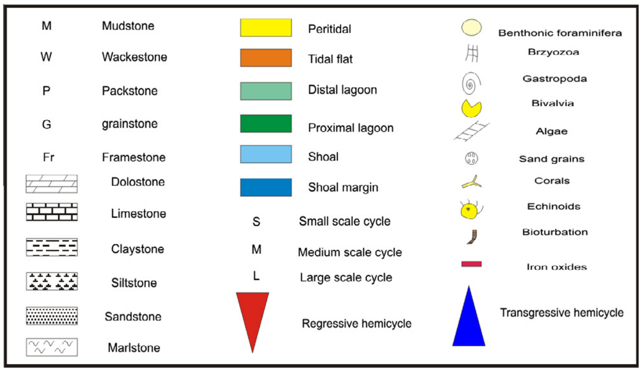

Fig. 4. Color coded texture (Embry and Klovan, 1971), lithology, lithofacies associations and fossils. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

fossiliferous, coarse grained and moderately sorted quartz arenite. Well preserved molluscan fauna and echinoids are common (LFT 2b). The facies stacking pattern is followed by up to 2 m thick units of bioclastic dolomitic wackestone that the major components of it represented by micritized foraminiferes (Miliolidae) and dominant echinoid fragments (LFT 3b). The middle part of this cycle is represented by bioclastic echinoidal packstone which contains a high amount of echinoid, algae, bryozoa and shell fragments (LFT 4c). The upper part of this cycle is several decimeters thick, consists of gray, moderately hard and poorly sorted bioclastic wacke/packstone, with subangular to subrounded mudclasts (LFT 4a).

The clastic basal part and the wackestones in the lower part of this cycle type could be interpreted as a proximal lagoon environment deposited under low energy conditions and could represent the transgressive hemi-cycle. Muddy, finely grained and prevailing echinoid beds could be interpreted as full marine distal lagoon environment and thus, the presence of a maximum flooding zone in the middle part. The regressive hemi-cycle is interpreted to be marked by the transition from the distal lagoon to proximal lagoon in the upper part.

2.3.1.3. Shoal cycle type. This rather asymmetrical cycle type ranges in thickness from 6 to 8 m (Fig. 8). The distribution of this cycle type is mainly observed in S2 and S3 in all sections. The base of this cycle is dominated by several decimeters thick, gray colored, moderately hard and poorly sorted bioclastic wacke/packstones that mostly contain polymictic bryozoans, algae, molluscan fragments, echinoids, foraminifera (*Operculina complanata*, *Amphistegina* sp., and *Miogypsina* sp.) and quartz grains (LFT 4a). These beds are overlain by up to 3 m of bioclastic pack/grainstone (LFT 5a), dominated by Shell fragments, foraminifera (*Heterostegina* sp.), algae, pelecypod fragments, echinoidal plates and spines. Above the grainstone beds, there are bryozoans wacke/packstones which contain different types of bryozoa, foraminifera (*Operculina complanata*, *Amphistegina* sp. and Miliolidae), algae, molluscan fragments, echinoids, algal oncoids and quartz grains (LFT 4b). The cycle is capped by a sharp top, marked by a bioturbated hard ground which consists of sandy wackestone.

The basal part of this cycle is represented by bioclastic wacke/packstones, dominated by bivalvian shells and foraminifera, which

Table 3
Overview of facies associations and description of sedimentary features.

LFA	Depositional environment	Sedimentary features	LFT
LFA: 1 Peritidal	The peritidal environment may develop close to the beach. The scarcity of fossils reflects unfavorable ecological conditions. The occurrence of gypsum-filled desiccation cracks in the shale facies can be related to arid climate in a supratidal sabkha setting (Bauer et al., 2001).	Siliciclastic rocks, especially a fissile shales dissected by gypsum veins. Sand and silt grains in the shale increase and localize in form of thin laminea or very thin intercalations in some parts. Iron oxides occasionally occur. Very slightly calcareous dipping to the west in Gabal Geneifa is recorded	1a
LFA: 2 Tidal flat	Low energy shallow subtidal quite marine water. Lack or rarity of evaporites suggests a humid tidal flat rather than supratidal conditions (Pope and Read, 1998)	Thin bedded fine sandstones and siltstones, interbedded by dolomudstones. Bivalve shell fragments are rare	2a,2b, 3a
LFA: 3 Proximal lagoon	Shallow protected water of a low-energy under normal marine salinities near a fair–water wave base on the proximal area of lagoon (Zinke et al., 2003)	Marlstones and sandstones, interbedded by sandy bioclastic wackestones consists mainly of *Operculina* sp., molluscan fragments and echinoids	3b, 3c, 4a
LFA: 4 Distal lagoon	Low to moderate energy shallow subtidal lagoonal setting frequently influenced by storm washovers	Bioclastics wackestones to packstones, abundant bivalves, gastropods, echinoids, bryozoans and foraminiferas are recorded	4a, 4b, 4c, 5b
LFA: 5 Shoal	Moderate to high energy of open circulation of fully marine waters, characterizing by active currents and waves suggesting shoal environment (Flügel, 2010)	Bioclastics pack- to grainstones, planar cross stratified, high diversity fauna of gastropods, corals, bivalves, bryozoans, shell debris highly abraded and echinoids	5a, 5b, 5c, 5d
LFA: 6 Shoal margin	High water energy of shoal margin deposits (Martin et al., 2011)	Low angle cross bedded and the good sorting of the components of bioclastics grainstones and coral framestone	5d, 6a

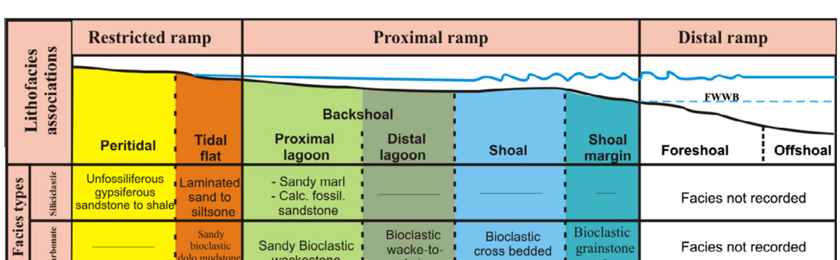

Fig. 5. Schematic depositional model displaying the relative position of the various siliciclastic and carbonate facies recorded in the Miocene studied sections. (FWWB: fair weather wave base). Not to scale.

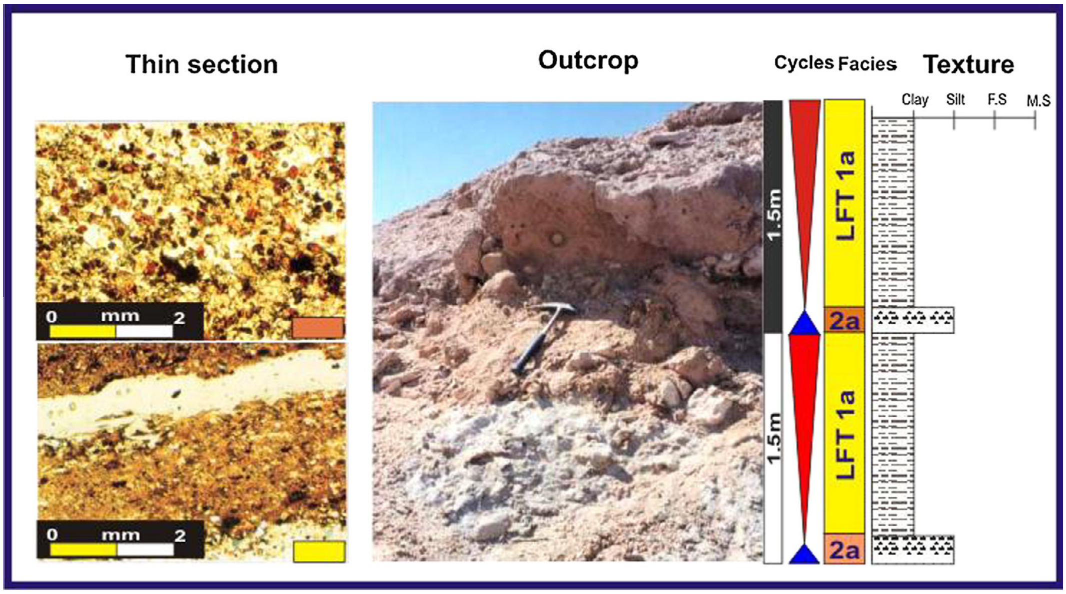

Fig. 6. Restricted ramp small scale cycle type.

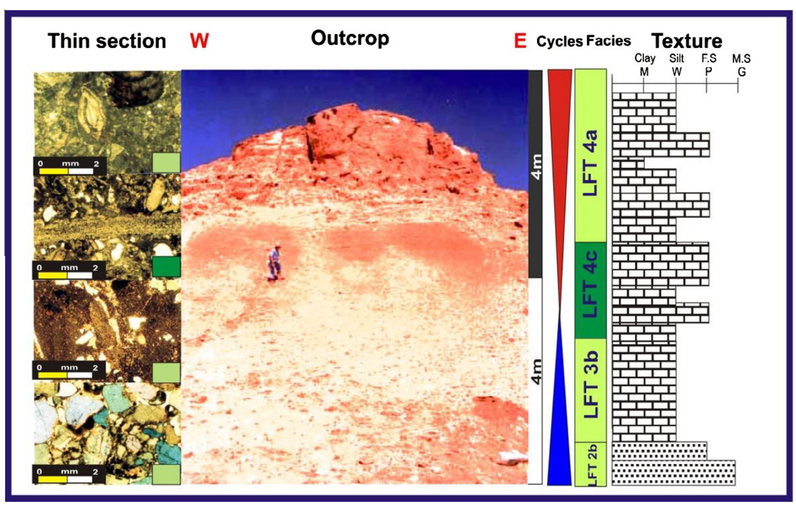

Fig. 7. Back shoal small scale cycle type.

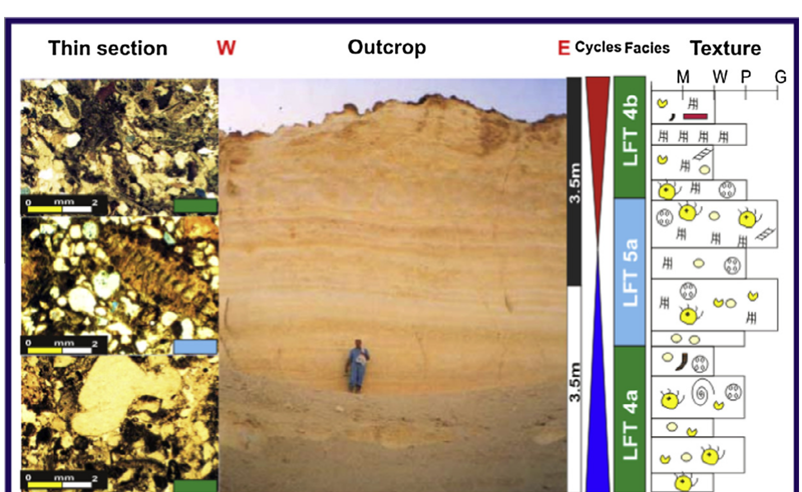

Fig. 8. Shoal small scale cycle type.

may indicate the back shoal and also could represents the transgressive hemi-cycle. The overlying shoal pack/grainstone beds could be interpreted as a maximum flooding zone. The regressive hemi-cycle shows the same succession of facies types like the transgressive hemi-cycle but in a reverse order. The sharp top of this cycle may represent the sequence boundary.

2.3.1.4. Shoal margin cycle type. This cycle ranges in thickness from 5 to 8 m (Fig. 9). They show asymmetrical patterns. The base of this cycle is dominated by several decimeters-thick sandy fossiliferous grainstones, represented by foraminifera (*Heterostegina* sp. and others) some serpulids, algae (*Lithothamnium* sp.), ostracods, bryozoa (*Holoporella* sp.), molluscan fragments (pelecypods and gastropods), echinoidal fragments (LFT 5c). The grainstones beds are overlain by 2–3 m thick of framestones. These beds contain huge amounts of scleractinian corals and algae, with frequent amount of foraminifera, shell fragments and echinoids (LFT 6a). The upper part of this cycle type is marked by sandy algal grainstones dominated by *Lithothamnium* sp., foraminiferal tests and little amount of pellets are also present (LFT 5d).

The base of this cycle is composed of fossiliferous grainstones which could be interpreted as shoal sediments, deposited under moderate to high energy conditions, forming a transgressive hemi-cycle. The continuous rise in sea level led to the deposition of algal coralline framestones indicating a shoal margin facies. The coarse-grained nature of the coralline framestones reflects high energy and could be interpreted as maximum flooding zone. A distinctive decrease in sea level is marked by decimeters algal grainstones forming the regressive hemi-cycle in the upper part.

2.3.2. Medium scale cycles (Cycle sets)

These cycle sets stack of 3 cycles, form transgressive–regressive cycle sets, some 10–25 m in thickness. Each studied section is subdivided into 3 sequences (S1, S2 and S3) which will be explained later. Each sequence contains 3 cycle sets.

2.3.2.1. Restricted ramp cycle set. This cycle set has an average thickness of 15 m and consists of 3 small scale cycles. It is found in CS 1.1, CS 1.3 and CS 2.3 in Gabal Genefe section (Fig. 10a), CS 1.1 and CS 1.3 in Gabal Gharra (Fig. 10b) and CS 1.1 and CS 2.1 in

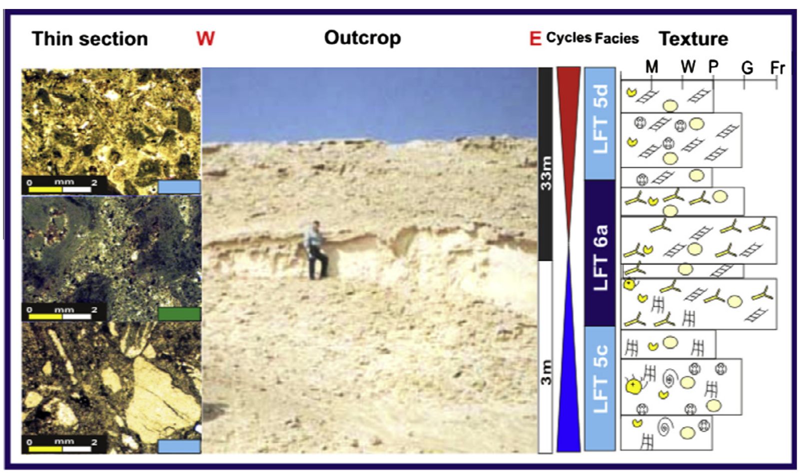

Fig. 9. Shoal margin small scale cycle type.

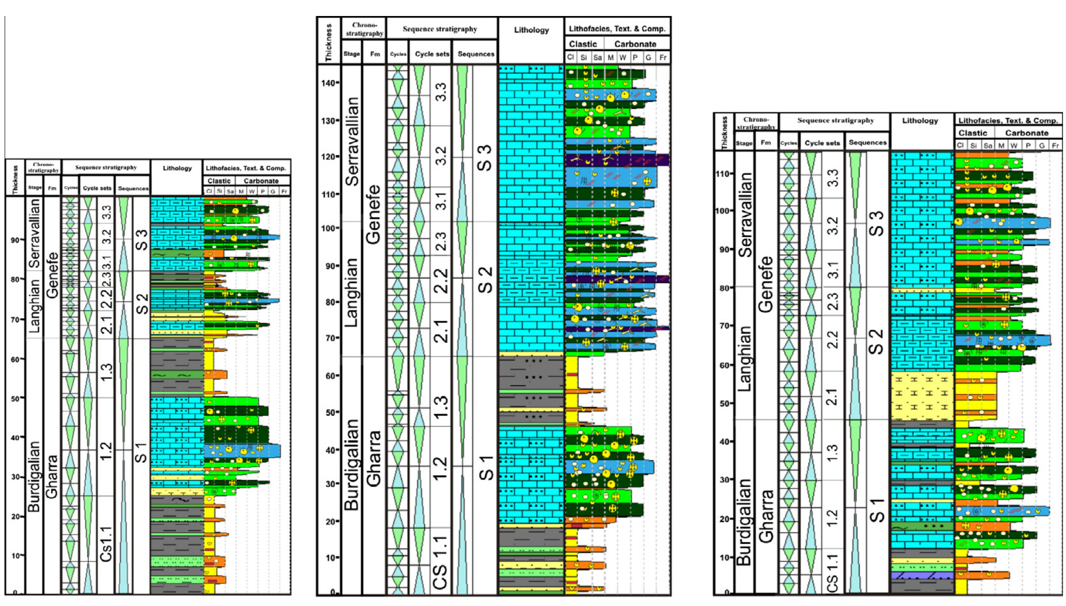

Fig. 10. The three studied sections. (A) Gabal Geneifa. (B) Gabal Gharra. (C) Gabal Homeira.

Gabal Homeira (Fig. 10c). This cycle set consists of a vertical stacking of peritidal to tidal flat small scale cycles. In the lower part, the tidal flat sediments have an average thickness of 5 m and decrease upward to a thickness of 2 m. In contrast, the upper part of the peritidal beds is of greater thickness.

The lower part is interpreted as tidal flat deposits forming a transgressive hemi-cycle while the upper part that consists mainly of unfossiliferous claystone indicates a shift toward a proximal supratidal setting and forms a regressive hemi-cycle set.

2.3.2.2. Back shoal to restricted ramp cycle set. It consists of a stack of up to 3 small scale cycles, ranges in thickness from 15 to 20 m. This cycle set type is identified in CS 2.1, CS 3.1 and 3.2 at the Gabal Genefe section (Fig. 10a). and CS 1.3, CS 2.3, CS 3.1 and CS 3.3 in Gabal Homeira (Fig. 10c). The lower part of this cycle set is about 12 m thick, which consists of yellowish brown to brown, compact, massive, argillaceous, fossiliferous, wacke/packstones, slightly ferruginous in the upper part. It contains echinoidal, molluscan and bryozoan fragments. The microfossils include algal fragments as *Lithothamnium* sp. and *Lithophyllum* sp.; foraminifers as *Operculina complanata* (Defrance), *Miogypsina intermedia* Drooger and *Amphistegina* sp. The beds grade upwards to brownish yellow and yellow bioclastic packstones and they contain a pectinids band, very crowded with *Pecten beudanti* Basterot, *P.* (*Amussiopecten*) *burdigalensis* Lamarck. These beds also yield *Gastrana* sp.; gastropods, crustacea as *Balanus*; bryozoa and algae. The upper part of this cycle set, up to 8 m thick, consists of dark brown and yellowish brown; moderately compact; laminated; gypsiferous; ferruginous; rare fossiliferous; very slightly calcareous silty claystones and sandstones.

The wacke/packstones in the lower part can be interpreted as an initial transgression within this cycle set. During sea level rise, the distal lagoon related facies types are interpreted as retrogradingn over the proximal lagoon deposits and may represent a maximum flooding zone. The regressive hemi-cycle is interpreted to be marked by the transition from the distal lagoon to the restricted ramp in the upper part.

2.3.2.3. Shoal to back shoal cycle set. This cycle set has an average vertical thickness of 18 m and consists of 3 small scale cycles that are identified in CS 1.2, CS 2.2 and CS 3.2 in Gabal Genefe section (Fig. 10a), CS 1.2, CS 2.3, CS 3.1 and CS 3.2 in Gabal Gharra (Fig. 10b) and CS 1.2, CS 2.2 and CS 3.2 in Gabal Homeira (Fig. 10c). The basal part of this cycle set ranges in thickness from 4 to 6 m and consists of yellowish white to yellowish brown; moderately compact sandy bioclastic wackestones, pebbly at its lower part. It is poorly fossiliferous, and contain some bad preserved bivalvia, *Balanus concavus* (Bronn.) and echinoid fragments. The basal part is overlain by 5 m of yellowish brown to light brown; soft to moderately compact; slightly argillaceous bioclastic grainstones that are rich with bivalves, gastropods, algae and foraminifers. The upper part is up to 6 m thick, which consists mainly of sandy bioclastic wacke/packstones which contain hunge amount of bivalvian shells as *Pecten* sp. and *Chlamys* sp., echinoides, froaminiferas and algae. This cycle set is capped by thin bedded gypsiferous, ferruginous, unfossiliferous and very slightly calcareous silty claystone.

The wackestones in the lower part could be interpreted as an initial transgression. The continuous rise in sea level led to the deposition of distal moderate to high energy bioclastic grainstones indicating a shoal facies, and could be interpreted as a maximum flooding zone. The upper part consists of muddy facies which exhibits a depositional shift toward back shoal settings during the fall of sea-level. The claystones on the top of this cycle set suggest a low accommodation restricted ramp environment and a sequence boundary.

2.3.2.4. Shoal margin to shoal cycle set. It consists of a stack of up to 3 small scale cycles and ranges in thickness from 15 to 20 m. This cycle set type was observed only at the Gabal Gharra section and is identified in CS 2.1, CS 2.2 and CS 3.2 (Fig. 10b). The basal part, up to 2 m thick, consists of yellow to yellowish white, compact, massive, slightly sandy bioclastic grainstones. They are crowded with bivalves, gastropods, echinoderms and foraminifera. Overlying the basal part, brown to yellow, moderately hard, massive and grain supported algal coralline framestones dominated by scleractinian reef which is monospecific (*Leptastrea* sp.), and it is replaced in parts with algal limestone band. The upper part of this cycle set has a range in thickness of 5 to 6 m, and is composed of yellowish white, moderately compact, chalky bioclastic algal grainstones domintated by algae *Lithothamnium* sp. and *Lithophyllum* sp., echinoids, bryozoans and few coral fragments are also recorded.

The transgressive hemi-cycle resulted in the deposition of bioclastic grainstone beds. The maximum flooding zone is built up of algal coralline framestones interpreted as a shoal margin environment. The upper beds of this cycle set exhibit a shift from the shoal margin toward the shoal settings representing a regressive hemi-cycle.

2.3.3. Large scale cycles (sequences)

Three large scale cycles (sequences) are distinguished in the studied sections. Sequence 1 ranges in thickness from 45 to 65 m, and it constitutes 3 medium scale cycles and 9 small scale cycles. The base of this sequence is unexposed and its age is interpreted to correspond to the Late Burdigalian stage (18–16.38 My), according to Snedden and Chengjie Liu (2010). Sequence 2 ranges in thickness between 20 and 40 m and is constituted of 3 cycle sets and 9 cycles. It matches the Langhian of the lower part of the Genefe formation. The base of this sequence is the boundary between Burdigalian and Langhian age. The age of S2 is interpreted to correspond to Late Burdigalian–Early Langhian stage (16.38–14.78 My). Sequence 3 ranges in thickness between 18 and 47 m and constitutes of 3 cycle sets and 9 cycles. S3 is matches the **Serravallian** of the upper part of the Genefe formation. The base of this sequence is the boundary between Langhian and Serravallian age. The age of S3 is interpreted to correspond to and Late Langhain–Early Serravallian stage (14.78–13.66 My).

2.3.3.1. Gabal genefe section.
2.3.3.1.1. Sequence 1. Sequence 1 is 65 m thick (Fig. 10a) and it starts with 25 m of yellowish gray; moderately compact; thinly laminated, jointed, unfossiliferous, ferruginous, gypsiferous shale, with gypsum bands and veins; very slightly calcareous, dipping to the West (20–30 deg.); intercalated with yellowish brown, subrounded to subangular, moderately sorted, semi-friable to moderately compact siltstones with shell fragments of bivalves overlain by 25 m of brownish white, compact, massive, jointed, slightly argillaceous sandy pack/grainstones. They are highly fossiliferous yielding many fossil species, including bivalvia as *Crassostrea frondosa* (De Serres), *Alectryonella plicatula* (Gmelin), *Chlamys gentoni* Fontannes; gastropod molds; echinoids as *Echinolampas amplus* Fuchs, *Clypeaster* sp., *Scutella* sp.; numerous *Balanus concavus* (Bronn.); red algae as *Lithothamnium* sp.; small coral heads, sometimes dissolved and leaving only their molds. The main foraminiferal species in this bed are *Operculina* sp., *Amphistegina* sp. and *Heterostegina* sp. The upper part of this sequence is about 15 m and consists mainly of brown, moderately compact, laminated, gypsiferous, ferruginous, unfossiliferous, very slightly calcareous marl.

The shale beds in the lower part of the sequence 1 indicate a restricted ramp related facies and could be interpreted as an initial transgressive hemisequence. During the sea level rise, the change from proximal shale beds to distal carbonate beds occurred. The

maximum flooding interval could be represented on the grainstones beds. The upper part, which is interpreted as a regressive hemisequence consists of muddy facies and might indicate a depositional shift toward the restricted ramp faceis again during a sea-level fall.

2.3.3.1.2. Sequence 2. Sequence 2 is 20 m thick (Fig. 10b). The lower 12 m consists mainly of yellowish white compact, fine to medium, subangular to rounded, moderately sorted dolomitic quartz arenite. It is sometimes associated with grains of ferruginous materials and poorly fossiliferous with some molluscan fragments. On top of the sandstones there is grayish white, moderately compact bioclastic sandy pack/grainstones. The sand content is made up of fine to medium, subangular to subrounded quartz grains. It yields *Chlamys radians* (Nyst), *Ch.* (*Ch.*) *costai* (Fontannes), *Ch.* (*Argopecten*) *macrotis* (Sowerby), *Pecten* (*P.*) *cristato-costatus* Sacco, *P.* (*P.*) *fraasi* Fuchs, *Crassostrea frondosa* (De Serres), *Natica* sp., *Ampullina* (*Pseudamaura*) *macfaydeni* Abbass, *Retepora* sp., *Holoporella* sp., *Amphistegina* sp., *Miogypsina intermedia* Drooger, *Operculina* sp. The upper part of this sequence is about 8 m thick and consists of greenish gray, soft to moderately compact, highly gypsiferous, ferruginous, unfossiliferous silty claystones.

The clastic beds in the lower part of the sequence 2 indicate a restricted ramp to back shoal related facies and could be interpreted as an initial transgressive hemisequence. During the sea level rise, the distal moderate energy shoal related facies types retrograded over the clastic beds and can be interpreted as maximum flooding zone. The upper part of this sequence could represent a regressive hemicycle. It consists of muddy facies which indicates a depositional shift toward a restricted ramp setting.

2.3.3.1.3. Sequence 3. The average thickness of sequence 3 is 3 to 18 m (Fig. 10a). The lower part is 10 m thick and is dominated by yellowish brown to brown, compact, massive, argillaceous, fossiliferous bioclastic wacke/packstones, slightly ferruginous in the upper part. These contain *Chlamys* (*Macrochlamis*) *sardoa* Ugolini, *Clypeaster intermedius* Desmoulins, *Lithothamnium* sp., *Lithophyllum* sp., *Operculina complanata* (Defrance), *Miogypsina intermedia* Drooger, *Amphistegina* sp. Above the bioclastic packstones, thick-bedded bioclastic grainstones beds are dominated by large sized pectinids as *Pecten* (*Oppenheimopecten*) *convexo-costatus* Abich, *Chlamys* (*Macrochlamis*) *sardoa* Ugolini and other molluscs, echinodermes, bryozoans and foraminifers as *Gastrana* sp., *Conus* (*Lithoconus*) *mercati* Brocchi, *Ampullina* (*Pseudamaura*) *maedai* Abbass, *Echinolampas amplus* Fuchs, *Clypeaster marginatus* Lamarck, *Holoprella* sp., *Operculina complanata* (Defrance), *Miogypsina intermedia* Drooger, *Amphistegina* sp. The thickness of the upper part is about 8 m, consisting of yellow to yellowish brown, moderately compact, bioclastic wacke/packstones. It yields bivalves and foraminiferas as *Crassostrea frondosa* (De Serres), and *Alectryonella plicatula* (Gmelin), *Miogypsina intermedia* Drooger. The uppermost part of this sequence is represented by 0.5 m of unfossiliferous gypsiferous claystones.

The lower part of this sequence could be interpreted as back shoal proximal sediments deposited under low energy conditions, forming a transgressive hemisequence. The continuous rise in sea level led to the deposition of moderate energy shoal related facies and could be interpreted as maximum flooding zone. The regressive hemisequence is interpreted to mark the transition from the distal shoal to the proximal back shoal environment.

2.3.3.2. Gabal Gharra Section.

2.3.3.2.1. Sequence 1. Sequence 1 of Gharra section has an average thickness of 65 m (Fig. 10b). The lower part with a thickness of about 35 m, starting with clastic sediments of sandstones, reddish brown; moderately compact to semi-friable; fine to medium quartz grains; subangular to subrounded; moderately sorted; unfossiliferous and reddish brown at the base, gray upwards; soft at bottom, firm upwards; sandy; silty claystones; very slightly calcareous, unfossiliferous, overlianed by a ferruginous hard sandstone band of 5 cm thickness. Above the clastic beds, there are yellowish white, moderately compact, slightly argillaceous, bioclastic sandy pack/grainstones. The biocalstics are represented by *Crassostrea frondosa* (De Serres), *Alectryonella plicatula* (Gmelin), *Chlamys gentoni* Fontannes, *Natica* cf. *millepunctata* Lamarck, *Scutella ammonis* Fuchs, *Parascutella stefaninii* (Desio), *Prionocidaris* cf. *avenionensis* (Desmoulins), *Echinolampas* sp., *Clypeaster* sp. and echinoid spines and bryozoan fragments. The upper 30 m are dominated by dark gray to gray, soft to moderately compact, gypsiferous, unfossiliferous sandy shale, interbedded with ferruginous bands of 5 cm thick for each. These bands increase in number upwards. Sand grains are fine and subrounded quartz grains.

The lower part of sequence 1 consists mainly of clastic sediments which indicates that restricted ramp deposition under low energy conditions and could represent a transgressive hemisequence. These beds are arranged in deepening upward cycle sets of an open marine environment, while the maximum flooding interval could be placed on the shoal beds. Falling sea level is interpreted by the transition from the distal open marine to proximal restricted ramp environment again in the upper part.

2.3.3.2.2. Sequence 2. The average thickness of sequence 2 of the Gharra section is about 38 m (Fig. 10b). Its lower part, 20 m thick, consists of bioclastic calcareous sandstones and fossiliferous pack/grainstones. The sandstones contain *Crassostrea frondosa* (De Serres), *Alectryonella plicatula* (Gmelin), *Chlamys scabrella* Lamarck, *Pecten* (*Flabellipecten*) *flabelliformis* (Brocchi), *Anomia burdigalensis* Defrance, *Clementia* sp., *Parascutella stefaninii* (Desio). The pack/grainstones beds contain *Crassostrea frondosa* (De Serres), *Alectryonella plicatula* (Gmelin), *Pecten* (*P.*) *cristato-costatus* Sacco, *Chlamys scabrella* Lamarck, *Ch.* (*Argopecten*) *macrotis* (Sowerby), *Ch. senatoria* (Gmelin), *Cardium* sp., *Callista* (*Costacallista*) *erycina* (Linné), *Paphia* (*Callistotapes*) *vetula* (Bastrot), *Clementia* sp., *Diplodonta* sp., *Gari* sp., *Lutraria* sp., *Gastrana laminosa* (Sowerby), *Turritella* (*T.*) *terebralis* Lamarck, *Echinolampas amplus* Fuchs, *Clypeaster marginatus* Lamarck, *Scutella ammonis* Fuchs, *Balanus concavus* (Bronn), *Lithothamnium* sp., *Lithophyllum* sp.

On top of these beds, there are algal coralline framestones that contain high amounts of a scleractinian coral *Leptastrea* sp., and it is replaced in parts with an algal grainstone bands. The upper part of this sequence is 18 m thick consisting of yellowish white, compact, massive, slightly argillaceous, and slightly sandy bioclasitic algal pack/grainstones. The algae are represented by *Lithothamnium* sp. and *Lithophyllum* sp. This sequence is capped by 1 m thick bioturbated wakestone beds, which exhibit a sharp contact. The wackestones partially display intense ferrugination and dolomitization.

Bioclastic sandstones and pack/grainstones facies which constitutes the lower part of this sequence is interpreted as a shoal environment and could represent an initial transgressive hemisequence. During the subsequent sea level rise, more distal coral reef related facies types retrograded over the shoal beds. The maximum flooding interval could be represented at the algal coralline framestone beds. The relative fall in sea level is marked by the transition from the shoal margin to the shoal facies in the upper part of the sequence. The bioturbated wackestone layer on the top of this sequence suggests a low accommodation restricted ramp environment and a sequence boundary between sequence 2 and sequence 3.

2.3.3.2.3. Sequence 3. The thickness of sequence 3 is about 40 m (Fig. 10b), starting with 18 m thick bioclastic pack/grain/framestones. Most beds are moderately sorted and rich in fossils like *Crassostrea frondosa* (De Serres), *Alectryonella plicatula* (Gmelin), *Chlamys* (*Argopecten*) *submalvinae* (Blanckenhorn), *Ch.* (*Argopecten*) *macrotis* (Sowerby), *Ch. malvinae* (Dubois), *Ch. senatoria* (Gmelin),

broken parts of echinoids, bryozoa, few corals, foraminifers as *Miogypsina intermedia* Drooger. The thickness of the upper part of the succession is about 22 m and consists mainly of yellowish white to white, moderately compact, chalky bioclastic algal pack/grainstones. It yields some shell fragments, echinoid plates and undefined foraminifera. Also, it yields *Lithothamnium* sp. and *Lithophyllum* sp.

The lower part of this sequence is interpreted as a shoal related facies, which may represent a transgressive hemi-sequence. During the subsequent sea level rise, more distal high energy shoal margin related facies types retrograded over the shoal beds and the maximum flooding interval is interpreted at the reef beds. The relative fall in sea level could be marked by the transition from the shoal margin related facies to the proximal shoal environment in the upper part of the sequence.

2.3.3.3. Gabal Homeira section.

2.3.3.3.1. Sequence 1. Sequence 1 is 46 m thick (Fig. 10c). The lower part is 23 m and begins mainly with varicolored, moderately compact, fractured, unfossiliferous, slightly calcareous shale; yellowish brown, fine to medium grained, subrounded, moderately sorted calcareous quartz arenite; poorly fossiliferous and intercalated with sandy dolostone bands. Above these clastic beds, there are yellowish brown, soft to moderately compact, slightly argillaceous, sandy pack/grainstones. They are rich with bivalves, gastropodes, echinoderms, bryozaons, foraminifers, algae, in the form of *Crassostrea frondosa* (De Serres), *Alectryonella plicatula* (Gmelin), *Pecten fuchsi* Fontannes, *P.* (*P.*) *ziziniae* Blanckenhorn, *Chlamys malvinae* (Dubois), *Ch.* (*Aequipecten*) *scabriscula* (Matheron), *Ficus* sp., *Turritella* (*T.*) *cleevelyi* Abbass, *T.* (*Eichwaldiella*) *fouadi* Abbass, *T.* (*T.*) *terebralis* Lamarck, *Bursa faizae* Abbass, *Echinolampas amplus* Fuchs, *E. plagiosomus* Agassiz, *Clypeaster marginatus* Lamarck, *Holoporella polythele* (Russ), *Lithothamnium* sp. and *Lithophyllum* sp., *Operculina complanata* (Defrance), *Miogypsina intermedia* Drooger.

The upper part is about 22 m thick and consists mainly of bioclastic wacke/packstone beds, dominated by bivalves, gastropods, echinoderms and crustaceas such as *Crassostrea frondosa* (De Serres), *Alectryonella plicatula* (Gmelin), *Pecten* (*P.*) *ziziniae* Blanckenhorn, *P. fuchsi* Fontannes, *P.* (*Oppenheimopecten*) *benedictus* (Lamarck), *P. erythraensis* Sowerby, *P. beudanti* Basterot, *P.* (*Flabellipecten*) *flabelliformis* (Brocchi), *Linga* (*L.*) *columbella* (Lamarck), *Cardium* sp., *Anomia burdigalensis* Defrance, *A.* (*A.*) *ephippium* Linné, *Conus* (*Lithoconus*) *mercati* Brocchi, *C.* (*Conolithus*) *melficus* Desio, *Ficus reticulatus* Lamarck, *Clypeaster* sp., *Balanus concavus* (Bronn). This sequence is capped by gray, moderately compact, fractured, fissile, unfossiliferous claystone.

The lower part of this sequence is characterized by clastic beds, could be interpreted as a restricted ramp environment deposited under low energy conditions forming a transgressive hemi-sequence. During the subsequent sea level rise, the distal open marine back shoal related facies types retrograde over the restricted ramp beds. So the maximum flooding interval is represented on the back shoal beds. Relative decrease in the sea level is marked by the transition from the distal back shoal to the proximal tidal flat related facies found in the upper part of the sequence. The claystone unit at the top of this sequence may indicate a low accommodation peritidal environment and represent the sequence boundary between sequence 1 and sequence 2.

2.3.3.3.2. Sequence 2. The thickness of sequence 2 of the Homeria section is about 35 m (Fig. 10c). The lower hemi-sequence is 21 m thick and starts with yellowish brown, moderately compact, angular to subrounded, moderately sorted, poorly fossiliferous fine to medium calcareous quartz arenite. Above these sandstone beds, there are yellowish white, moderately compact, sandy bioclastic pack/grainstones. They are rich in *Scutella ammonis* Fuchs, *Parascutella stefaninii* (Desio), *Pecten* (*P.*) *cristato-costatus* Sacco, *Miogypsina intermedia*. The thickness of the upper part of this sequence is 14 m containing marl beds crowded with oyster bank. The sediments represent the matrix between oyters, which are mainly represented by *Crassostrea frondosa* (De Serres), *Alectryonella plicatula* (Gmelin). Also, it yields *Pecten* (*P.*) *cristato-costatus* Sacco, broken parts of *Scutella ammonis* Fuchs and *Parascutella stefaninii* (Desio).

The lower part of this sequence consists of sandstone beds which could be interpreted as a restricted ramp environment that was deposited under low energy conditions and formed a transgressive hemi-sequence. During the subsequent sea level rise, the distal open marine shoal related facies types retrograded over the restricted ramp beds. The maximum flooding interval is interpreted at the grainstone shoal beds. The relative decrease in sea level is marked by a transition from the distal shoal to the back shoal related facies in the upper part of this sequence.

2.3.3.3.3. Sequence 3. Sequence 3 attains about 35 m thick in Homeira section (Fig. 10c). The thickness of the lower hemi-sequence is 16 m and starts with yellowish white bioclastic wacke/packstone beds, containing broken parts of echinoids as *Scutella ammonis* Fuchs, *Parascutella stefaninii* (Desio) and echinoid spines; algae as *Lithothamnium* sp. and *Lithophyllum* sp.; and foraminifera as *Amphistegina* sp. Above wacke/packstone beds, there are brownish white, moderately to highly compact, massive sandy bioclastic pack/grainstone beds. They yield oysters and *Chlamys* (*Macrochlamys*) *sardoa* Ugolini and other small-sized pectinids; molds of other bivalves as *Cardium* sp., *Clavagella* sp., *Gastrana* sp., *G. laminosa* (Sowerby), *Arca* (*Anadara*) *grondica* Mayer; gastropods as *Turritella* (*T.*) *terebralis* Lamarck, *Ficus* sp., *Lanistes* (*L.*) *mahmoudi* Abbass, *Luria* (*L.*) *salwae* Abbass, *Oliva* (*Neocyclindrus*) *wagihi* Abbass, *Planorbis* (*P.*) *nakanoi* Abbass; scleractinian corals and bryozoans. Also they yield foraminifers as *Heterostegina* sp., *Amphistegina* sp. and red algae. The upper hemi-sequence is 19 m thick, it consists of bioclastic sandy wacke/packstone beds intercalated with mudstone bands containing broken shells, echinoids and gastropods.

The lower part of this sequence consists of bioclastic wacke/packstone beds that could be interpreted as the back shoal facies deposited under low energy conditions during a transgressive hemi-sequence. During the subsequent sea level rise, the distal open marine shoal related facies types retrograded over the inner back shoal beds. The maximum flooding interval could be interpreted at the grainstone beds. A relative decrease in sea level is marked by the transition from the distal shoal to the proximal back shoal facies in the upper part of this sequence.

3. Conclusions

The overall sedimentary nature of the Miocene sediments in Genefa, Gharra and Homiera sections at Cairo–Suez District in northern Egypt is dominated by shallow marine carbonate-siliciclastic rocks and included in Gharra and Geneifa formation.

14 Different facies types have been distinguished based on textures, rock color, grain size, sorting, roundness, components, thickness, bedding style, sedimentary features, interpretation of depositional setting and the appearance according to lithofacies code. These facies types were grouped into 6 lithofacies associations (LFA) ranging from peritidal (LFA 1) to shoal margin (LFA 6).

The lithofacies types are stacked into 4 cycle types. These cycle types build up to nine 4th order cycle sets, which are vertically arranged in three 3rd orders and subsequently subdivided into fourth order cycle sets and fifth-order cycles. The age the three cycles are interpreted to correspond to the Late Burdigalian stage (18–16.38 My), Late Burdigalian–Early Langhian stage (16.38–14.78 My) and Late Langhain–Early Serravallian stage (14.78–13.66 My).

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