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ORIGINAL ARTICLE

Facies analysis and depositional environments of the lower Eocene–lower Miocene succession in Northeast Libya

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Abstract
The lower Eocene-lower Miocene succession in the central part of the Al Jabal Al Akhdar, northeast Libya was investigated to determine its depositional environments and shed some light on diagenetic alterations. This succession is composed mainly of carbonate rocks and includes five formations from base to top; the Apollonia, Darnah, Al Bayda, Al Abraq, and Al Faidiyah. Relatively uniform shallow-marine carbonates were accumulated across northeast Libya, including the study area. Facies analysis of the studied carbonate rocks enables determination of four shallow-marine carbonate facies associations. These facies associations are: (1) restricted lagoon with limited circulation at/or below fair-weather wave base, (2) lagoon with open circulation below the fair-weather wave base, (3) platform-margin reefs, and (4) continental slope setting between the fair-weather and storm wave bases. The abundance of shallow marine carbonates indicates the presence of epeiric or epicontinental sea that covered the whole northern Africa. The depositional history in the studied area was controlled primarily by tectonics and relative sea-level changes. Four unconformities (i.e., sequence boundaries) were observed and separating five depositional sequences in the studied succession. Each depositional sequence shows shallowing-upward trend. The recorded unconformities reflect episodes of non-deposition and/or erosion and are associated with major fall in eustatic sea level. The diagenetic processes of the studied carbonate rocks include; micritization, pyritization, compaction, cementation, aggrading neomorphism and partial dissolution.

Keywords Lower Eocene–lower Miocene succession · Facies analysis · Depositional environments · Diagenetic alterations · Sequence stratigraphy · The Al Jabal Al Akhdar · NE Libya

Introduction

Outcrops in the Al Jabal Al Akhdar, NE Libya, consist mainly of upper Cretaceous and Cenozoic marine sediments that were deposited along the southern border of the Tethys. Excellent exposures of lower Eocene–lower Miocene have allowed detailed sedimentological and stratigraphical investigations. The study area lies in the central part of the Al Jabal Al Akhdar between latitudes 32°30″ to 33°00″ N and longitudes 21°30″ to 22°00″ E along the Mediterranean Sea coast of Libya (Fig. 1). The area extends for about 50 km with 40 km width. The sedimentary succession has a maximum thickness of about 106 m; dominated by marine carbonate units ranging in age from the early Eocene to the early Miocene. The studied succession includes five rock units from bottom to top: the Apollonia, Darnah, Al Bayda, Al Abraq and Al Faidiyah formations.

Several authors studied and described the stratigraphy of the Al Jabal Al Akhdar. Gregory (1911) subdivided the Eocene succession into three lithostratighraphic units; Salantah, Darnah, and Apollonia formations. Desio (1968) made review on the geological exploration in Cyrenaica (NE Libya) and gave a summary on the stratigraphy and structural history of the Al Jabal Al Akhdar. Barr and Hammuda (1971) studied the basal part of the Apollonia Formation and recorded the lower boundary of this formation, which unconformably overlies the late Cretaceous Al Athrun Formation. Rohlich (1974, 1980) discussed the tectonic history of the Al Jabal Al Akhdar and defined three structural stages initiated in the late Cretaceous and ended in the middle Miocene.

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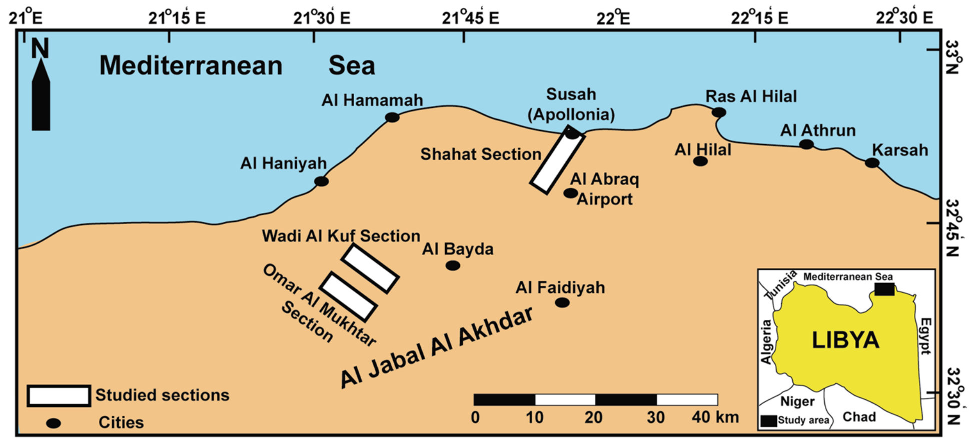

Fig. 1 Location map of north-east Libya including the three studied sections; the location of Libya and the study area is given in inset map

El Hawat and Shelmani (1993) published a booklet of short notes and guidebook on the geology of the Al Jabal Al Akhdar. Abdulsamad et al. (2009) studied the Eocene to Miocene rock units in the Al Jabal Al Akhdar and stated that the shallowing upward trend in the Apollonia Formation continued until the close of the Miocene time. They concluded that *Nummulites* are the dominant fossil during deposition of the middle Eocene, where they are missing in the late Eocene deposits. Abd El-Wahed and Kamh (2013) described the deformation in the central part of the Al Jabal Al Akhdar and concluded that this deformation is dominated by E–W right-lateral strike-slip fault zones that form a conjugate system with the N–S left-lateral strike-slip faulting. Muftah et al. (2017) recognized two disconformity surfaces at Tobruq-Burdi area. The first disconformity surface was observed at the basal part of the Oligo–Miocene Al Faidiyah Formation. The second disconformity surface exhibits an angular unconformity surface separating the Al Bayda Formation from the underneath Campanian Al Majahir Formation.

Detailed facies analysis, depositional environments, and diagenetic alterations of the studied rock units have not been published as the authors are aware. The present work aims to determine depositional environments and diagenetic history of the studied lower Eocene–lower Miocene succession. Construction of a depositional model of the studied succession is another goal of the present work and it is the first attempt to draw such model in the studied area.

Material and methods

Two field expeditions were carried out to the Al Jabal Al Akhdar district for collecting the lower Eocene–lower Miocene rock units. Thirty-four rock samples were obtained from three localities; Shahat, Wadi Al Kuf, and Omar Al Mukhtar. Collection of samples is based on the lithological variation; texture, color and fossil content. Thirty-four thin sections were prepared to determine depositional environments and diagenetic processes. Carbonate microfacies were determined following the classification of Dunham (1962) and its modifications after Embry and Klovan (1971). The paleo-environmental reconstructions of Wilson (1975) and Flügel (2010) were applied to the studied carbonate rocks.

Stratigraphy

The stratigraphic succession of the Al Jabal Al Akhdar is represented mainly by a thick succession of carbonate rocks, ranging in age from the late Cretaceous to the early Miocene. The present work focuses only on the lower Eocene–lower Miocene rock units that includes five formations; from bottom to top: the Apollonia, Darnah, Al Bayda, Al Abraq, and Al Faidiyah (Fig. 2). A brief description of each formation is given below.

The Apollonia formation

This formation is composed of thick-bedded, creamy white limestone, which is sometimes dolomitic and/or siliceous. This limestone is alternating with thin, soft, chalky and marly limestone (Fig. 3A, B). Dark brown chert nodules are common in this formation. Abdulsamad and Barbieri (1999) determined the age of the lower part of the Apollonia Formation as early Eocene due to the presence of *Nummulites globulus* and *globigerinids*. El Khoudary (1980) determined the age of the Apollonia Formation as middle Eocene based on the planktonic and benthic foraminifera, whereas Muftah et al. (2017) assigned its age as early–middle Eocene.

The Darnah formation

The Darnah Formation was introduced for the first time by Pieterz (1968). The formation is composed mainly of thick-bedded, fine to coarse-grained limestone of yellowish

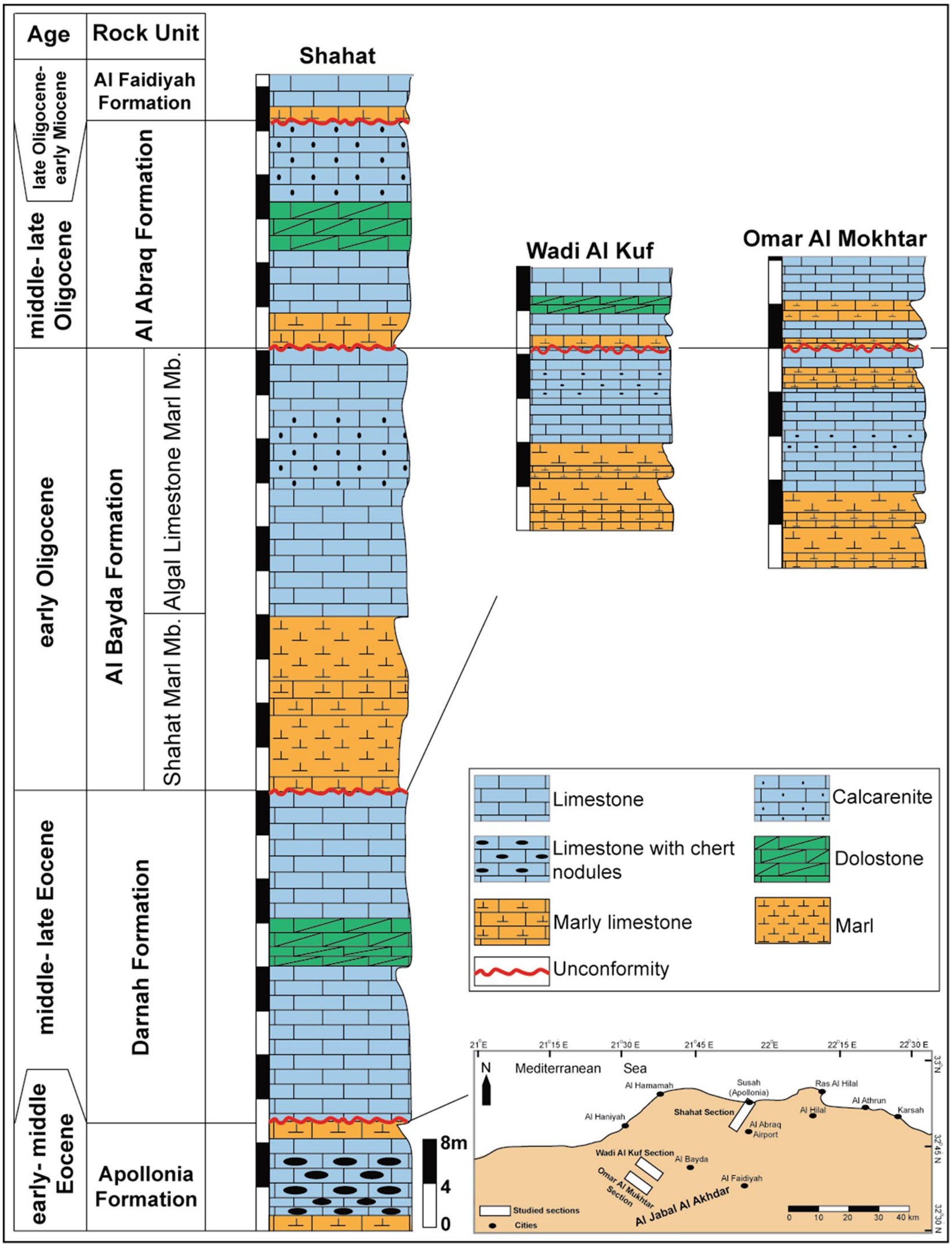

Fig. 2 Correlation chart showing the lithostratigraphy of the three studied sections; Shahat, Wadi Al Kuf and Omar Al Mukhtar. Datum is the unconformity surface between the Al Bayda and Al Abraq formations. Ages of the studied formations are based on the work of Abdulsamad and Tmalla (2009) and Muftah et al. (2017)

white and yellowish gray colors (Fig. 3C). The limestone is hard and massive with intercalations of dolomitic limestone. *Nummulites* of different sizes in addition to gastropods, bivalves, corals and echinoderms are embedded in a carbonate mud matrix. Generally, the fossils are dominated by large-sized *Nummulites* spp, *Orbitolites complanatus* and few *Discocyclinids* (Abdulsamad and Barbieri 1999). Based on the planktonic foraminifera and ostracoda, Helmdach and El Khoudary (1980) determined the age of the Darnah Formation as late Eocene. Muftah et al. (2017) assigned the age of the Darnah Formation as middle Eocene based on the presence of *Nummulites gizehensis*.

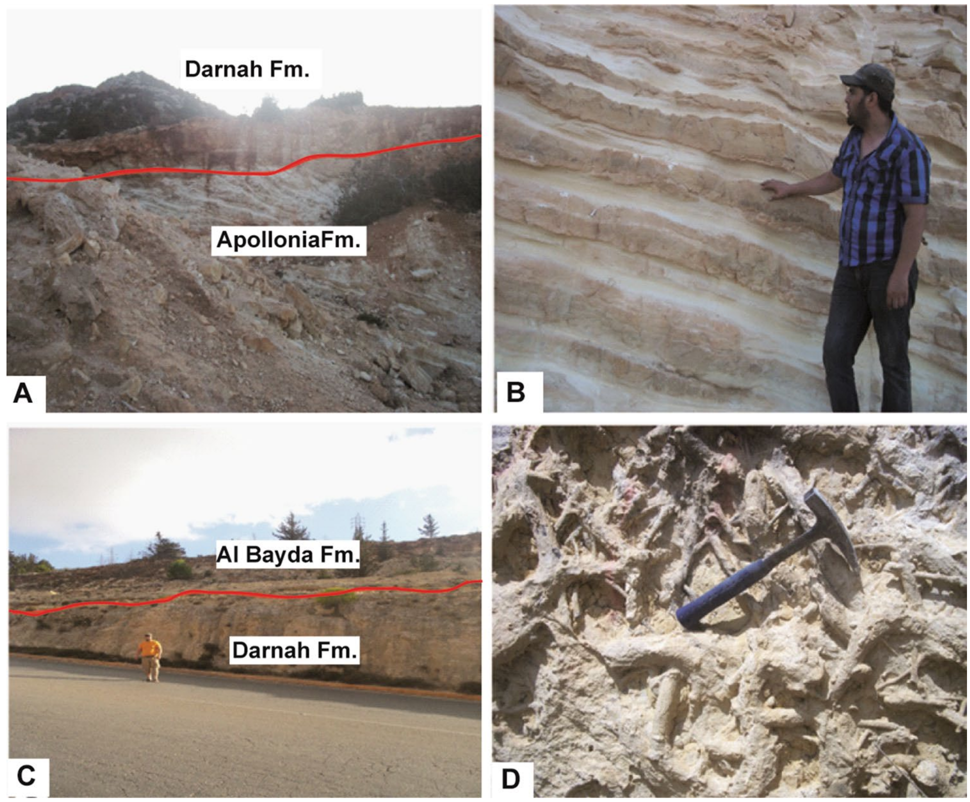

Fig. 3 Field photographs of the studied formations. **a** General view of Shahat section showing the Apollonia Formation unconformably underlay the Darnah Formation. **b** Thick-bedded creamy white limestone alternating with thin, soft, chalky and marly limestone, the Apollonia Formation of Shahat section, person for scale is 1.85 m. **c** General view showing unconformity surface between the Darnah and Al Bayda formations at Shahat section, person for scale is 1.85 m. **d** Abundant trace fossils in a yellowish gray marly limestone, the Al Bayda Formation (the Shahat Marl Member) of Wadi Al Kuf section, geologic hammer for scale is 32 cm long

The Al Bayda formation

The Al Bayda Formation was introduced for the first time by Rohlich (1974). It is marked by upper and lower disconformities with the underlying Darnah Formation (Fig. 3C) and the overlying Al Abraq Formation. The Al Bayda Formation is subdivided into two members; the Shahat Marl Member that is heavily bioturbated (Fig. 3 D) and the overlying Algal Limestone Member. Abdulsamad and Tmalla (2009) and Muftah et al. (2017) assigned the age of the Al Bayda Formation as early Oligocene based on the presence of *Nummulites vascus and N. fichteli*.

The Al Abraq formation

The Al Abraq Formation is defined for the first time by Rohlich (1974) after the village of Al Abraq. The formation is disconformably underlain by the Al Bayda Formation and overlain by the Al Faidiyah Formation. It is composed of yellowish white, soft to moderately hard limestone. The microfossils are represented by *Nummulites fichteli*, *Lepidocyclina*, and *Operculina africanus* (Muftah and Erhoma 2002; Abdulsamad et al. 2009). Muftah et al. (2017) recorded the presence of macrofossils such as oysters and echinoderms. They assigned the age of the Al Abraq Formation as middle Oligocene.

The Al Faidiyah formation

The Al Faidiyah Formation is disconformably underlain by the Al Abraq Formation. The formation consists of thin glauconitic marl at the base and argillaceous limestone beds grading upward into yellowish, fossiliferous, massive and cross-bedded limestone forming a series of coarsening upward cycles (El Hawat and Abdulsamad 2004). Green glauconite grains occur at the contact between the Al Faidiyah Formation and the underlying Al Abraq Formation. Only the lower part of the Al Faidiyah Formation was observed in the studied area. Muftah et al. (2017) determined the age of the Al Faidiyah Formation as late Oligocene–early Miocene.

Microfacies analysis

This step is very important to determine texture, microfacies association, depositional environments and subsequent diagenetic processes that affected the studied succession. The recognized microfacies are lime-mudstone, wackestone, packstone, grainstone, floatstone, rudstone and boundstone. The description of each microfacies will be introduced hereinafter and in Table 1.

Table 1 The recorded microfacies in the studied succession and their depositional environments

Microfacies	Rock unit	Allochems	Depositional environments
1. Foraminifera lime-mudstone	The Al Bayda Formation of both Shahat and Wadi Al Kuf sections	The recorded allochems include benthic foraminifera (Fig. A) and echinoderm spines and plates. Abdulsamad et al. (2009) recognized fine- to coarse-grained mudstones and wackestones with small-sized *Nummulites* in the Apollonia Formation. This interval is low in diversity and includes rare *Nummulites gizehensis*	Lime-mudstones usually accumulate in inhabitable environments under low energy conditions that allow carbonate mud to settle down (Flügel 2010). Deposition of the foraminifera lime-mudstone microfacies took place in relatively quiet less energetic marine conditions under fluctuating sea level. This microfacies is deposited in open lagoon with open circulation above fair-weather-wave base in normal marine salinity. So, it is equivalent to SMF 9 and FZ 7 (Wilson 1975; Flügel 2010)
2. Echinoderm foraminifera wackestone	The Apollonia, Darnah, and Al Bayda formations of Shahat section	Allochems are represented by benthic foraminifera (*Nummulites* and *Assilina*), echinoderm spines and plates, and bivalve fragments (Fig. B). Rare planktonic foraminifera, ostracods (*Bairdia*, *Paracypris*), and undifferentiated shell debris are also recorded	Benthic foraminifera live in a narrow range of depths and have characteristic tolerances to salinity and temperature (van der Zwaan et al. 1999). Most benthic foraminifera occur in areas of normal oxygen concentration (Racey 2001). *Nummulites* and *Assilina* live in shallow, oligotrophic, circum-Tethyan ramps (inner- to mid-ramp settings; Buxton and Pedley 1989; Racey 2001). Open lagoon environment with open circulation is suggested for this microfacies (SMF9 and FZ7) (Wilson 1975; Flügel 2010)
3. Bioclastic packstone	The Al Abraq and Al Faidiyah formations of Shahat section	Allochems are abundant and include different types of benthic foraminifera (*Assilina*, *Amphistegina*, *Peneroplis*, *Lepidocyclina* and coiled foraminifera), echinoderm spines and plates, coralline algae, bivalve fragments, ostracods, and undifferentiated shell debris that are cemented by carbonate mud (Fig. 4C). The allochems are moderately packed, moderately sorted and range in size from medium sand to very coarse sand	The presence of coralline algae indicates very shallow, warm, normal marine depositional environment with redistribution of grains by waves and currents (Adey and Macintyre 1973) so it is accumulated in an agitated shoal environment. Accumulation of benthic foraminifera occurs in platform of shelf-margin settings particularly in the circum-Mediterranean region and the Middle East (Racey 2001). This microfacies is similar to SMF18 and FZ8 (shallow lagoons and bays (i.e., restricted platform) (Wilson 1975; Flügel 2010)

Table 1 (continued)

Microfacies	Rock unit	Allochems	Depositional environments
4. Glauconitic foraminifera packstone	The Al Bayda Formation of Wadi Al Kuf and Omar Al Mukhtar sections	Allochems are represented by scattered benthic foraminifera (*Nummulites* (Fig. 4D) and *Discocyclina* (Fig. 4E)), echinoderm plates and spines, undifferentiated shell debris, bivalve fragments, oyster fragments, bone fragments and glauconite grains. The allochems are packed and embedded in a carbonate mud matrix. Minor intraclasts and lithoclasts are recorded	Echinoderms indicate relatively open marine settings, either in muddy low-energy facies or in carbonate sands (Heckel 1972). The abundance of *Nummulites* indicates tropical, shallow marine water and saline to hypersaline restricted lagoonal conditions (Beavington-Penney and Racey 2004). *Discocyclina* occurs in relatively deep-water environments than smaller, lenticular *Nummulites* that lives in shallower, inner ramp settings (Beavington-Penney and Racey 2004). Glauconite points to a low rate of sedimentation with normal salinity and reducing environments (McRae 1972; Odin and Matter 1981). Glauconite grains are slow to form so they are usually common with transgressive events (Huggett and Gale 1997; Anan 2014; Hegab et al. 2016). This microfacies was accumulated in lagoons with open circulation below the fair-weather wave base, so this microfacies is equivalent to SMF 18-FOR and FZ 7 (Wilson 1975; Flügel 2010)
5. Foraminifera grainstone	The Al Abraq and Al Faidiyah formations of Shahat section	Allochems are represented by benthic foraminifera (*Operculina*, *Peneroplis*, and *Triloculina*), coralline algae, micritized shell fragments, ostracods, and echinoderm plates and spines (Fig. 4F). Minor lithoclasts are also recognized in this microfacies. Green glauconite grains are recorded, whereas brown color of the glauconite grains may be due to oxidation effect after emergence	Abundance of benthic foraminifera indicates shallow-marine water, restricted lagoonal conditions (van der Zwaan et al. 1990). *Operculina* lives in an intermediate interval ranging from 80 to 100 m (Hottinger 1983), whereas *Triloculina* usually lives in inner ramp settings (protected open lagoon and skeletal beach barrier) (Gilham and Bristow 1998). This microfacies resembles SMF 18-FOR and FZ8 (Wilson 1975; Flügel 2010). Sediments of this microfacies occur as bars and channels and in sand shoals
6. Foraminifera floatstone	The Darnah and Al Bayda formations of Shahat and Omar Al Mukhtar sections	These rocks are highly fossiliferous containing whole fossils; up to granules and pebble-sizes. Large *Assilina*, *Discocyclina* and *Operculina* (whole and fragmented) and miliolids are the main components. Echinoderms and oyster fragments in addition to other benthic foraminifera are also recorded but with limited distribution. The chambers of foraminifera are partially to completely filled with a sparry calcite and locally with micrite. The matrix is composed of micrite and bioclastic fragments (Fig. 5A)	Larger benthic foraminifera are usually associated with tropical and subtropical shallow-water carbonate sediments (Hottinger 1983). They can form a considerable portion of the skeletal debris of reef and platform environments (Hottinger 1997). Abundant well-preserved benthic foraminifera indicate a low-energy environment with circulation. This microfacies is similar to SMF 5 and FZ4 (Wilson 1975; Flügel 2010). It is accumulated in forereef position and reef slopes

Table 1 (continued)

Microfacies	Rock unit	Allochems	Depositional environments
7. Foraminifera rudstone	The Al Bayda Formation of Omar Al Mukhtar section	Allochemical components of this microfacies are benthic foraminifera (*Assilina*, *Operculina*, *Lepidocyclina*), coralline red algae, bivalve fragments, oyster fragments, serpulids, and echinoderm plates and spines. The allochems are packed and embedded in a sparry calcite cement (Fig. 5B)	This microfacies was deposited below the fair-weather wave base, with a long-term high-energy current or wave activity. High degrees of taphonomic damage point to a prolonged exposure time on the sediment/water interface (Kidwell and Bosence 1991; Perry 1999). This microfacies is equivalent to SMF5 and FZ4 (Wilson 1975; Flügel 2010) which refers to deposition in forereef position and reef slopes
8. Oyster foraminifera rudstone	The Al Bayda Formation of Shahat and Omar Al Mukhtar sections	Allochems of this microfacies include *Nummulites* and *Operculina*, *Assilina*, oyster and other bivalve fragments, coralline algae, echinoderm spines and plates and serpulids. Rare green glauconite grains are observed. The recognized allochems are moderately packed and embedded in a carbonate mud matrix (Fig. 5C)	Oysters live in shallow-marine environments of the Tethys near North Africa (Dhondt et al. 1999). They were deposited in relatively deep subtidal areas; close to the carbonate shoals where large skeletal debris were reworked and transported by storms. The oyster foraminifera rudstone microfacies was deposited below the fair-weather wave base. This microfacies resembles SMF5 and FZ4 (Wilson 1975; Flügel 2010) which indicates deposition in reef slopes
9. Algal Boundstone	The Algal Limestone Marl Member of the Al Bayda Formation of Shahat section	The dominant allochems in this microfacies include coralline red algae that bound together during deposition (Fig. 5D). Rare benthic foraminifera, echinoderms, and bryozoa are recorded	Coralline red algae are dominantly marine, photosynthetic and live in marine water with salinities vary between 33 and 42 ppt (Scholle and Ulmer-Scholle 2003). Modern coralline algae live in tropical to polar oceans. Tropical taxa occur in depths down to about 80 m. The majority of coralline algae prefers hard substrates, faint light conditions and agitated water (Flügel 2010). This microfacies is equivalent to SMF7 and FZ 5 (Wilson 1975; Flügel 2010) that is characterized by in-situ growth of sessile organisms (organic boundstone)

Lime-mudstone microfacies

Lime-mudstone microfacies represent about 4% of the total thin sections of the studied rock units. They are encountered in the Al Bayda Formation of both Shahat and Wadi Al Kuf sections. One lime-mudstone microfacies was recognized in the studied succession (Table 1).

Wackestone microfacies

Wackestone microfacies in the studied carbonate rocks represent about 11% of the total thin sections of the studied limestone. Rocks of this microfacies are recognized mainly in the Apollonia, Darnah, and Al Bayda formations of Shahat section. One wackestone microfacies was identified and described (Table 1).

Packstone microfacies

Packstone microfacies represent about 33% of the total thin sections of the studied rock units. They are encountered in the Al Bayda, Al Abraq and Al Faidiyah formations. Two packstone microfacies were recorded in the studied succession (Table 1).

Grainstone microfacies

Grainstone microfacies represent about 7% of the total thin sections of the studied microfacies. They are encountered in the Al Abraq and Al Faidiyah formations of Shahat section. One grainstone microfacies was recognized in the studied succession (Table 1).

Floatstone microfacies

These rocks are highly fossiliferous, containing algae, benthic foraminifera, bivalve fragments and echinoderms. They represent about 11% of the total thin sections. One floatstone microfacies was encountered in Shahat and Omar Al Mukhtar sections (Table 1).

Rudstone microfacies

These rocks are characterized by the presence of benthic foraminifera, coralline red algae and echinoderms; up to granule and pebble-sizes. They represent about 29% of the total thin sections. Rocks of this microfacies are recognized mainly in the Al Bayda Formation of Shahat and Omar Al Mukhtar sections. Two microfacies were recognized in the studied interval (Table 1).

Boundstone microfacies

These rocks represent about 5% of the total thin sections. They contain coralline red algae as the main fossil component. Some bryozoa are recorded. One microfacies was recognized in the Algal Limestone Marl Member of the Al Bayda Formation in Shahat section (Table 1).

Depositional environments

Based on field relationships, fossil content and facies analysis; depositional environments of the studied carbonate rocks are illustrated in Figs. 4, 5, 6. The recorded microfacies were accumulated in four different facies associations (Fig. 7). These facies associations are restricted lagoon, open marine lagoon, platform margin reef and slope. The first facies association, restricted lagoon, contains bioclastic packstone and foraminifera grainstone microfacies. Sediments of this association were accumulated in quiet water at/or below the fair-weather wave base (Fig. 7). In addition, some microfacies of this association occur as sand shoals that are influenced by tidal currents. The second facies association of microfacies accumulated in open marine lagoon with open circulation below the fair-weather wave base. Microfacies of the second facies association include foraminifera lime-mudstone, echinoderm foraminifera wackestone, bioclastic packstone, and glauconitic foraminifera packstone. The third facies association was deposited in platform-margin reefs. This facies association includes algal boundstone. The fourth facies association comprises three submicrofacies; foraminifera floatstone, foraminifera rudstone, and oyster foraminifera rudstone. It was accumulated in slope setting (Fig. 7). The aforementioned associations reflect shallow marine carbonate rocks that were accumulated in most of northeast Libya. This conclusion was recorded by Abdulsamad et al. (2009). These shallow settings reflect the occurrence of shallow sea (epicontinental sea) during the deposition of studied succession. The whole studied succession can be subdivided into five shallowing-upward depositional sequences that were separated by four unconformities.

Due to the scarcity of planktonic foraminifera, Abdulsamad et al. (2009) determined the depositional environment of the Apollonia Formation as warm-water, shallow carbonate platform. However, they stated that the carbonate sediments of the Apollonia Formation refer to Wilson's facies SMF 3. In the present work, the Apollonia Formation microfacies resemble SMF9 and FZ7 (Wilson 1975; Flügel 2010). The Apollonia Formation contains benthic foraminifera such as *Nummulites*, *Assilina, Triloculina*.

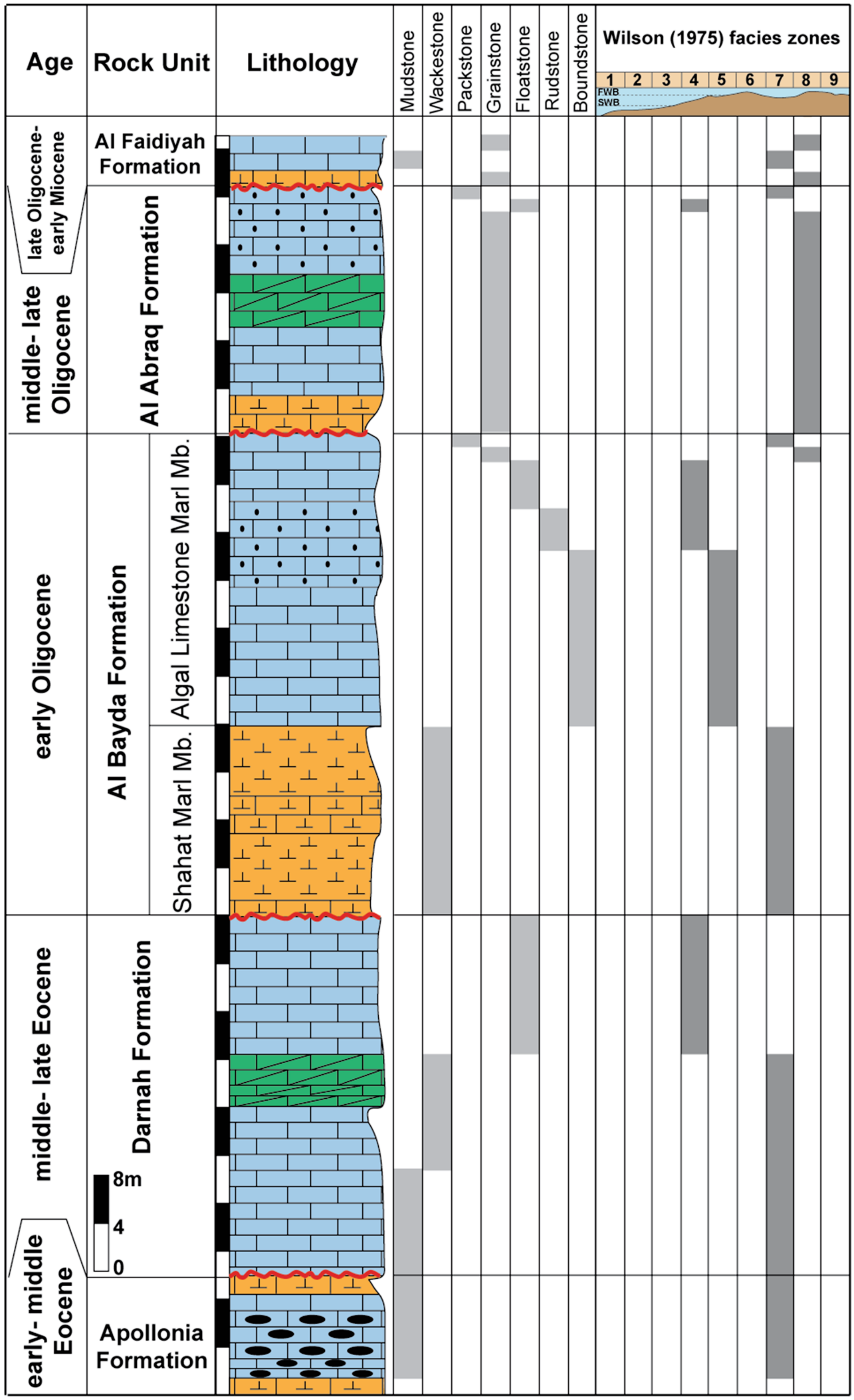

Fig. 4 The lithostratigraphy and depositional settings of the studied rock units at Shahat section. See legend in Fig. 2

Such species live in shallow inner ramp settings (protected open lagoon with moderate circulation). Also, ostracods (e.g., *Bairdia* and *Paracypris*) are recognized. Large-sized foraminifera (*Nummulites*) are observed in the middle and upper parts of the Darnah Formation. In addition, *Assilina* and *Operculina* were observed in thin sections. *Operculina* lives in an interval varying in depth between 80 and 100 m (Hottinger 1983). Deposition of the Darnah Formation took

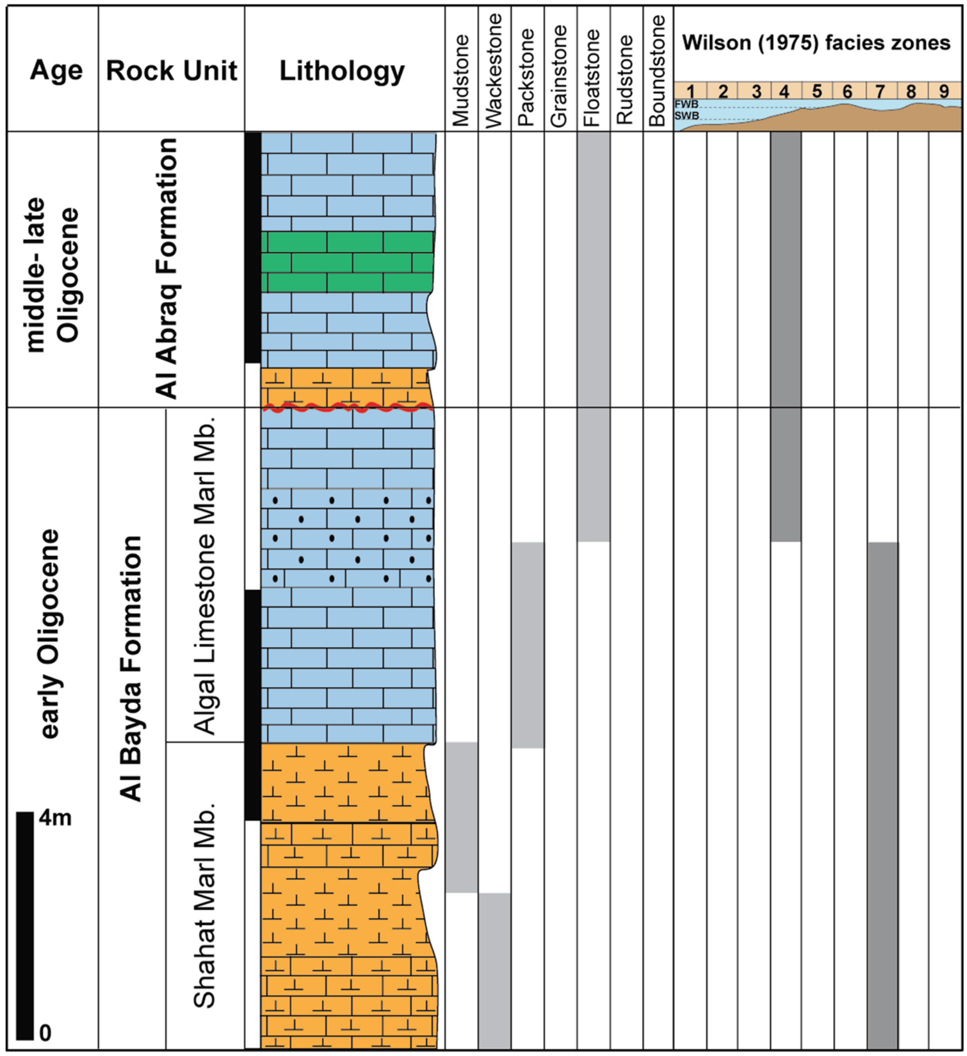

Fig. 5 The lithostratigraphy and depositional settings of the studied rock units at Wadi Al Kuf section. See legend in Fig. 2

place in shallow warm-water carbonate platform. However, in the present work, the Darnah Formation includes echinoderm foraminifera wackestone and foraminifera floatstone microfacies. Wackestones were deposited in SMF9 and FZ7, whereas floatstones are correlatable with SMF 5 and FZ4 (Wilson 1975; Flügel 2010).

Several authors (e.g., Muftah and Erhoma 2002; Abdulsamad et al. 2009) determined depositional environment of the Al Bayda Formation as a carbonate platform dominated by facies SMF 4, 5 and 6 (Wilson 1975). This interpretation is based on the dominance of small-sized *Nummulites* and abundant coralline red algae. The dominance of the coralline red algae is an indication of shallow water environment (Hassan and Ghosh 2003). The Al Bayda Formation includes benthic foraminifera such as small-sized *Nummulites*, *Assilina*, *Operculina*, *Peneroplis*, and *Discocyclina*. The recorded microfacies suggest depositional environments ranging from shallow or coastal settings, open shelf and normal marine (inner ramp to mid ramp environments).

An environment with open circulation and muddy substrates is suggested for deposition of the Al Abraq Formation (Wilson's facies SMF7; Abdulsamad et al. 2009). In the present work, the Al Abraq Formation contains benthic foraminifera such as *Discocyclina*, *Operculina*, and *Peneroplis*. Bioclastic packstone and foraminifera grainstone microfacies were recorded in this formation. Packstone microfacies were deposited in an agitated shoal environment, whereas grainstone microfacies occur as bars and channels and sand shoals.

Abdulsamad et al. (2009) determined depositional environment of the Al Faidiyah Formation as open to restricted platform and it is correlated with Wilson's facies SMF7 and SMF8. In the current work, different microfacies were recognized; bioclastic packstone and foraminifera grainstone. These microfacies were deposited in shallow inner shelf bayment, agitated shoal environment and shelf lagoon with open circulation, respectively.

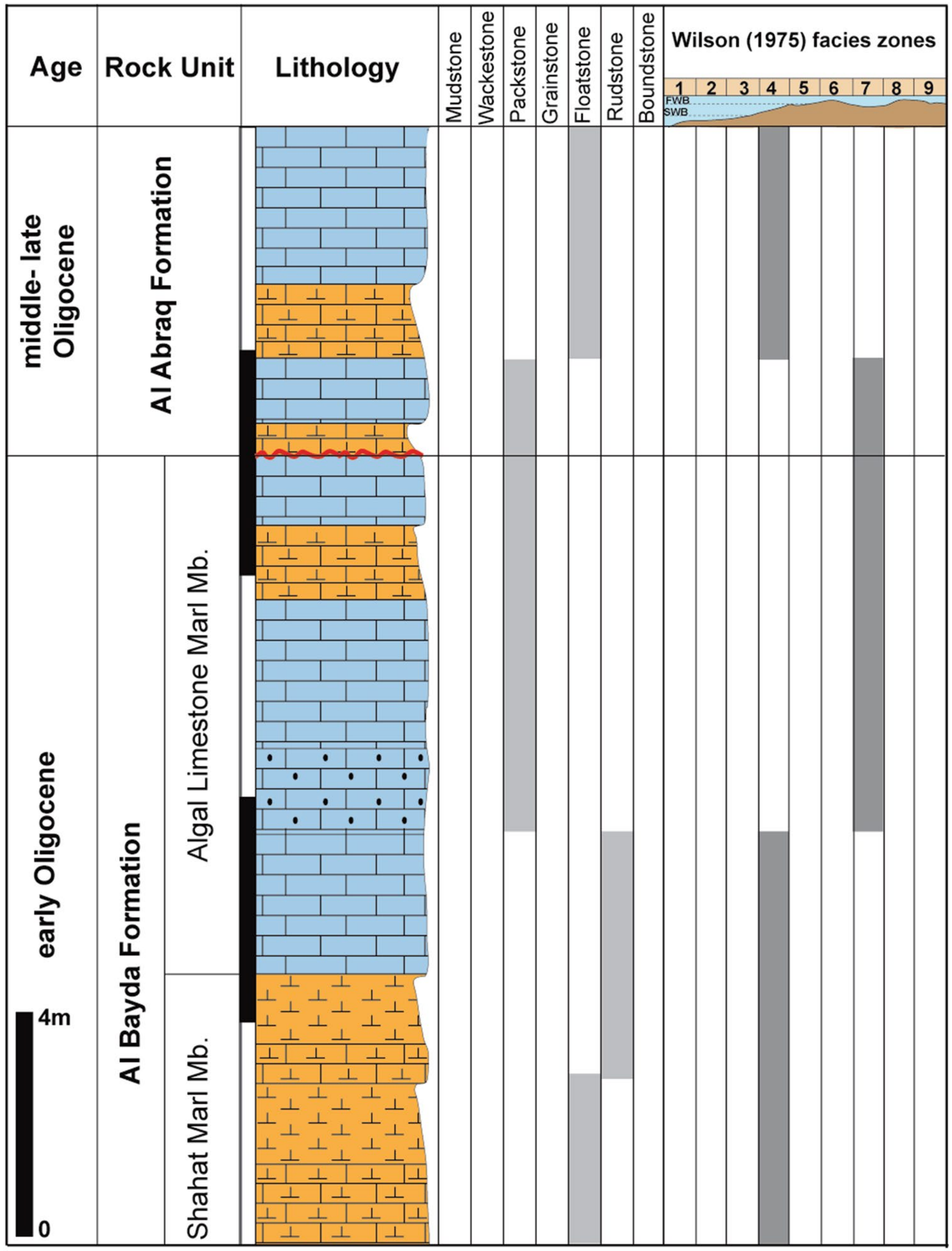

Fig. 6 The lithostratigraphy and depositional settings of the studied rock units at Omar Al Mokhtar section. See legend in Fig. 2

Diagenetic alterations

There are many diagenetic processes affected the lower Eocene–lower Miocene carbonates in the studied sections. These processes include micritization, pyritization, compaction, cementation, aggrading neomorphism and partial dissolution.

Micritization

Micritization is represented by micrite envelopes surrounding the skeletal bioclasts. Micritization is considered as a primary diagenetic process in origin and occurs shortly after deposition. Its occurrence is associated with algae and fungi which are responsible for forming the voids that are filled later by micrite (Bathurst 1975). The association of micritization with the occurrence of algae reveals that micritization usually occurs in shallow marine environments due to the need for sunlight (Flügel 2010). This process has been recorded in some of the studied carbonates especially in the bivalve fragments that were bored by the activity of algae and the pores were filled with the surrounding micritic matrix (Fig. 8A).

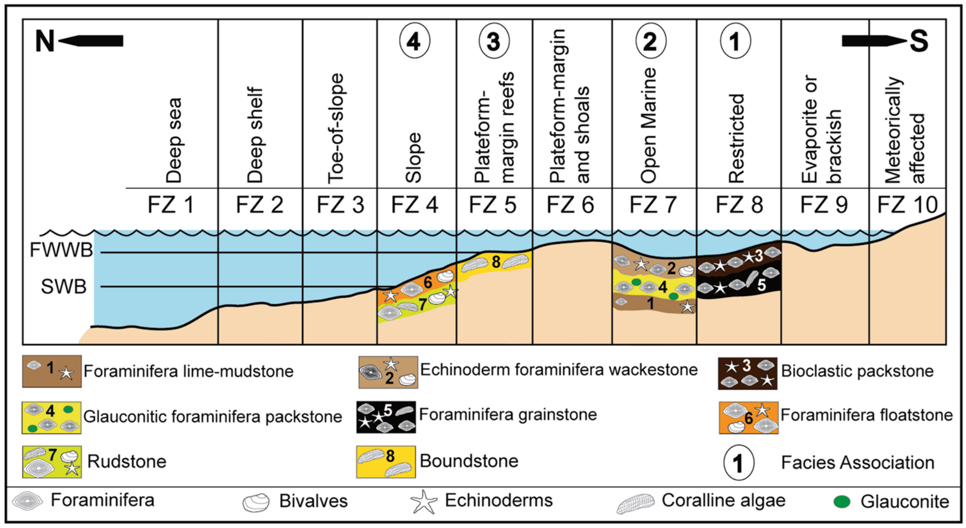

Fig. 7 The proposed depositional environments of the microfacies recorded in the lower Eocene-lower Miocene succession. The interpreted facies associations are; (1) restricted lagoon, (2) lagoon with open circulation, (3) platform-margin reefs, and (4) continental slope

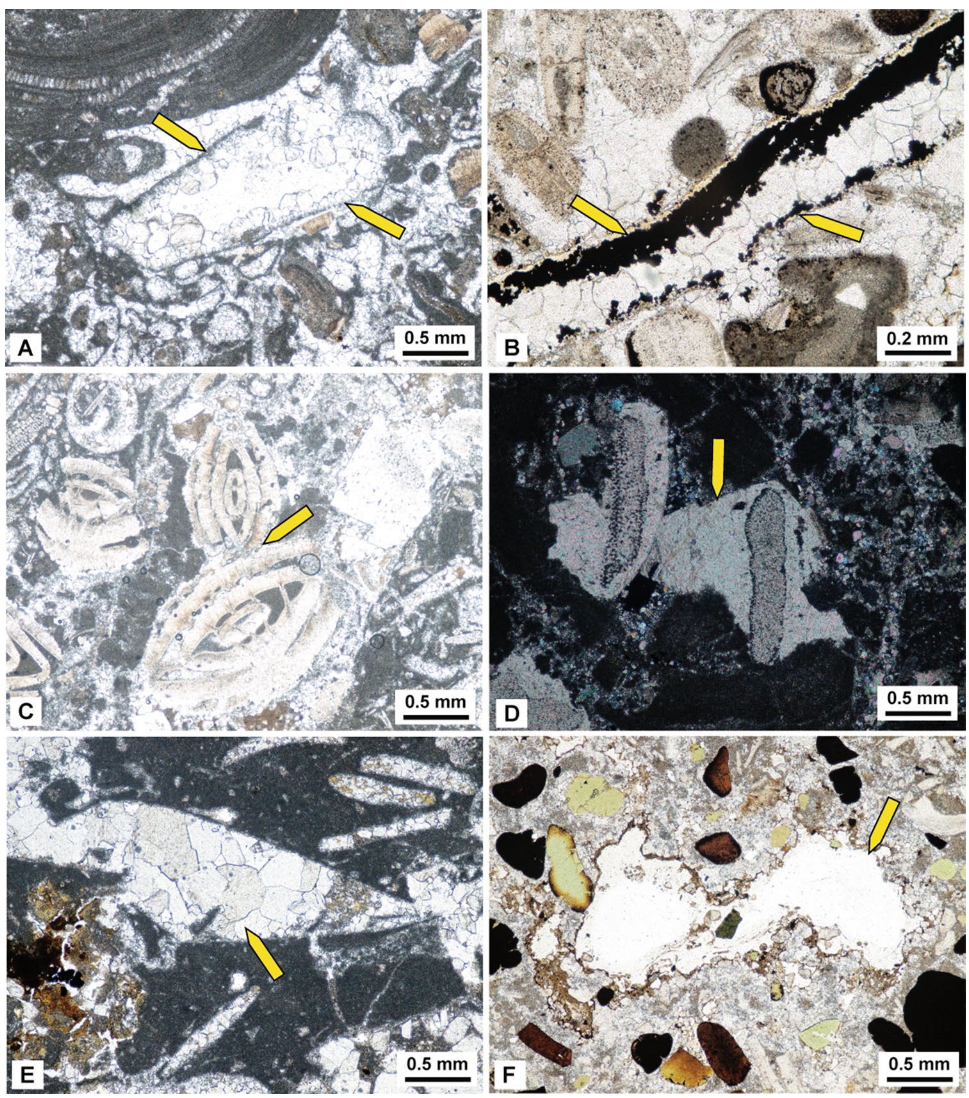

Fig. 8 Photomicrograph showing: **a** micrite envelopes around a bivalve fragment (arrows). The bivalve fragments as a mold infilled with sparry calcite cement that increases in size towards the center of mold void, the Al Faidiyah Formation, Shahat section, PPL. **b** Photomicrograph showing pyrite framboids inside shell fragments, the Al Bayda Formation, Shahat section, PPL. **c** Photomicrograph showing compaction of two benthic foraminifera (arrow), the Darnah Formation, Shahat section, PPL. **d** Photomicrograph showing the clear syntaxial overgrowth cement enclosing echinoderm grains plates, the Al Bayda Formation, Shahat section, XPL. **e** Photomicrograph showing microspar due to aggrading neomorphism (arrow), the Al Faidiyah Formation, Shahat section, PPL. **f** Photomicrograph showing partial dissolution of the micritic groundmass (arrow), the Al Bayda Formation, Shahat section, PPL

Pyritization

Replacement by pyrite is recorded in the studied carbonate rocks, whereby pyrite framboids are disseminated in the sparry calcite which filled molds of skeletal particles (Fig. 8B). Pyrite framboids are spheroidal or sub-spheroidal aggregates of equant, equidimensional pyrite microcrystals (Butler et al. 2000). The framboids in the studied rocks vary in size between 10 and 25 µm. According to Wilkin et al. (1996), this narrow size distribution of framboidal pyrite could reflect relatively short growth times, suggesting that most pyrite in the studied carbonates formed near the sediment/water interface under conditions of super-saturation with respect to pyrite. Cavalazzia et al. (2014) stated that the presence of pyrite points to deposition under anoxic conditions.

Compaction

When carbonate sediments are buried under an overburden, grain come together and grain fractures occurs. In addition, porosity is lowered by a closer packing. This process is called mechanical compaction. The limestone in the studied rocks underwent mechanical compaction with different degrees. This is clear due to the presence of different types of contacts among allochems (Figs. 8C and 9B, C). This feature occurs mainly in floatstone and rudstone microfacies that underwent little or minor cementation prior to burial and overburden load.

Cementation

Cementation is an important process in all diagenetic realms. Cement forms in both primary and secondary pores and requires supersaturation of the pore fluid with respect to the cement mineral. Cementation process extensively affected the studied formations and represents the commonest one among other diagenetic processes. Two types of cement were recognized; drusy calcite cement and syntaxial overgrowth cement.

Drusy calcite cement

This kind of cement is characterized by pore-filling calcite crystal increasing in size towards the center of interparticle pores or voids (Fig. 8A, B). This is commonly interpreted to be

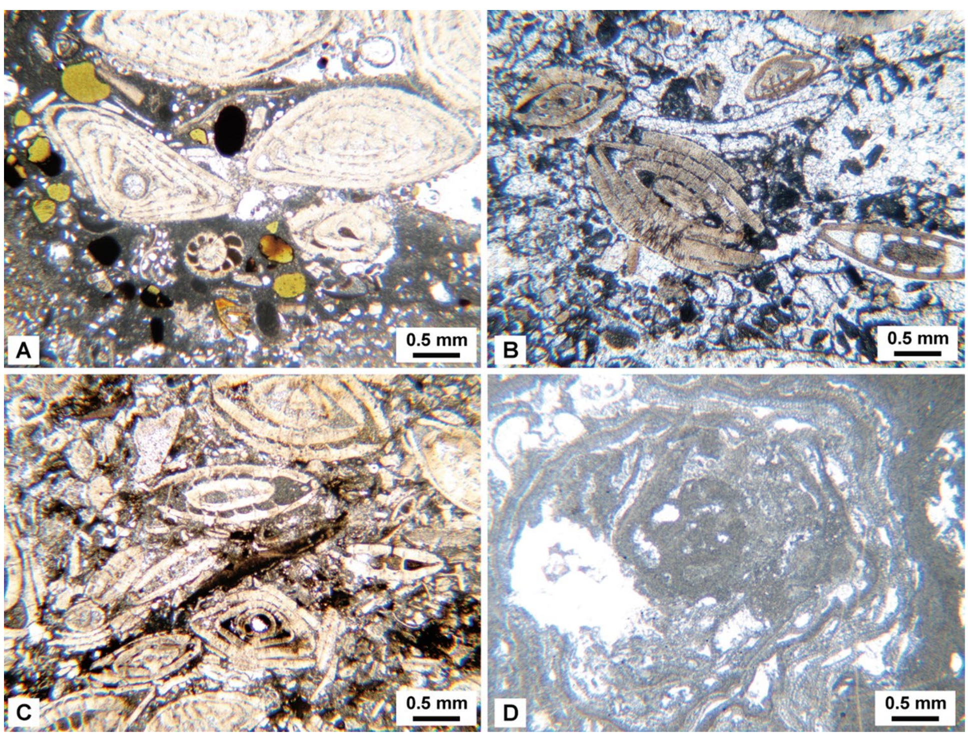

Fig. 9 Photomicrographs showing **a** Foraminifera floatstone microfacies. Larger benthic foraminifera and glauconite grains are abundant. Silt-sized quartz grains are recorded, the Al Faidiyah Formation, Shahat section, PPL. **b** Foraminifera rudstone microfacies. Large benthic foraminifera are cemented by a sparry mosaic calcite. Compaction is indicated by the long contact between foraminifera (arrow), the Al Faidiyah Formation, Shahat section, PPL. **c** Oyster foraminifera rudstone microfacies. Oyster fragments and large benthic foraminifera (*Nummulites*) are the main components. The allochems are highly packed. Notice the long contacts among benthic foraminifera which suggest a phase of compaction (arrow), the Al Bayda Formation, Shahat section, PPL. **d** Algal boundstone microfacies. This microfacies is characterized by abundance of coralline red algae. Minor bryozoa are recoded, the Al Bayda Formation, Shahat section, PPL

of late diagenetic process (Flügel 2010). It is usually observed in most studied sections.

Syntaxial overgrowth cement

Syntaxial overgrowth occurs around a host grain made by a single crystal (especially high-Mg calcitic echinoderm plates). It is usually in crystallographic continuity with the host grain. There is a color difference between the syntaxial overgrowth and the skeletal grain (Fig. 8D). Syntaxial overgrowth cement forms in different settings; near-surface marine, vadose–marine, and meteoric–phreatic environments (Flügel 2010). The origin of this type of cement is explained by different opinions. These are: (1) syntaxial overgrowth prior to the deposition of marine muds (Evamy and Shearman 1965), (2) syntaxial overgrowth as a secondary pore filling that is created by the selective dissolution of carbonate mud in the vicinity of echinoderm grains (Walkden and Berry 1984), (3) neomorphic replacement of carbonate mud (Orme and Brown 1963), this model has been used in many studies and finally (4) syntaxial overgrowth into primary sheltered pore space beneath echinoderm fragments (Görur 1979).

Aggrading neomorphism

Aggrading neomorphism is produced as enlargement of micrite crystals, a process by which crystals that measure only a few microns in diameter may enlarge to a size measuring tens of microns in diameter. This creates a neomorphism product similar to sparry cement in crystal size (Fig. 8E). Neomorphism of micrite matrix (<4 µm) into microspar (4–10 µm) and pseudospar (10–50 µm) is observed in the studied carbonates (Fig. 8E).

Partial dissolution

Carbonate sediments, skeletal particles and cements may undergo dissolution on a small or large scale when pore fluids are undersaturated with respect to the carbonate mineralogy (Tucker and Wright 1990). Dissolution may be active at any time in the burial history of the carbonates after mineral stabilization (Moore 1989). Depending on the size of pores, they are commonly called vugs, channels and caverns (Choquette and Pray 1970). The partial dissolution process has been encountered in most of the studied carbonates that contain abundant algae and *Nummulites* (Fig. 8F).

Impact of diagenetic alterations on depositional facies

Diagenetic processes are effective at near-surface conditions and during progressive burial and controlled by fluid flow and/or diffusion (Morad et al. 2012). Depositional carbonate facies tend to adjust to new physical and chemical conditions to reach equilibrium. The observed diagenetic alterations, micritization, pyritization, compaction, cementation, aggrading neomorphism and partial dissolution, affected wackestone, packstone, grainstone, floatstone and rudstone microfacies. Compaction is the only physical process that affected the studied carbonate rocks, whereas physicochemical processes in the study area include dissolution, cementation, replacements, micritization, aggrading neomorphism. Compaction is observed in both grainstone (Fig. 10F) and floatstone/rudstone microfacies (Fig. 9C) that contain large allochems (>2 mm).

Cementation is recorded in all of the studied microfacies (Figs. 9B and 10F). Syntaxial overgrowth occurs mainly in microfacies that contain echinoderm such as echinoderm foraminifera wackestone (Fig. 10B) and bioclastic packstone (Fig. 10C). Replacement by pyrite affected grainstones and rudstones as scattered pyrite framboids were replaced sparry calcite (Fig. 8B). Partial dissolution process has affected most of the studied carbonates that contain abundant *Nummulites* and algae. The grainstone, floatstone, rudstone and boundstone microfacies contain variable amounts of moldic porosity that have resulted from partial dissolution (Figs. 8F and 9D).

Sequence stratigraphy

Based on the available data, sequence stratigraphic analysis of the studied succession is considered as preliminary results. Four sequence boundaries (SB) were recognized (SB1–SB4) (Fig. 11). In Shahat section, the four sequence boundaries were observed, whereas SB3 is the only recorded sequence boundary in both Wadi Al Kuf, and Omar Al Mukhtar sections. According to the criteria of Vail et al. (1984), these boundaries are considered as Type 1 boundaries. Type 1 sequence boundaries form during a stage of rapid eustatic sea-level fall. Five proposed depositional sequences (sequences 1–5) were observed in the studied succession (Fig. 11). The proposed depositional sequences show shallowing-upward trend.

During the Eocene, marine limestone was accumulated in the central and eastern parts of the Sahara (Swezey 2009). In northeast Libya, changes in relative sea level through the Cenozoic are accompanied by a gradual fall

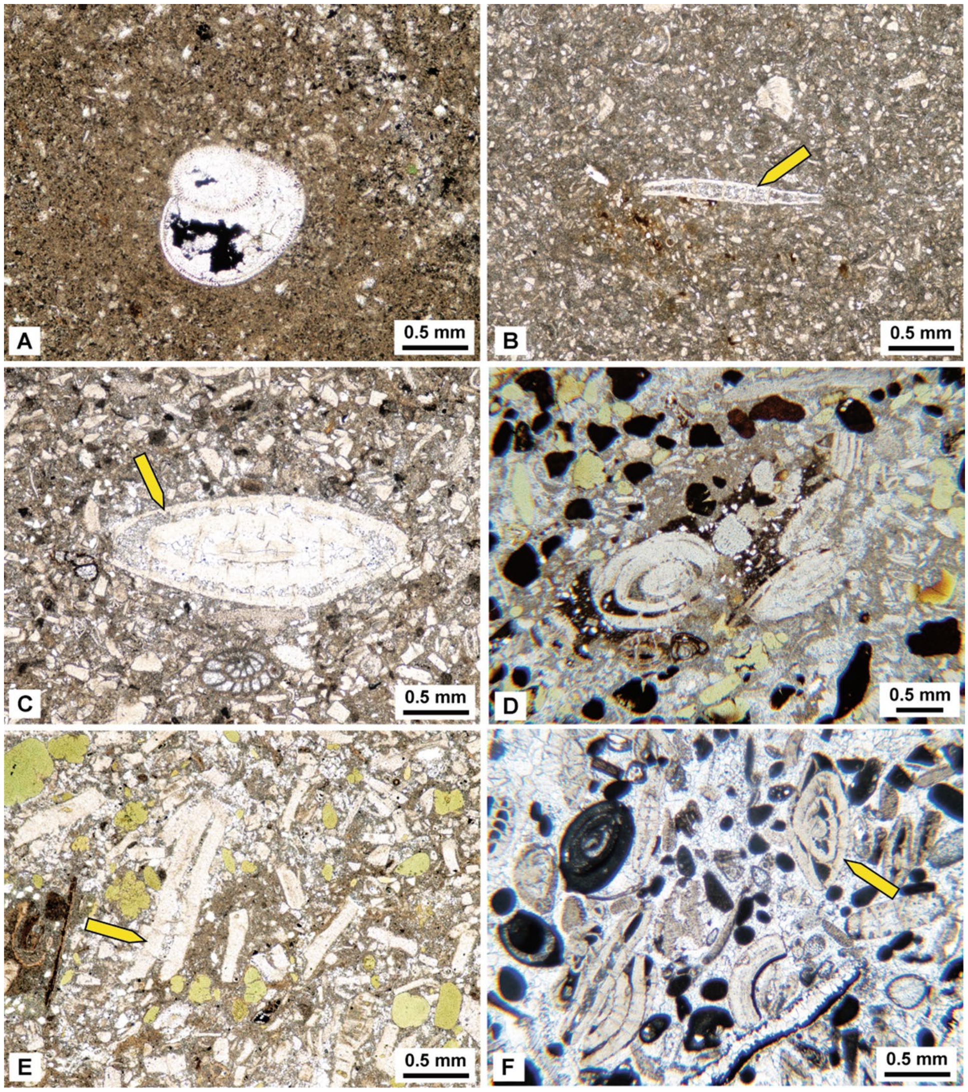

Fig. 10 Photomicrographs showing **a** Foraminifera lime-mudstone microfacies. Notice the presence of benthic foraminifera, the Al Faidiyah Formation of Shahat section, PPL. **b** Echinoderm foraminifera wackestone microfacies. Benthic foraminifera (*Assilina*, arrow), echinoderms, and undifferentiated shell fragments represent the dominant allochems, the Al Bayda Formation of Shahat section, PPL. **c** Bioclastic packstone microfacies. Benthic foraminifera (*Nummulites*, arrow), echinoderms, coralline algae, bivalve fragments, and undifferentiated shell debris are recorded, the Al Bayda Formation, Wadi Al Kuf section, PPL. **d** Glauconitic foraminifera packstone microfacies. Benthic foraminifera (*Nummulites*), undifferentiated shell debris, and glauconite grains are encountered as the main allochems. Notice the effect of compaction of two benthic foraminifera (arrow), the Darnah Formation, Shahat section, PPL. **e** Glauconitic foraminifera packstone microfacies. Notice the presence of benthic foraminifera (*Discocyclina*, arrow) and green glauconite grains, the Al Bayda Formation, Omar Al Mukhtar section, PPL. **f** Foraminifera grainstone microfacies. Benthic foraminifera (arrow), miliolids, and micritized shell fragments. Green glauconite grains are common. Silt-sized quartz grains are also recorded. Notice the presence of pyrite framboids in bivalve fragment (red arrow), the Abraq Formation, Shahat section, PPL

in eustatic sea level (Miller et al. 2005). In addition, during the Cenozoic, global climate changes from late Cretaceous–early Eocene warm settings to late Eocene–Quaternary cool settings (Frakes et al. 1992). The Eocene rock units in northeast Libya are capped by an unconformity that is called end-Eocene unconformity (Fig. 11). They overlain by the early Oligocene Al Bayda Formation that is composed of limestones and marl. This formation was deposited in open marine, shallow water platform. The Al Bayda Formation is covered by an unconformity that overlain by the late Oligocene Al Abraq Formation which is composed mainly of limestone and marl. It was deposited in open marine shelf to brackish settings. The Al Abraq Formation, in turn, is capped by an unconformity (Fig. 11) that overlain by the early Miocene Al Faydiyah Formation (Swezey 2009).

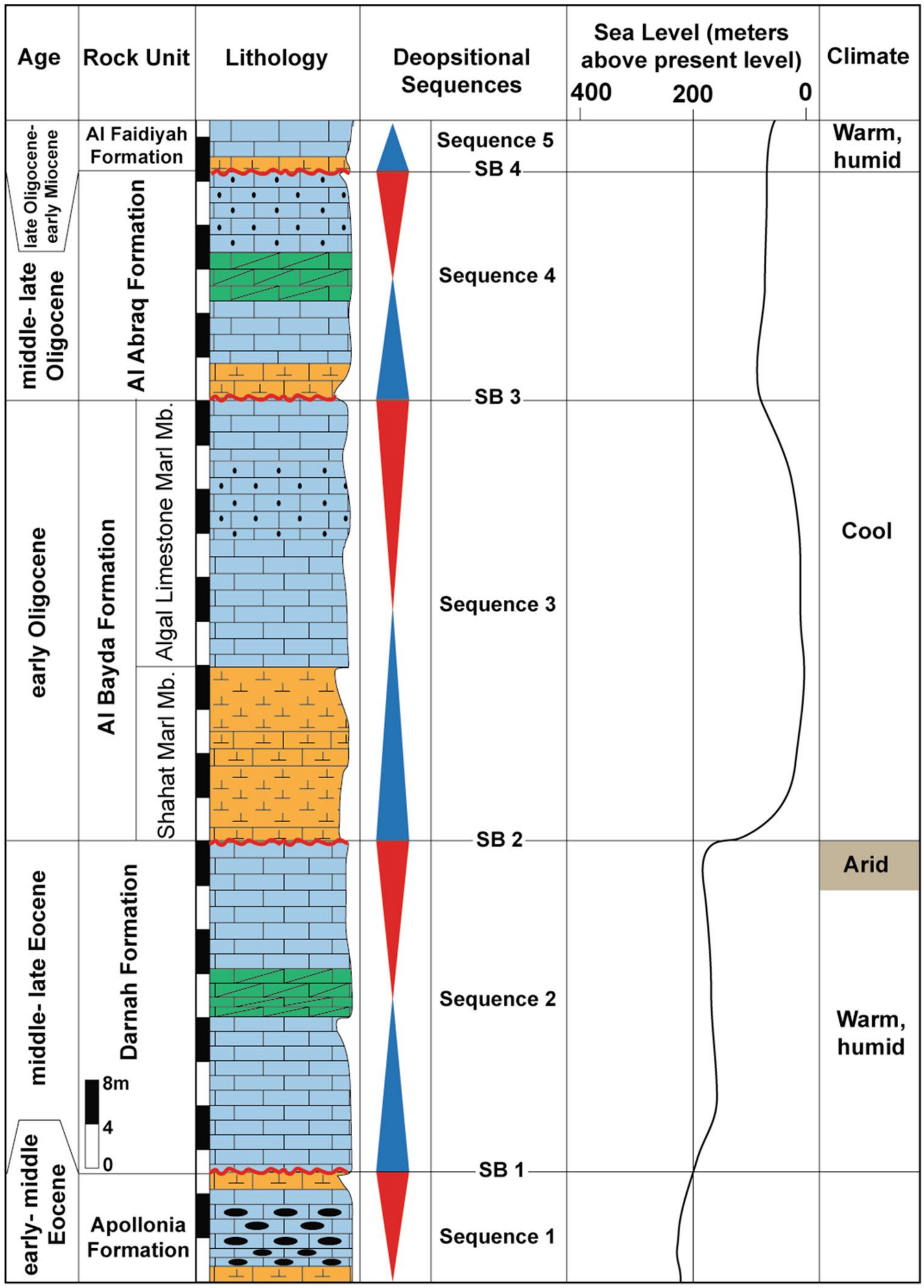

Fig. 11 Sequence boundaries and depositional sequences of the lower Eocene-lower Miocene succession in Shahat section. The sea level curve is derived from Gradstein et al. (2004). Climate of the northeast Libya after Frakes et al. (1992). See legend in Fig. 2

Regional unconformities (proposed sequence boundaries, Fig. 11) in northeast Libya are associated with major fall in eustatic sea level. Such fall was caused due to ice buildup at one or both poles. A regional unconformity that has resulted from eustatic sea level fall may point to tectonic component to its origin (Swezey 2002). Compressional tectonic activity has prevailed during the Eocene time (Swezey 2009). The mid-Oligocene and the end-Oligocene unconformities were resulted from falls in eustatic sea level. These events were recorded by Haq et al. (1987) and Miller et al. (2005).

Conclusions

The lower Eocene–lower Miocene succession in northeast Libya comprises five formations from bottom to top: the Apollonia, Darnah, Al Bayda, Al Abraq, and Al Faidiyah formations. The studied interval is represented by a thick succession of carbonate rocks.

- *Nummulites* are the dominant fossil group in the studied middle Eocene shallow water carbonates, whereas, they are missing in the upper Eocene rocks.

- Five transgressive/regressive cycles were recognized during the early Eocene–early Miocene times and separated by four unconformities that are considered as sequence boundaries.
- Facies analysis has revealed four depositional facies associations. These associations are restricted lagoonal settings with limited circulation, open marine lagoon with open circulation, platform-margin reefs and slope setting.
- The first association includes bioclastic packstone and foraminifera grainstone microfacies, whereas, the second facies association comprises foraminifera lime-mudstone, echinoderm foraminifera wackestone, and glauconitic foraminifera packstone. The third facies association includes algal boundstone, while the fourth facies association comprises foraminifera floatstone and rudstone.
- Benthic foraminifera such as *Nummulites*, *Assilina, Triloculina* were recognized in the Apollonia Formation. Large-sized benthic foraminifera (*Nummulites*, *Assilina* and *Operculina*) were observed in the Darnah Formation. The Al Bayda Formation contains small-sized *Nummulites*, *Assilina*, *Peneroplis*, and *Discocyclina*. The Al Abraq Formation includes *Discocyclina*, *Operculina*, and *Peneroplis*. These benthic foraminifera live in inner ramp to mid ramp settings. These shallow conditions point to the presence of epicontinental or epeiric sea that covered north Africa.
- The main diagenetic alterations affected the studied carbonates (particularly wackestones, packstones, grainstones, floatstones and rudstones) include micritization, pyritization, compaction, cementation, aggrading neomorphism and partial dissolution.
- Four sequence stratigraphic boundaries were observed in the lower Eocene–lower Miocene succession. Accordingly, five depositional sequences were recorded. The recorded depositional sequences show shallowing-upward trend.
- Regional unconformities in the studied area are associated with major fall in eustatic sea level.

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