

# Miocene Rocks Around the Mar álah Oasis, Central Sirt Basin, Libya: Facies Development and Implication on Stratigraphy

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## Abstract

The Miocene rocks of the Mar álah Formation have been stratigraphically investigated from four stratigraphical sections around the Mar álah Oasis in the Central Sirt Basin of Libya. The field investigations led to the identification of two members, the lower Qarat Jahannam Member and the upper Ar R álah Member. Fourteen sedimentary facies at the outcrop-scale representing a gradual development of sedimentation from a continental clastic witness in the southwestern outcrops to transitional estuarine, lagoonal, and beaches to the proximal offshore in the northern outcrops, were recognized. The results indicates that the accumulation of the Mar álah Formation is transgressive in nature and corresponding to two phases of deposition which have been mentioned in the earlier studies.

The first phase is continental-dominated facies in which cross-bedded sandstones and calcareous sands comprise most of the depositional sequence of the lower Qarat Jahannam Member at the southwestern outcrops. This phase, however, is characterized by extremely bioturbated laminated-shale conquered by *Skolithos* ichnofacies in the lower part of the upper Ar R álah Member at the northern outcrops. This phase is providing further evidence that the contact between the two members is diachronous everywhere in the study area. The clastic-phase has thought to be deposited in the Lower Miocene (Aquitania-Burdigalian) since the lower Qarat Jahannam Member rests on an erosional surface of submarine origin in the southwestern outcrops above a 0.5 m. thick of a nummulitic unit of the Oligocene Bu Hashish Formation.

The second phase is marine-dominated facies in which a bioclastic limestone unit rich in thick and disarticulated oysters, including *Crassostrea gryphoides* (Schlottheim), characterizes the sediments of the Ar R álah Member at the southwestern outcrops. This phase also includes the upper part of the latter member at the northern outcrops in which a detrital limestone unit rich in turritelline gastropods is overlying by thick-bedded calcarenites rich in disarticulated oysters, gastropods, irregular echinoids (notably, *Clypeaster* and *Echinolampas*), bryozoans, and celestite corals. The upper part of the Ar R álah Member at the northern outcrops, nevertheless, is terminated by a quite hard dolomitic limestone and by a pretty soft dolomitic marly limestone. Both lithologies, however, are combined with medium-sized oysters, including *Ostrea digitalina* Fuchs, and pectinid bivalves. The second phase, however, is interpreted to be deposited in the Middle Miocene (Langhian and Serravallian) based on the total-stratigraphic range of the larger benthic foraminifera *Borelis melo melo* (Fichtel & Moll), which recovered from the studied washed residues, and the associated microfacies.

**Keywords:** Libya, Sirt Basin, Miocene, Mar álah Formation, Sedimentary Facies

## 1. Introduction

The Oasis of Mar álah lies about 120 km inland from the Mediterranean coast in the Sahara Desert of Libya (Figure 1). On the northern side of the Oasis, the majority of rocks are cropping out in more or less east-west elongate scarps with an elevation of more than 150 meters reported in the northeast. On the southern side of the Oasis, however, several residual table hills rise from the plains ranging in height from a few meters to over 300 meters reported in the southwest. Geologically, the entire region is belonging to the central part of the Sirt Basin.

The whole of the sequence, nevertheless, is built-up of horizontal to subhorizontal strata with a general dip of few degrees

toward the NE direction. The sequence is dissected by some isolated hills, and several wadis and it consist of clastic and carbonate sedimentary rock units that were laid-down in the Lower-Middle Miocene (Maštera, 1985). Lithological variation, however, is abrupt both vertically and laterally, making the correlation of beds somehow difficult. In general, however, marine-dominated facies (principally, calcarenite limestones) become more abundant in the northern scarps whereas continental-dominated facies (notably, calcareous sandstones and unconsolidated sands) increase in importance in the southern escarpments.

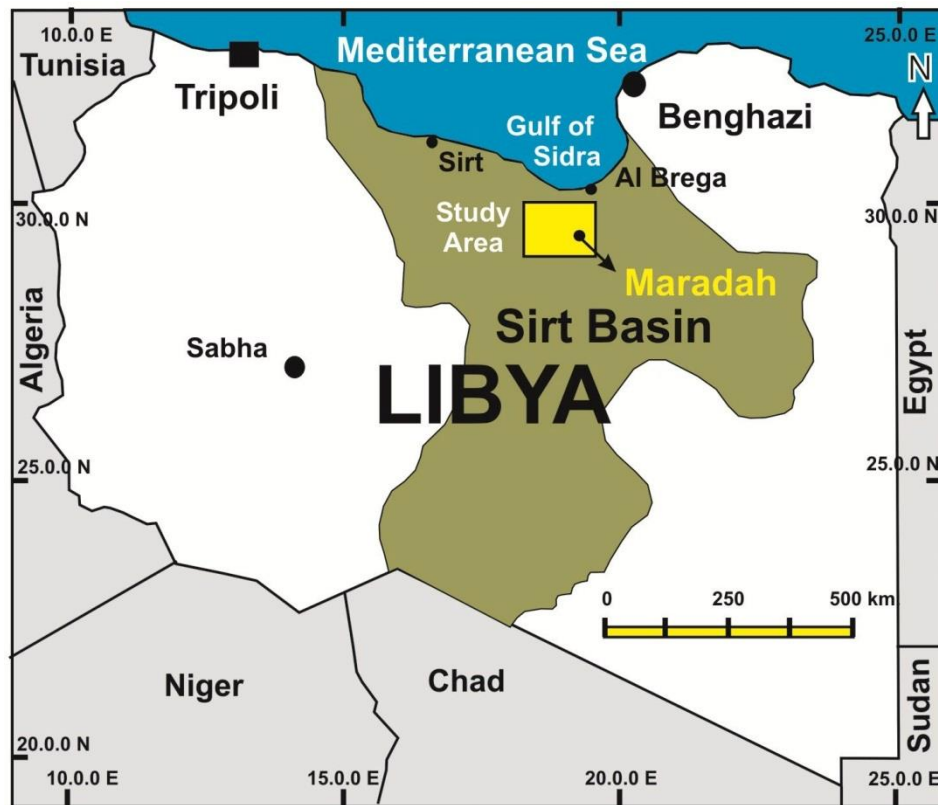


Figure 1. Index map of Libya showing the location of the studied area. The boundaries of the Sirt Basin are represented hereafter by Abdunaser and McCaffrey (2015)

In the current study, four stratigraphic sections of the Maradah Formation were measured and systematically sampled (Figure 2). The first and second sections (S1 and S2) are up to 100 m in thickness and were measured in the south-western side of the Maradah Oasis (Figure 3). The majority of the sequence in this locality is considered here to represent the Qarat Jahannam Member (Maštera, 1985) which corresponds to the continental-dominated facies. The third and fourth sections (S3 and S4), however, are up to 80 m in thickness and were measured at the northern part of the Maradah Oasis (Figure 4). They are considered here to represent the Ar Rahlah Member (Maštera, 1985) in which the lower part of the member corresponds to the continental-dominated facies whereas the upper part corresponds to the marine-dominated facies. To understand the lateral continuity of the studied deposits, all sections, though, have been compiled by spot samples, from different isolated hills in the northern and south-western parts of the Maradah Oasis. All measured sections, nevertheless, are located broadly between latitudes 18 °00' and 19 °30' E and longitudes 29 °00' and 30 °00' N (see Figure 2).

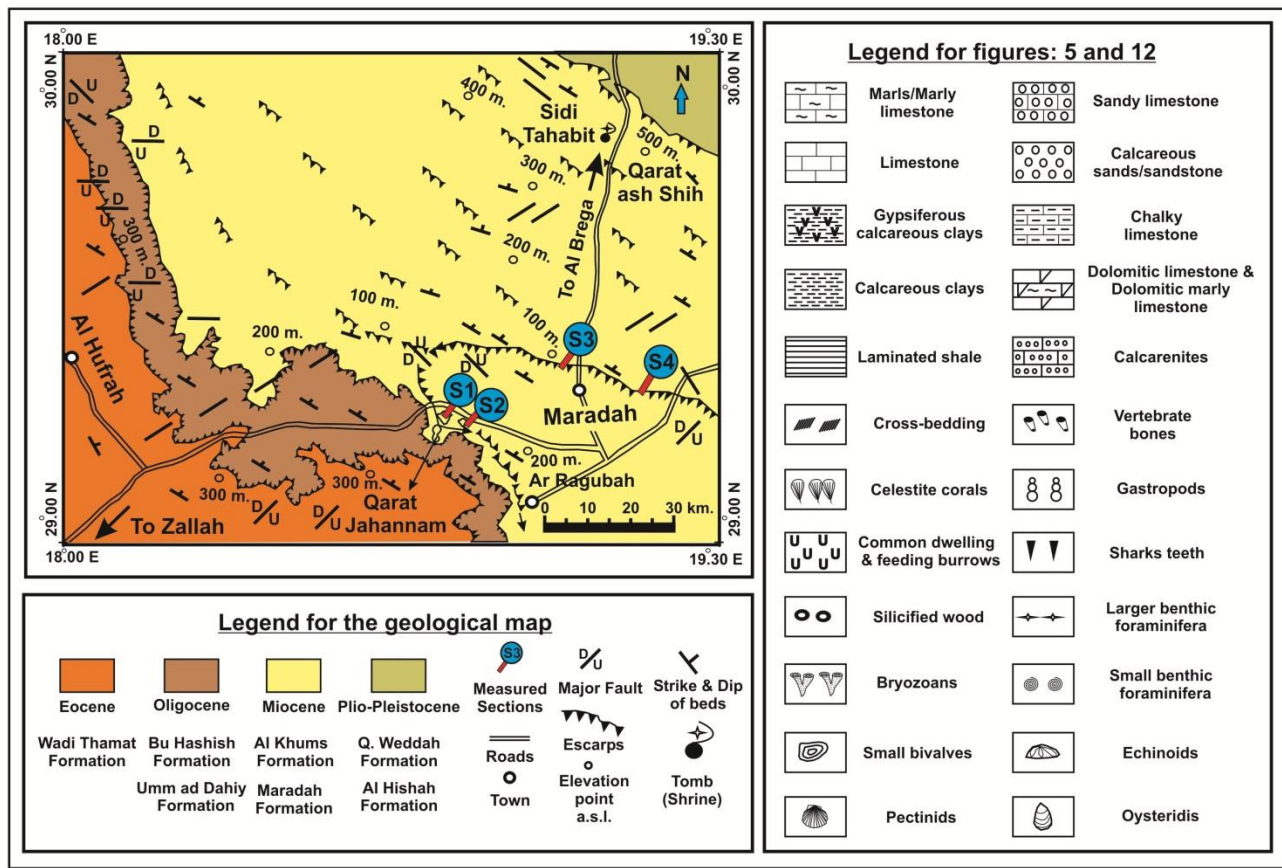


Figure 2. Geological map of the Maradah area showing the locations of the studied sections (S1-S4) modified after Maštera (1985)

The current study is part of a larger project to revise the surface outcrops of the Sirt Basin in which has been received little attention in the last two decades compared to the subsurface. The project starts with two publications on the stratigraphy and sedimentology of the western part of the Sirt Basin. The first study is discussed the Upper Cretaceous to Upper Paleocene succession (Abdulsamad et al., 2020a), whereas the second study is discussed the Upper Paleocene to Lower Eocene deposits (Abdulsamad et al., 2020b). The Middle Eocene to Oligocene deposits is under consideration and the results will be discussed in a separate publication. The Miocene rocks of the Maradah Formation, in the current survey, however, are described and discussed with the aim to improve the stratigraphy of the region based on information derived from the facies analysis and the associated trace and body fossil accumulation at outcrop-scale. The results, however, were also augmented by other data derived from petrographic thin-sections and washed residues of critical stratigraphic intervals wherever possible.



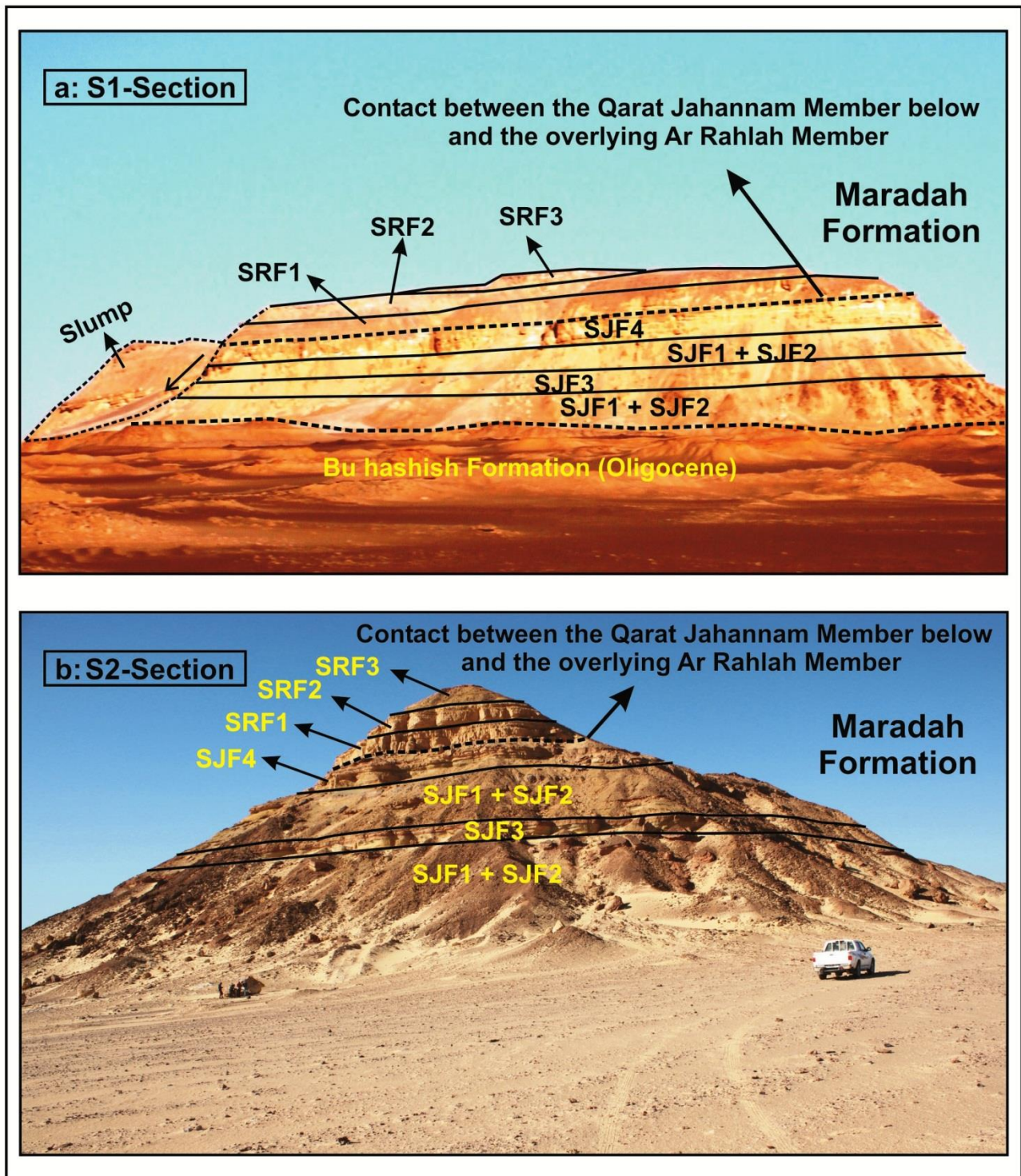


Figure 3. Views of the studied sections of the Maradah Formation showing S1-Section (a), and S2-Section (b) at the southwestern of the Maradah Oasis. SJF1-SJF4 are representing facies one to facies four which recognized in the Qarat Jahannam Member while SRF1-SRF3 are representing facies one to facies three which recognized in the Ar Rahlah Member. The dashed line represents the contact between the Qarat Jahannam Member below and the overlying Ar Rahlah Member



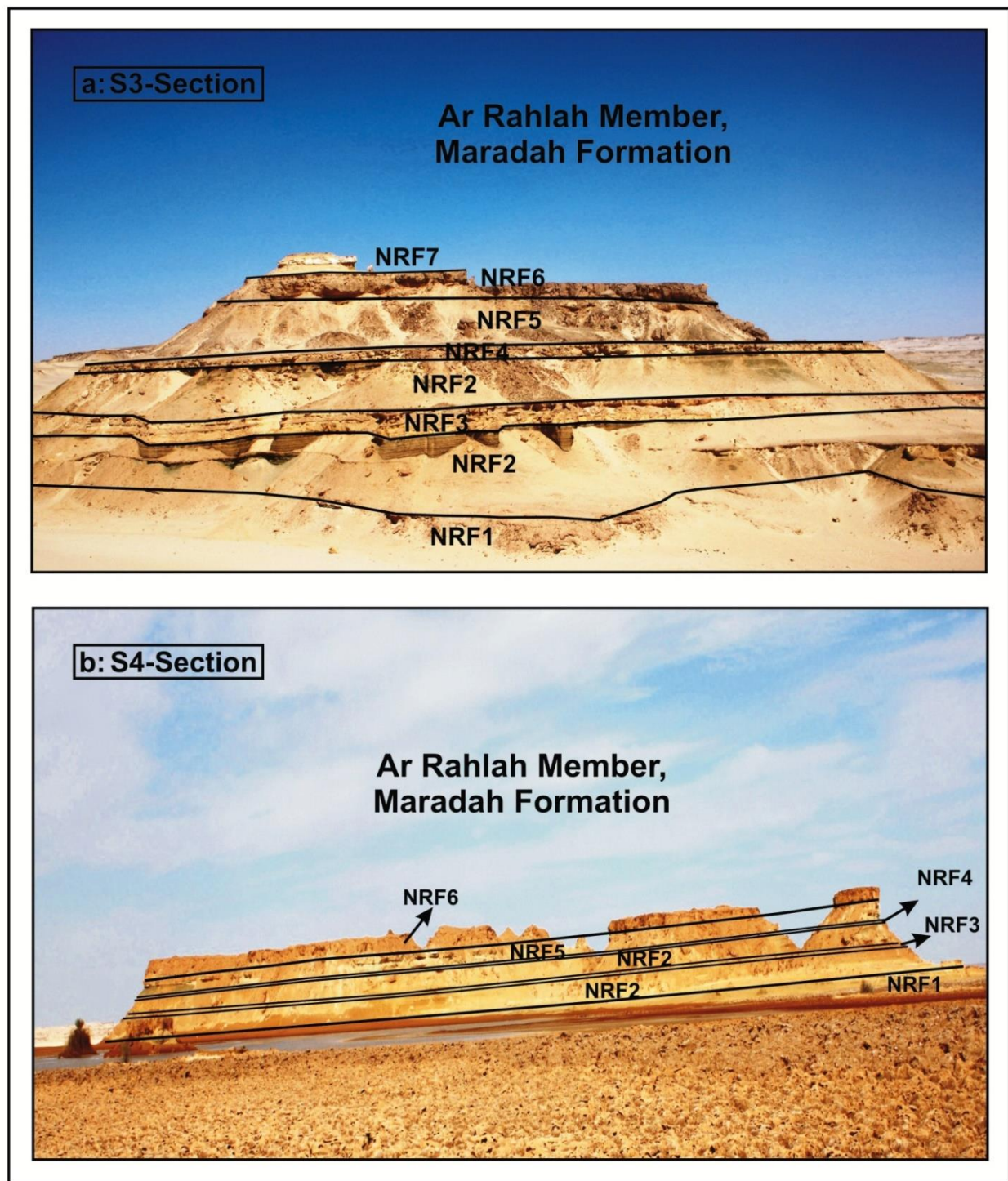


Figure 4. Views of the studied sections of the Maradah Formation showing S3-Section (a), and S4-Section (b) at the northern of the Maradah Oasis. NRF1-NRF7 is representing facies one to facies seven in the Ar Rahlah Member

## 2. Materials and Methods

Outcrop samples of clastic and carbonate sedimentary rocks were collected at a maximum interval of every 2 m; near lithologic facies changes the samples were more closely spaced. Composition, sedimentary structures, bed thickness, and macrofossil content were examined using terms proposed by Tucker (2011). The majority of the hard samples collected were subsequently processed for thin-section analysis, with several lithologies being recognized. Their litho- and bioclastic components are expressed using terms recommended by Flügel (2010). Several samples of soft lithologies, however, were crushed and disaggregated in a hydrogen peroxide solution and washed through a 63- $\mu$ m sieve. Although,

almost all samples were barren of microfossils, few samples from critical levels, however, are containing foraminifera, ostracods, and shell-fragments of mollusks, echinoids, and bryozoans. Unfortunately, the recovered specimens (mostly foraminifera) were poorly preserved and none of them were good enough for photomicrographs. We were able, nevertheless, to identify few specimens including some specimens of miliolids and alveolinids. Selected carbonate samples from the studied rock unit were also inspected for the study of calcareous nannofossils for age determination; however, the calcareous nannofossil samples did not yield any recovery. All laboratory analyses were undertaken at the Micropaleontology Laboratory of the Earth Sciences Department of the Benghazi University.

The study material will have a final repository in the Geological Museum of the University of Benghazi (Benghazi, Libya).

### 3. Background and Stratigraphy

The first published geological account on the area was that of Desio (1935) who designated the Miocene sequences, north, and east of Mar álah area, the "Marada Series". From his studies, he suggested that the rocks of the region were laid down along an ancient shoreline near a delta which more or less ponded a lagoon. He considered the marine-dominated facies exposed in the northern escarpment as Lower-Middle Miocene in age, whereas the continental-dominated facies exposed upon the southern escarpments as Lower Miocene. Magnier and Belgiers (1959) described the Mar álah Formation as Lower Miocene, distinguishing "Facies Marin Marada" and Facies Continental Zelten". Goudarzi (1970) introduced the term Marada Group and dated the unit to Middle Miocene. Both Selly (1968, 1969; 1971), and El-Hawat (1975; 1980) have dealt with the facies development in the region and they recognized several important lithofacies. Both authors, however, assumed that their recognized facies show lateral transitions throughout the region. The work of Doust (1968), however, is quite comprehensive and included paleontological and sedimentological details from the Mar álah area and southern Jabal Zelten area. In fact, these details have provided crucial evidence for the interpretation of the depositional history of the entire region. Doust (1968) recognized two phases of deposition in the region. An earlier (Lower Miocene) clastic phase found in the southern parts, indicating a tropical savannah climate, and a later phase (Middle Miocene) of carbonate deposition found in the northern parts, indicating shallow marine deposition. Both phases, however, are in accordance with the findings of Desio (1935), and Magnier and Belgiers (1959).

Other publications in the region were focused on the clastic deposits of the Jabal Zelten area, south of the study area, as it contains diverse fossil vertebrates. A concise overview of mammal faunas can be found in Savage and Hamilton (1973). Based on Gaziry (1987), from Jabal Zelten area, the deposits of the Mar álah Formation contain mammal faunas of different ages (Middle to Upper Miocene). Small Mammal faunas from Jabal Zelten area, however, are discussed by Wessels et al. (2003; 2008). The last two publications suggested that the age of the Mar álah Formation in the southern region is Lower-Middle Miocene.

A comprehensive data of mostly Oil-prospects boreholes in the region were studied by Wright and Edmunds (1971), Barr and Weegar (1972), and Benfield and Wright (1980). Unfortunately, the results of these publications were not particularly helpful for providing further insights into the depositional history but assigned a Lower-Middle Miocene age for the deposits of Mar álah Formation. More recently, El Ebaidi and Muftah (2015) present a geochemical and petrographical analysis of the Mar álah Formation at Jabal Zelten. They inferred that the depositional environment is dominated by very hypersaline lagoons of arid to semi-arid conditions with a restricted shallow platform to intertidal pulses. In fact, their conclusion is based on an analysis of the clayey and dolomite horizons which represent minor deposits compared to the overwhelming calcareous sands and sandstone sediments of the rock unit at Jabal Zelten. Unlike the later study, fish excavations by Argyriou et al. (2016) from the Mar álah Formation in Jabal Zaltan, however, assumed that the depositional environment of the formation was in tropical shallow estuarine to deltaic conditions.

Although the stratigraphic nomenclatures of sedimentary units of the region are contained in the work of Megerisi and Mamgain (1980), the stratigraphical subdivisions are introduced for the study region by Maštera (1985), however, has been adopted in the current work. The later author assigned a Lower-Middle Miocene age to the deposits of the Mar álah Formation and divided it into a lower unit, namely Q árat Jahannam Member, and an upper unit, namely the Ar R álah Member. The lithological boundary between the two members has been interpreted by the last author as diachronous and is the reflection of the change of facies due to the deposition in the Sirt Basin. Both units, however, are representing the clastic and the carbonate phases of Doust (1968) respectively.

The name of the type section of the Q árat Jahannam Member was derived by Maštera (1985) from the most residual hill, the Q árat Jahannam, in the southwestern Mar álah Oasis. It is located along the road that connects Mar álah to Zallah (see Figure 2). According to Selly (1969), the Q árat Jahannam Member is probably equivalent to Moghra Formation in Egypt (Said, 1962; 1990). Based on sedimentary structures and ichnofossil contents the Moghra Formation was deposited in a tidally-influenced fluvial environment (see Tawfik et al., 2018). The total thickness of the Q árat Jahannam Member is about 123 m. and the rocks are dominated by whitish fine-grained, usually cross-bedded sands with sporadic laminae of

claystone and siltstone. The lower contact with the underlying Oligocene sediments is disconformable while the upper contact with the Middle Miocene sediments of the overlying Ar Āhlāh Member is transitional (Maštera, 1985).

The name of the type section of the Ar Rāḥlah Member, however, was also given by Maštera (1985), to a sequence located in the northeast of the Mar āḍah Oasis where the escarpment is dissected by an asphaltic road. According to the Maštera (1985) the Ar Rāḥlah Member is equivalent to the Ar Rajmah Group of Al Jabal al Akhdar area of northern Cyrenaica and the Marmarica Formation in Egypt (Said, 1962; 1990). The average thickness of the member is about 150 m. and the rocks are dominated by fossiliferous creamy limestones and dolomites and subordinate intervals of claystone and other non-carbonate rocks. The lower boundary with the underlying Q ārat Jahannam Member is gradual in most cases. The upper boundary with the overlying Wadi Yunis Member of the Al Khums Formation, however, is abrupt towards the northeast of the Mar āḍah Oasis (Maštera, 1985).

## 4. Results and Discussions

#### 4.1 The Southwestern Outcrops

The studied sequence at this locality is represented by section one (S1) and section two (S2) (Figure 5). They are located close to the type section, the Q'arat Jahannam (see Figure 2). The total thickness of the studied sequence is up to 100 m. and the stratigraphic succession is generally similar in both sections, the difference being only in the slight thickness variations of each lithological unit (i.e. facies) (see Figure 5).

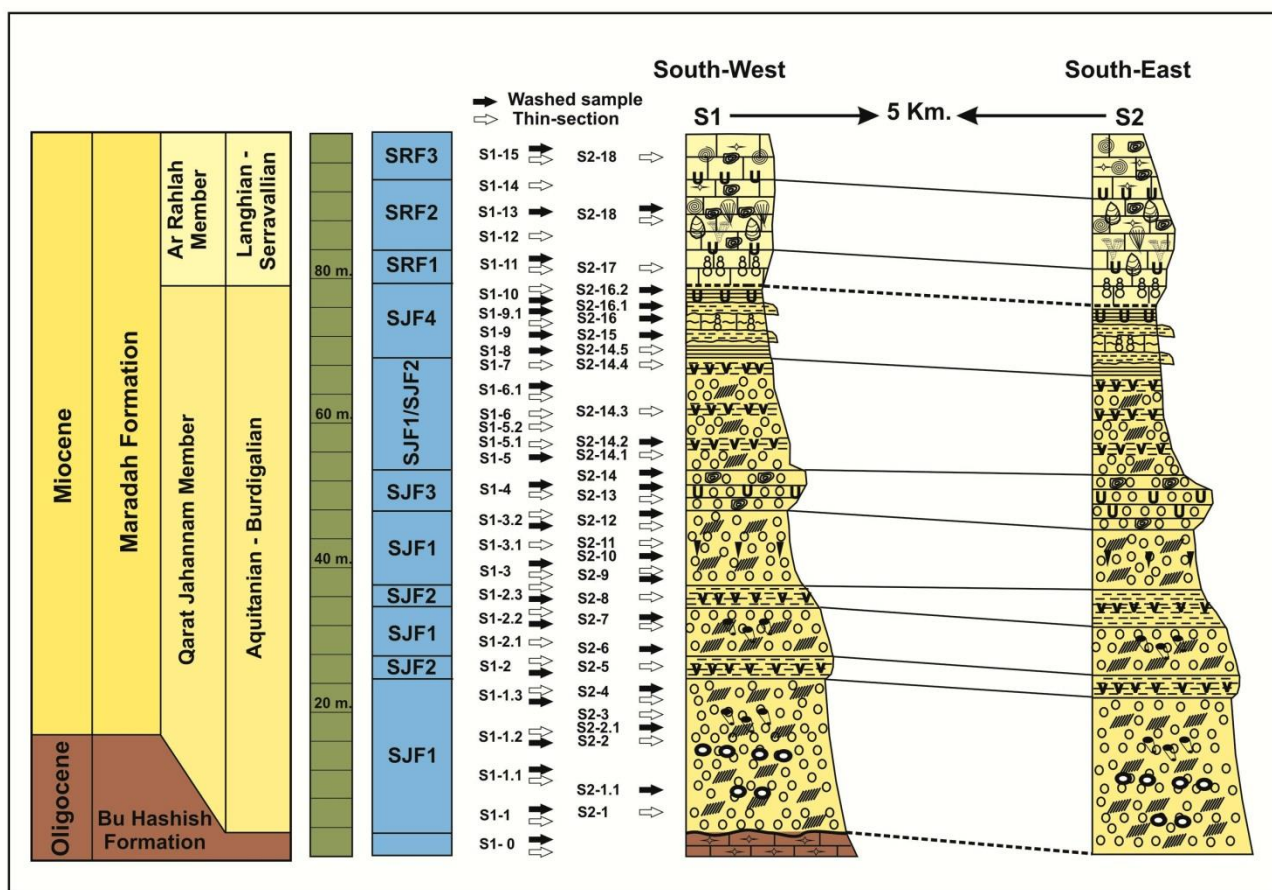


Figure 5. Stratigraphic characteristics of the Mar álah Formation showing the different recognized facies (SJF1-SRF3) at the outcrop-scale and the correlation between section one (S1) and section two (S2) at the southwestern Mar álah Oasis

It is worth noting, that the base of the Mar ʿālah Formation in this region rests on an erosional surface in section one (S1) above a 0.5 m. thick of a nummulitic unit of the Oligocene Bu Hashish Formation (see Figure 5). The unit is showing wackestone texture under the microscope and is enriched by leached A-form *Nummulites fichteli* Michelotti, with other shell-fragments of bivalves and nummulitids (Plate 1, figures 1; 2). Normally, A-Form nummulites arise favorably when environmental conditions are optimal for growth (Reiss & Hottinger, 1984). B-Form nummulites, however, are few both in thin-section and in hand specimen. The lack of abrasion and abundance of intact A- and B-forms witnesses in the study samples, reflect autochthonous to para-autochthonous accumulations of nummulites (Racey, 1995; 2001; Abdulsamad & Tmalla, 2008). In the surrounding of the Q ʿārat Jahannam, the nummulitic unit, however, is showing nummulites coquina



and almost entirely made of A-Form *Nummulites fichteli* Michelotti (Figure 6). According to Maštera (1985), this unit is of several meters in thickness and extends for about 150 km in the surrounding region. It is interpreted by the later author to originate in the shallow marine environment of the inner shelf. The age of this unit, however, has been interpreted as Upper Oligocene (lower Chattian) by most workers in the region based on the occurrence of *Nummulites fichteli* Michelotti. As this species is well known from the Lower Oligocene (Rupelian) in the circum-Mediterranean region and in the neighborhood region of Cyrenaica (see Abdulsamad, 2000; Abdulsamad et al., 2009), the age of the Bu Hashish Formation has been revised by the current authors and will be discussed elsewhere.

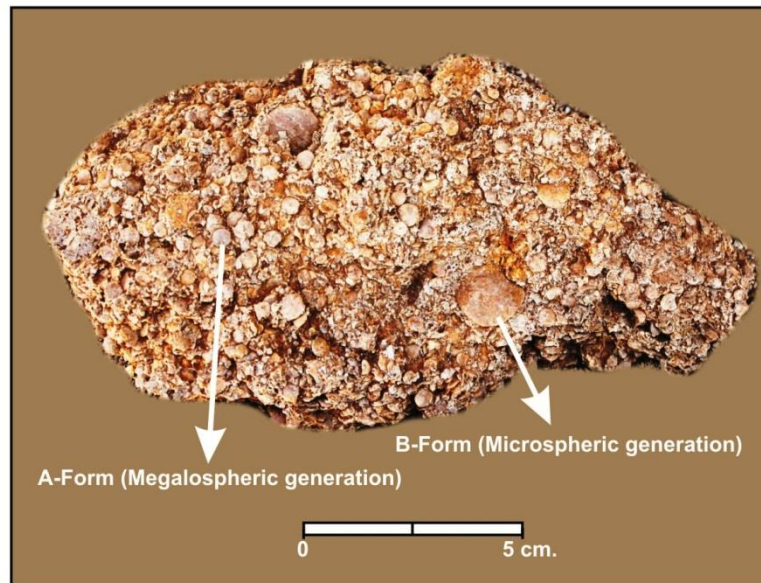


Figure 6. Show a sample of the nummulites coquina in the surrounding of the Q árat Jahannam. Note, although the B-forms of the nummulites are present, the majority of the rock consists of A-Form *Nummulites fichteli*

In section two (S2), however, the contact is covered by the outwash of weathered sands from the overlying units (see Figure 3b).

The Mar álah Formation at the southwestern outcrops (S1 and S2) is representing by the lower Q árat Jahannam Member and the upper Ar R álah Member. Both units, however, are representing the so-called continental and the carbonate phases mentioned in earlier studies. The lower Q árat Jahannam Member interpreted to deposit in the Lower Miocene (Aquitanean-Burdigalian) based on its stratigraphic position in which rests unconformably on the Oligocene Bu Hashish Formation. The boundary between the lower Q árat Jahannam Member and the upper Ar R álah Member, however, has been set based on a major facies change (see Figure 5) and supports by the recovery of the first aberrance of the larger benthic foraminifera *Borelis melo melo* (Fichtel & Moll). The recovery of this subspecies from the washed residue and in thin-section indicates that the upper Ar R álah Member at the southwestern outcrops is Middle Miocene (Langhian and Serravallian) in age. The attribution of the latter subspecies to the Middle Miocene is based on its overall spherical morphology in the Mediterranean region (see Adams, 1984). Yet based on the stratigraphic data provided by Jones et al. (2006), one can conclude that *Borelis melo melo* (Fichtel & Moll) is abundant from the Middle Miocene deposits of the Mediterranean region, whereas this subspecies is infrequent from the Upper Miocene in the same region (e.g., Messinian of southeast Spain, Cabo de Gata, Province Almeria; see Betzler & Schmitz, 1997). *Borelis melo melo* (Fichtel & Moll) has been observed in Libya by Berggren (1967); by Sherif (1991) from the Middle Miocene Al Khums Formation (northwest Libya); by Abdulsamad et al. (2009) and more recently by Abdulsamad et al. (2018) from the coeval deposits in the neighboring coastal area of al Jabal al Akhdar of the northern Cyrenaica of NE Libya.

The Q árat Jahannam Member at the southwestern outcrops (S1 and S2) is about 80 m thick (see Figure 5) and primarily consists of four different facies (SJF1-SJF4) at the outcrop-scale. They are representing cyclic sedimentation for most of the measured sequence and are briefly described below in stratigraphic order.

Facies one (SJF1) is the dominant facies and representing about 75% of the Q árat Jahannam Member. It principally consists of whitish-yellowish soft and fine-grained calcareous sands (Figure 7a; Plate 1, figure 3) interbedded with low angle and small scale cross-bedded sandstone (Figure 7b). The sandstone is poorly sorted, composed largely of subangular to subrounded quartz grains with a common detrital clay matrix (Plate 1, figure 4). At the outcrop-scale, this facies is associated with common reworked mammal bones, sharks-teeth, and silicified wood. The calcareous sands are



interpreted by Selly (1969) to deposit in an estuarine environment whereas the cross-bedded sandstones are described by him as fluvial in nature. As the two lithologies are often compositionally immature which reflect rapid deposition in subaerial environments, such as a river (Miall, 1985; 2006) and lack of any shelly fauna representing estuarine settings, we have grouped them under one facies (SJF1) and the whole sediments are considered here to deposit in a fluvial environment.

The overlying, facies two (SJF2) consists of claystone and is representing the second main lithology in the studied sequence. It represents about 15% of the total sediments of the Q árat Jahannam Member in this area. It is normally intercalated with facies one (SJF1) at upper levels where secondary gypsum patches are commonly found between the sandstones and the claystones (Figure 8a). At least two thick-bedded of claystone can be recognized at the lower levels. Herein, the claystone (Figure 8b) is yellowish in color, massive, and locally gypsified suggesting deposition in low-energy shoreline or lagoon. At the microfacies-level, the sediments are very fine-grained and regularly show homogenous composition (Plate 1, figure 5). At the top of the sequence, the claystone becomes laminated and may reflect quite a water of deposition (Figure 9a).

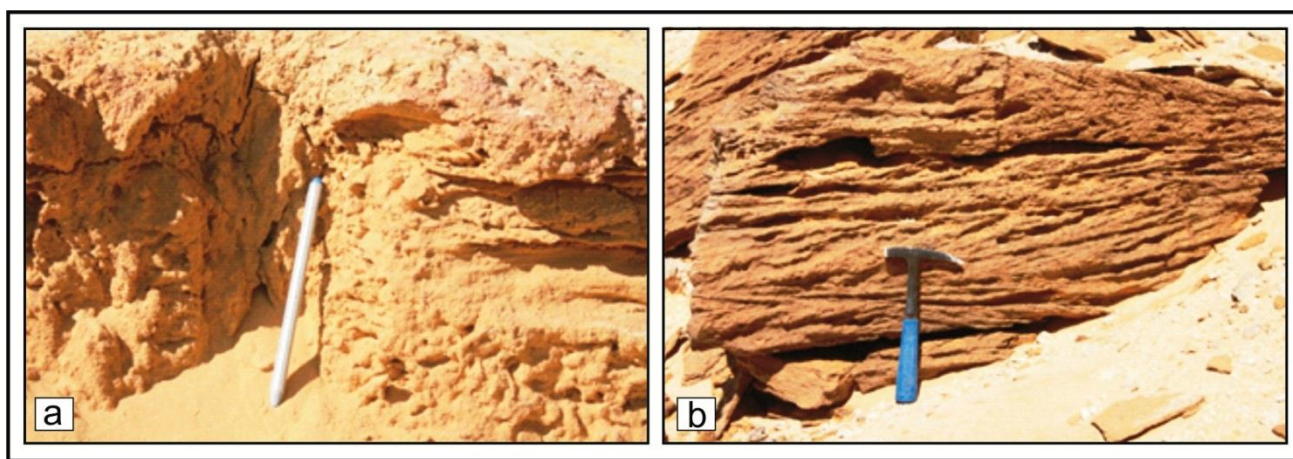


Figure 7. Views showing the calcareous sands (a), and the cross-bedded sandstone of the facies one (SJF1) (b) at the southwestern outcrops

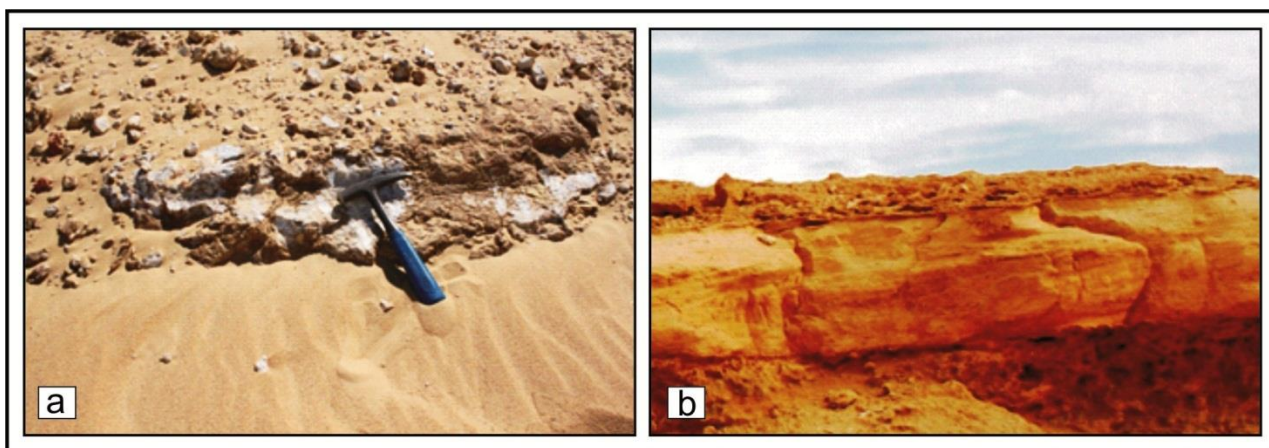


Figure 8. Views showing secondary gypsum (a), and a thick-bedded of yellowish claystone of facies two (SJF2) (b) at the southwestern outcrops

A reddish-brown thick-bedded of a bioturbated calcareous sandstone unit is representing the overlying facies three (SJF3). This facies is separating the lower and upper parts of the Q árat Jahannam Member in the studied sections (see Figures 3; 5). At the microfacies-level, the rock texture is largely fine-grained, poorly sorted with common large grains of quartz (Plate1, figure 6). The bedding, however, is largely disturbed by dwelling simple to complex burrow system (Figure 9b). Simple straight tubes (*Skolithos*), however, are representing the major contributors to the burrow system. Normally, *Skolithos* ichnofacies represent a marginal marine setting but may occur also in high-energy continental environments (Buatois et al., 1998; Melchor et al., 2003). Their associations with abraded small-sized pelecypods at this level, however, may indicate that the deposition was in sandy shoreline in very shallow depth with high-energy.



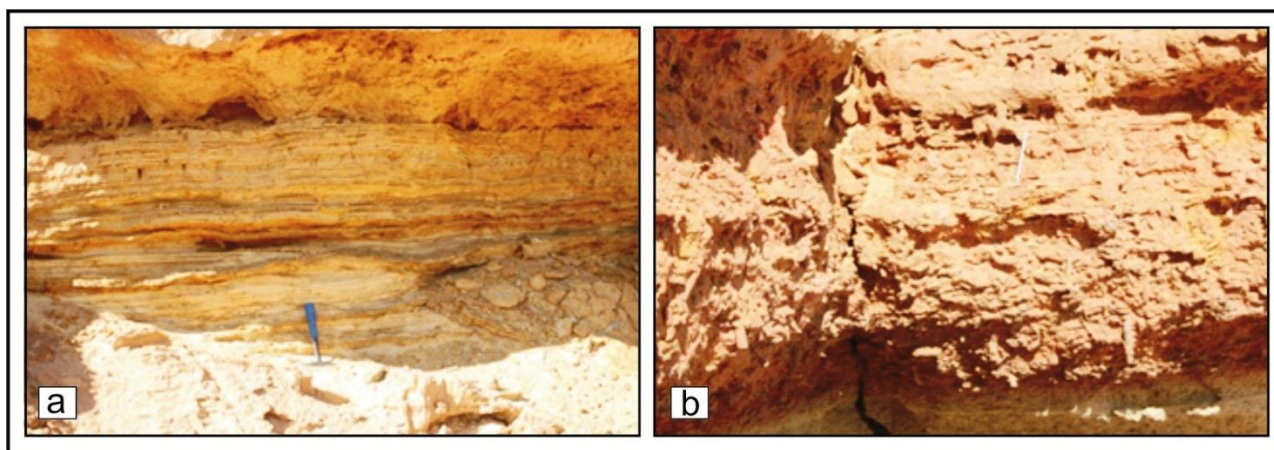


Figure 9. Views showing the laminated-claystone of facies two (SJF2) (a), and the bioturbated calcareous sandstone of facies three (SJF3) (b) at the southwestern outcrops

The remaining sediments of the Qarat Jahannam Member are represented by facies four (SJF4) (Figure 10a). Herein, the lithology is mainly dominated by yellowish-brown and green laminated calcareous shale interbedded with claystone similar in lithology to the claystone examined in facies two (SJF2). The claystone in this interval, however, is rarely gypsified and intercalated with laminae of silty marlstone enriched by small-sized internal casts of gastropods. The uppermost of this facies, however, is represented by thin-bedded laminated calcareous shale and show subareal bioturbation by roots that infer deposition in river-floodplain or low-energy shoreline (Bentham et al., 1993). The laminated-shale, nevertheless, is interpreted by Selly (1969) as Lagoonal.

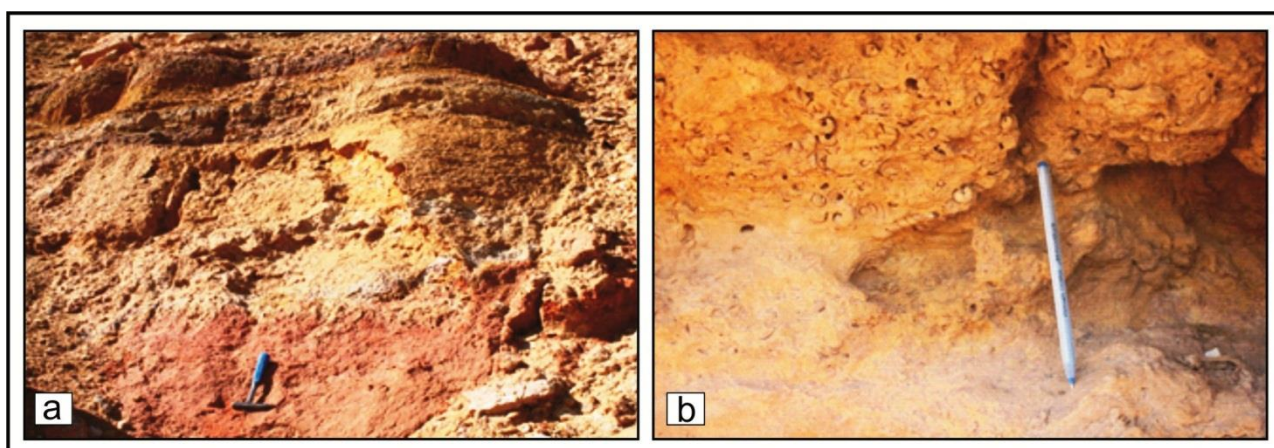


Figure 10. View displays the laminated calcareous shale intercalated with claystone and silty marlstone of the facies four (SJF4) of the Qarat Jahannam Member (a). A view shows the gastropod bed of facies one (SRF1) of the Ar Rahlah Member (b)

The overlying Ar Rahlah Member in this locality is about 20 m thick in both studied sections and mainly consists of three distinct facies (SRF1-SRF3). The first facies (SRF1) is observed on the base above the contact with the underlying Qarat Jahannam Member. Herein, the lithology is represented by whitish to yellowish detrital limestone which is composed largely of cemented shell-fragments. At the microfacies-level, the sediments at both study sections are mostly showing grainstone texture although mud-supported wackestone-texture with common micrite-clasts is locally observed (Plate 2, figures 1; 2). In section two (S2), the washed residue of the detrital limestone contain poorly preserved specimens of *Borelis melo melo* (Fichtel & Moll), nonetheless, the facies show low-angle stratification and terminated by a gastropod bed at the outcrop-scale (Figure 10b). The gastropods, however, are largely represented by large-sized suspension feeder species of Turritellids which indices shallow nearshore conditions (Pashko, 2018). As the assemblage of gastropods include other biconical and trochiform forms which are often abraded because of transport and sorting the accumulation of facies one (SRF1) is interpreted here to deposit in high-energy environments like beaches or raised banks.

The overlying facies two (SRF2) of the Ar Rahlah Member is whitish to reddish bioclastic limestone rich in thick-oysters (notably, *Crassostrea gryphoides* (Schlottheim)) at the outcrop-scale (Figure 11a). Such oysters are normally a dweller adapted to shallow-marine towards estuarine intertidal environments (Harzhauzer et.al, 2016) but as all the recovered

specimens were disarticulated, which reflect transportation under high-energy conditions, a different habitat such as shoreline environment is further reliable. Their association with celestite corals, bryozoans, and small-sized and thick bivalves may provide supporting evidence. At the microfacies-level, the sediments are showing a packstone-grainstone texture with common shell-fragments of bivalves, and bryozoans (Plate 2, figures 3; 4). A temperate bioturbation rate by burrowing, however, has been recognized and characterizes the lower and upper limits of this facies at the outcrop-scale which may infer a sandy shore environment of deposition (see Figure 5).

Up-section, the studied sequence is terminated with facies three (SRF3) which consists of white and fairly firm limestone (Figure 11b). Here, few thick and large-sized sublittoral inhabitant gastropods *Turritella* and *Conus* are recovered and documented as indices nearshore environments (Harzhauzer, 2004; Wielandt-Schuster et al., 2004). The overall lithology, however, is quite distinguishable by its tiny and fragmented shelly aberrance which provides further evidence for a nearshore environment with similar water energy seen in the underlying facies (SRF2). At the microfacies-level, the sediments are showing mostly wackestone-texture with sparsely fossiliferous micrite clasts. It includes shell-fragments of bryozoans, and *Borelis melo melo* (Fichtel & Moll) (Plate 2, figures 5; 6). The lowermost part of facies three (SRF3), however, is representing modest bioturbation by simple straight tubes and burrows whereas the uppermost part is massive and has been extensively used by the local community for industrial purposes.

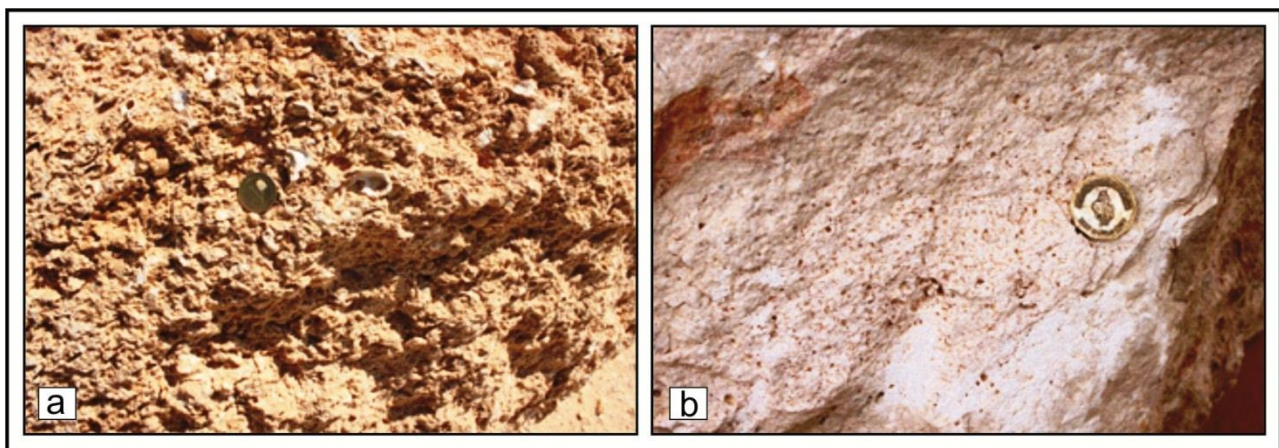


Figure 11. Views showing the detrital limestone with common oysters of the facies two (SRF2) at section two (S2) (a), and the white limestone with shell-fragments of facies three (SRF3) of the Ar Rāḥlah Member at section one (S1) (b)



## PLATE 1

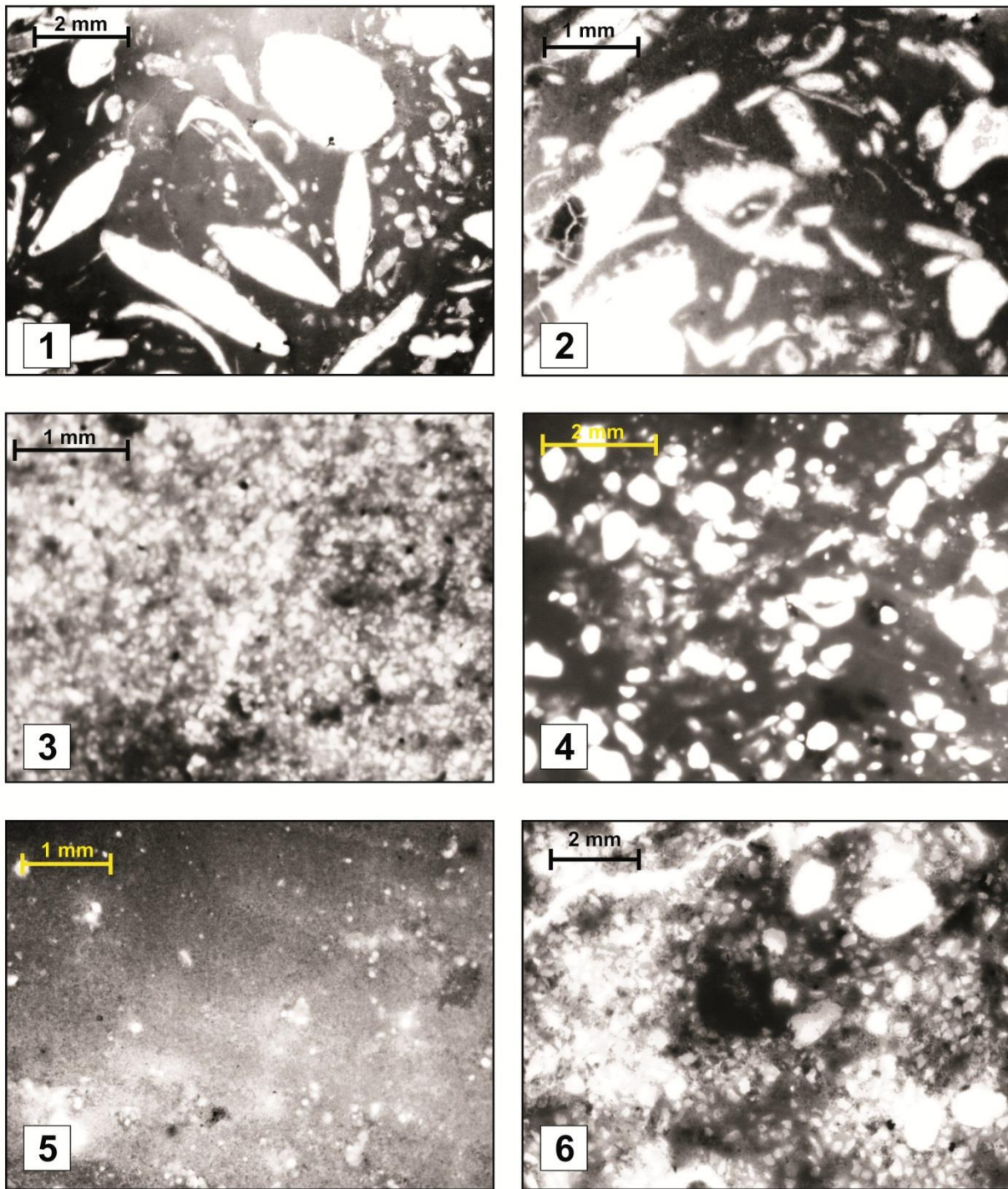


Plate 1. Figures 1; 2. Photomicrographs show mud-supported wackestone of the Oligocene Bu Hashish Formation. The sediments are enriched by leached A-form *Nummulites fichteli* Michelotti, with other shell-fragments of bivalves and nummulitids. Figures 3; 4. Photomicrographs showing facies one (SJF1) of the Q árat Jahannam Member of the Mar álah Formation, which consists largely of fine-grained calcareous sands (figure 3) interbedded with poorly sorted sandstone (figure 4). The latter texture is made mostly of subangular to subrounded quartz grains and common detrital clay matrix. Figure 5. Photomicrograph showing facies two (SJF2) of the Q árat Jahannam Member of the Mar álah Formation, which consists of claystone. The sediments are very fine-grained, and more than half of the composition is showing clay-sized



particles. Figure 6. Photomicrograph showing facies three (SJF3) of the Qárat Jahannam Member of the Mar álah Formation, which consists of calcareous sandstone. The rock texture is composed mostly of fine-grained, poorly sorted with common large grains of quartz.

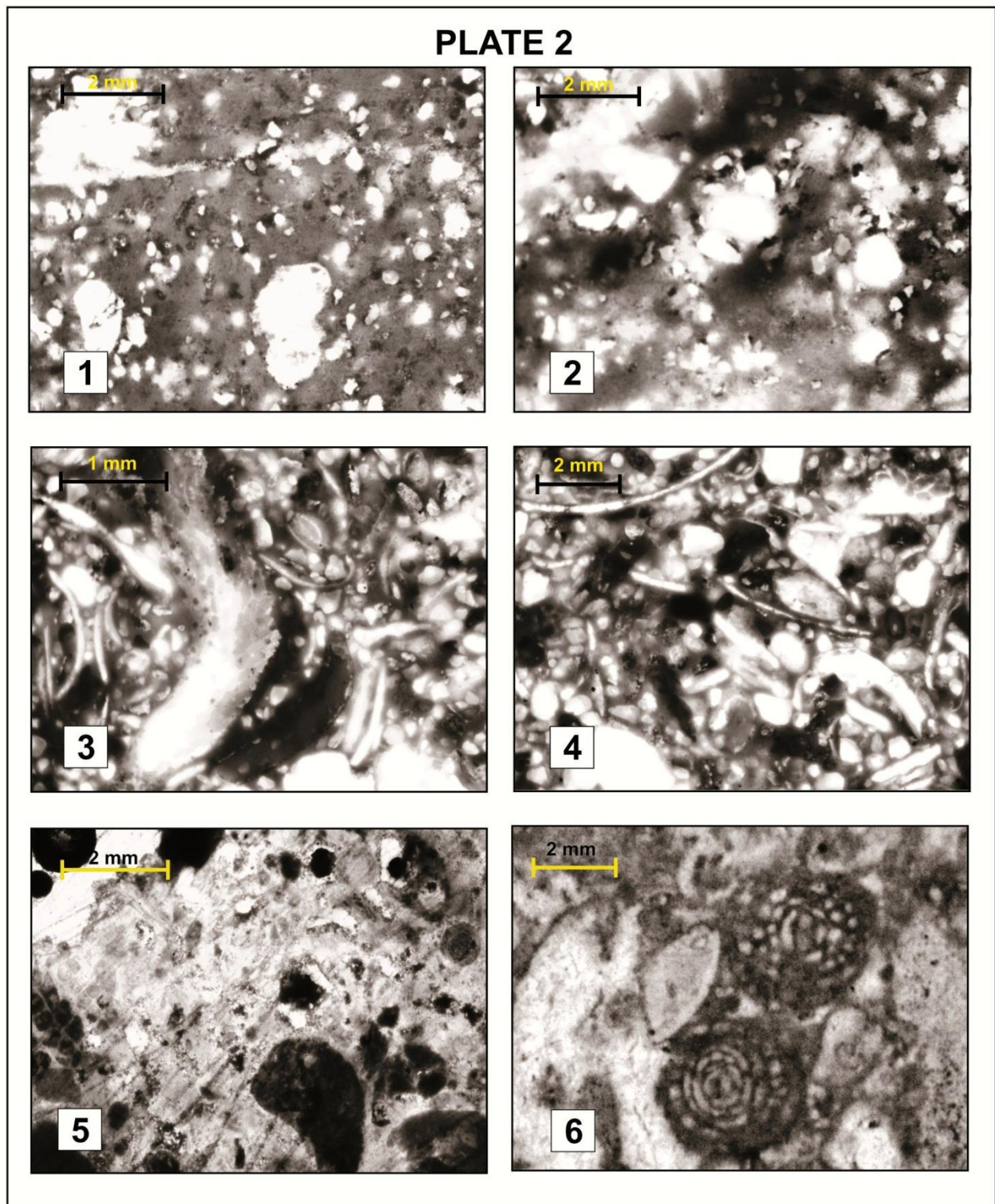


Plate 2. Figures 1; 2. Photomicrographs showing facies one (SRF1) of the Ar Rahlah Member of the Mar álah Formation, which consists mostly of mud-supported wackestone-texture with common micrite-clasts and large shell-fragments of bivalves. Figures 3; 4. Photomicrographs showing facies two (SRF2) of the Ar Rahlah Member of the Mar álah Formation,

which consists of bioclastic limestone. The sediments are showing a packstone-grainstone texture with common Shell-fragments of bivalves and a large fragment of bryozoa (Figure 3). Figures 5; 6. Photomicrographs showing facies three (SRF3) of the Ar Rahlah Member of the Mar álah Formation, which consists mostly of wackestone-texture with sparsely fossiliferous micrite clasts. It also includes shell-fragments of bryozoans and *Borelis melo melo* (Fichtel & Moll) (Figure 6).

#### 4.2 The Northern Outcrops

The studied sequence at this locality is represented by section three (S3) and section four (S4) (Figure 12). They are representing by two different residual hills located in the northern part of the Mar álah Oasis (see Figure 2). The total thickness of the studied sequence is about 80 m. and the Mar álah Formation is represented here only by the upper member, namely the Ar R álah Member. Apart from the uppermost facies (NRF7) which is present only in section three (S3), the stratigraphic successions are generally similar, the difference being only in the slight thickness variations of each individual lithological unit (i.e. facies). The lower and upper contacts of this member with the underlying Q árat Jahannam Member of the Mar álah Formation and the overlying Wadi Yunis Member of the Al Khums Formation are not recognized in these localities. The upper contact, however, can be recognized in Q árat ash Shih, further north near Sidi Tahabit along the road to Al Brega (see Figure 2). Herein, the lower unit of the Wadi Yunis Member is consisting of quite hard gypsiferous limestone rests unconformably over a soft unit of dolomitic marly limestone of the Ar R álah Member of the Mar álah Formation (Figure 13a). Large internal casts of oysters (notably, *Crassostrea gryphoides*) are recovered from the dolomitic marly limestone unit below the contact (Figure 13b) whereas large-sized internal gypsified casts of gastropods (notably, *Conus* sp. and *Turritella* sp.) and pelecypods (essentially, *Codakia lionina* (Basterot)) are recovered from the overlying limestone (Figure 14).

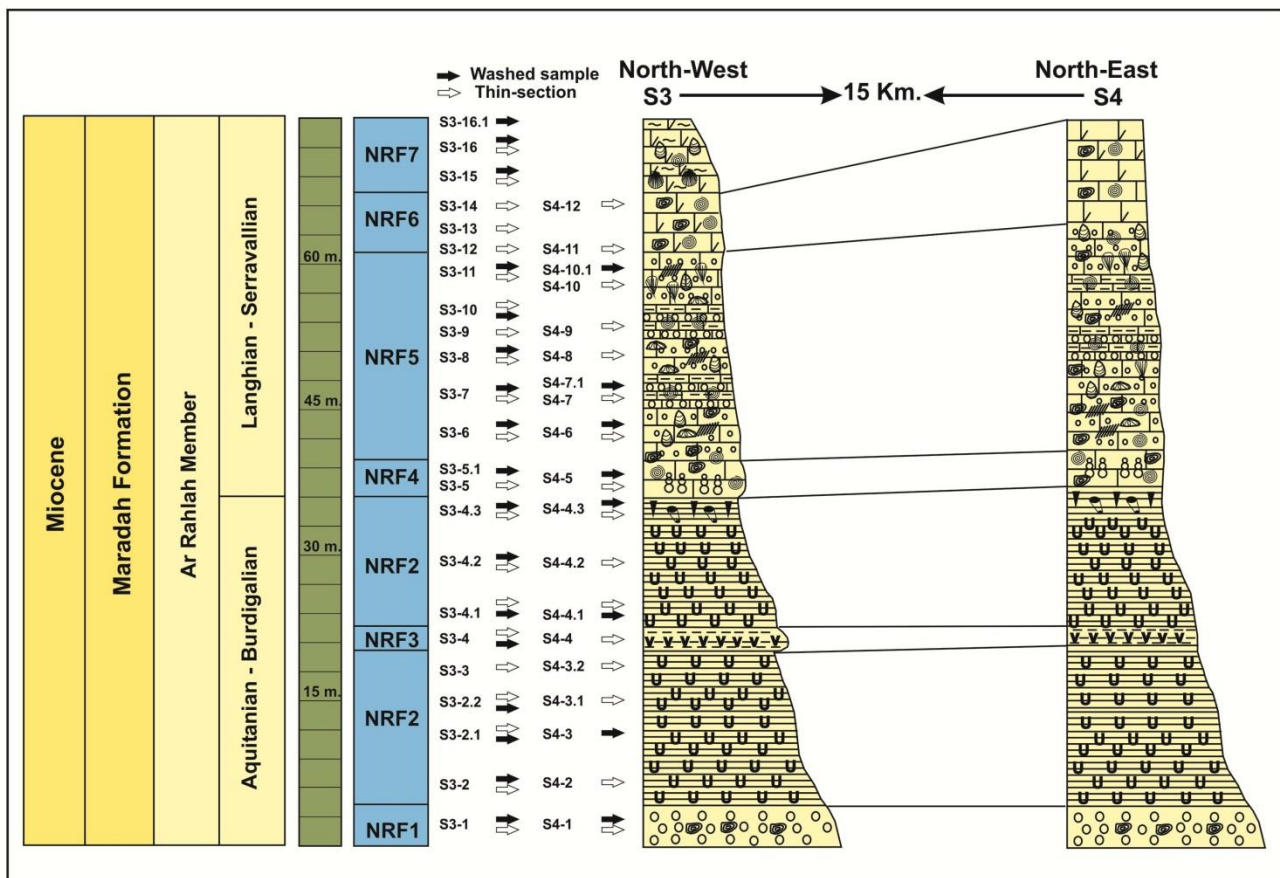


Figure 12. Stratigraphic characteristics of the Ar R álah Member of the Mar álah Formation showing the different recognized facies (NRF1-NRF7) at the outcrop-scale and the correlation between section three (S3), and section four (S4) at the northern Mar álah Oasis



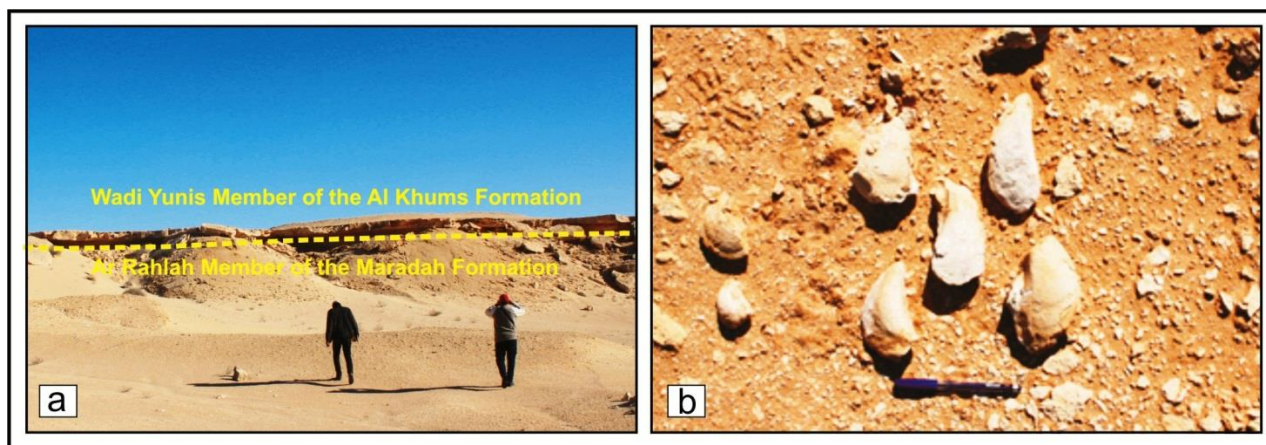


Figure 13. View showing the contact between the Ar Rahlah Member of the Maradah Formation and the overlying Wadi Yunis Member of the Al Khums Formation near Sidi Tahabit (a). Large internal casts of *Crassostrea gryphoides*, which recovered from the uppermost unit of Ar Rahlah Member of the Maradah Formation near Sidi Tahabit (b)

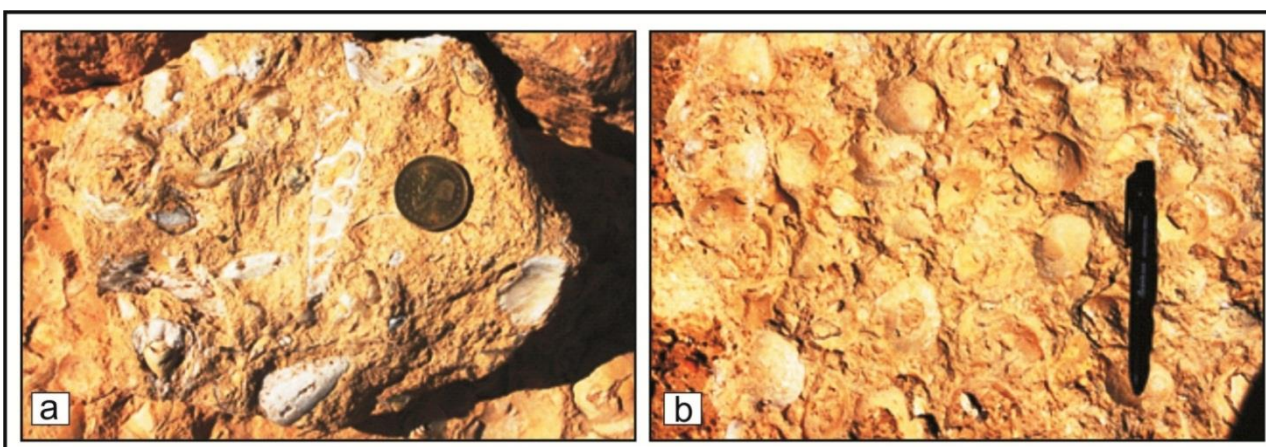


Figure 14. Views of internal gypsified casts of turreted and biconical gastropods (a), and internal and external casts of *Codakia lionina* (b), which recovered from the overlying limestone unit of the Wadi Yunis Member of the Al Khums Formation near Sidi Tahabit

The Ar Rahlah Member of the Maradah Formation at the northern outcrops, however, is represented by seven different facies (NRF1-NRF7). Herein, the lower part of Ar Rahlah Member is denoted by NRF1-NRF3 which primarily resembles the continental-dominated phase mentioned above and consequentially the sediments have been assigned to the Lower Miocene (Aquitainian-Burdigalian). The overlying facies (NRF4-NRF7), nevertheless, are corresponding to the carbonate-dominated phase in the region and the deposits have been attributed to the Middle Miocene (Langhian and Serravallian) based on the total-stratigraphic range of *Borelis melo melo* (Fichtel & Moll), which recovered from the washed residues at both studied sections (S3 and S4). Below, however, a brief description of the main recognized facies is presented in stratigraphic order.

Facies one (NRF1) is representing the base of the Ar Rahlah Member of the Maradah Formation in these localities (see Figure 12). It consists of whitish-yellowish calcareous sands and sandstones similar in aberrance to the calcareous sands and sandstones facies (SJF1) present at the southern outcrops (S1 and S2) (see Figure 5). Facies one (NRF1) at these localities, however, is mostly representing by fine calcareous sands at the microfacies-level (Plate 3, figure 1) but includes fragmented marine organisms such as pelecypods and rare but regular occurrences of vertical bioturbation structures at the outcrop level. Such characteristics are consistent with estuarine settings where substrate shifting and fluctuations in turbidity and salinity are common (Frey & Howard, 1986; Buatois et al., 2002). A similar facies in the neighborhood region, however, has been interpreted to deposit in estuarine channel mouths and on the edges of the lagoons by Savage and White (1965). Moreover, the latter facies is reported to increase considerably in thickness toward the east and are considered by many authors (e.g., El Hawat, 1980) as the lowermost part of the Maradah Formation (i.e. the Qarat Jahannam Member). Based on stratigraphic criteria and the lack of an erosional surface separating facies one (NRF1)

from the overlying facies two (NRF2), the current survey, nevertheless, is considered the facies one (NRF1) as the base of the Ar R ʿālah Member of the Mar ʿālah Formation.

Up-levels, the sequence considerably consists of facies two (NRF2) where conspicuous yellowish-green laminated-shale represents about 50% of the total sequence. Unlike, the laminated calcareous shale (SJF4) examined from the uppermost part of the Q ʿārat Jahannam Member in the southwestern outcrops (see Figure 5); the laminated-shale in the northern outcrops (see Figure 12) is very distinct, very thick, and extremely bioturbated (Figure 15). Herein, the bedding is extensively disturbed by a complex burrow system. Simple vertical tubes such as *Skolithos* and burrows with pelleted walls such as *Ophiomorpha* are the major contributors to the burrow system. Branching dwelling burrows such as *Thalassinoides*, however, are faint and infrequently perceived. The vertical trace fossil assemblage (*Ophiomorpha*, *Skolithos*) is indicative of the *Skolithos* ichnofacies of Seilacher (1967; 2007) which corresponds to the beach, foreshore, and shoreface with high-energy levels (Frey et al., 1990). The lithological features of the studied *Ophiomorpha*, however, suggest that the trace-makers preferentially colonized high-energy sand environments (Nagy et al., 2016). Microfacies associated with this interval, though, are mostly showing fine-grained sand texture with common quartz and irregular skeletal grains (Plate 3, figure 2) which suggest that the total sediments of facies two (NRF2), were deposited in the sublittoral zone with high-energy (NRF2).

Up-sequence, the laminated calcareous shale (NRF2) is intercalated by facies three (NRF3) which is representing by a thick-bedded fine-grained and gypsiferous yellowish claystone (see Figure 12). The latter facies (NRF3) is similar to facies two (SJF2) which is examined in the southern outcrops at the outcrop-scale (see Figure 5). At the microfacies-level, conversely, the texture of the rock show quite sub-rounded detrital quartz sand grains which display deposition in the low-energy shoreline or lagoonal setting (Plate 3, figure 3). It is worth noting, however, that the separation between the laminated calcareous shale facies (NRF2) and gypsiferous yellowish claystone (NRF3) is not possible in several places at the northeastern part of the Mar ʿālah Oasis which led some authors in the area to treat them as a single facies. The absence of body and trace fossils in facies three (NRF3) and the occurrence of a large amount of gypsum in the northeastern area led Selley (1966) to suggest that this facies has been deposited in a restricted lagoonal environment.

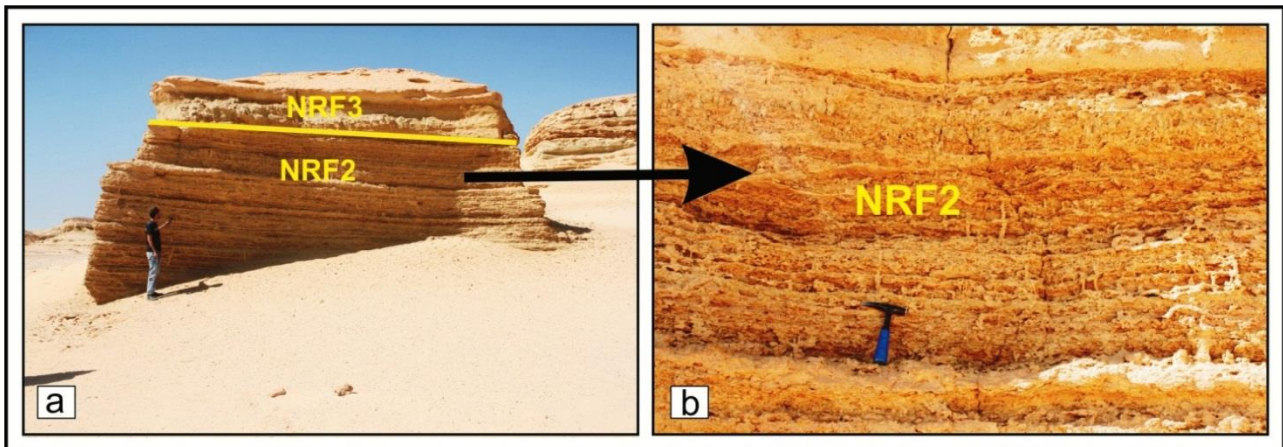


Figure 15. Views from section three (S3) at the northern outcrops. (a) A slump-block showing yellowish-green laminated-shale (NRF2) overlying by yellowish and fine-grained claystone (NRF3) of the Ar R ʿālah Member of the Mar ʿālah Formation. (b) A close-up view of the laminated-shale facies (NRF2) showing a complex burrowing system

The overlying facies four (NRF4) is represented by a whitish-yellowish detrital limestone bed rich in a diverse assemblage of gastropods (Figure 16). This facies resembles facies one (SRF1) examined in the southwestern outcrops (see Figure 5). The gastropods in this locality, however, are chiefly represented by high-spired turreted with scarce biconical and trochiform tests. Present-day mass occurrences of turrilline gastropods are occurring world-wide from shallower to deeper seas (0-1500 m. water-depth, more typically 10-100 m). They are suspension feeders and their mass occurrences usually occur in shallow-subtidal, siliciclastic environments rich in nutrients due to upwelling (see Rasser & Nebelsick, 2007). As the turrilline gastropods are often found abraded in this interval, it may suggest accumulation in high-energy environments like beaches. The washed residue from this interval, nevertheless, contains numerous miliolids with infrequent *Borelis melo melo* (Fichtel & Moll) which may support an open-shelf setting down to a water depth of a few dozen meters water (Abdulsamad et al., 2018).



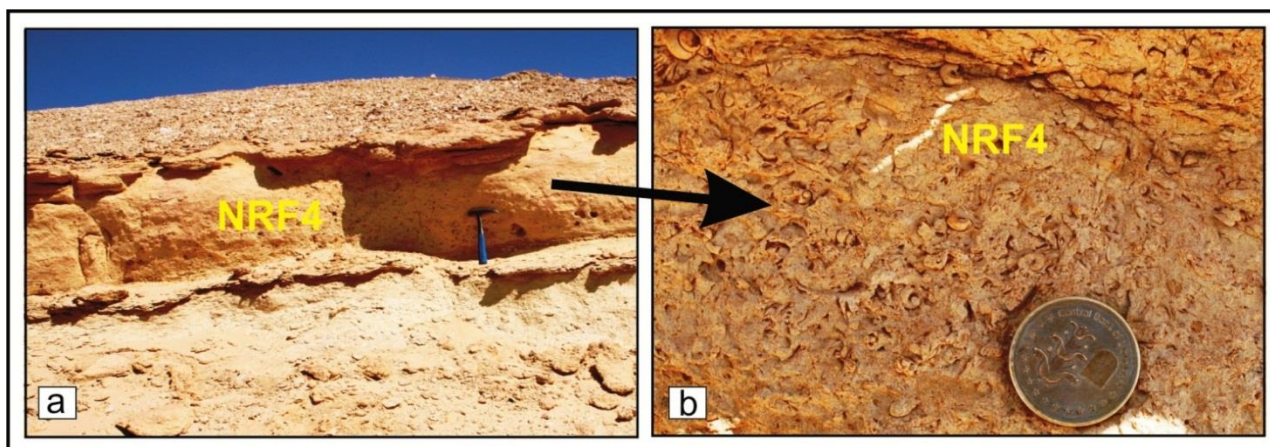


Figure 16. Views from section three (S3) showing the detrital limestone bed (NRF4) of the Ar R ʿġlah Member (a). A close-up view shows a concentration of diverse assemblage of gastropods (b)

Up-sequence, the Ar R ʿġlah Member is represented by facies five (NRF5) which consists of thick-bedded and whitish-reddish calcarenites (Figure 17a). Low-angle cross-bedding is normally associated with this facies particularly at the upper levels of section three (S3). Steeply-dipping cross-bedding which is reported in some local literature is not found in the current study. The studied facies is representing the main lithology of the upper part of the studied member in the northern outcrops. It is intercalated, however, in the middle part, with thin-bedded of sandy limestone and chalky limestone (see Figure 12). The overall unit, however, is quite fossiliferous and the primary lithology (the calcarenites) can be described as packstone-grainstone (Plate 3, figures 4; 5). Fossils, at the outcrop-scale, are diverse throughout facies five (NRF5) nonetheless irregular echinoids (notably, *Clypeaster* and *Echinolampas*) are representing the main fossil group and deduce deposition in a littoral-sublittoral environment (Mancosu & Nebelsick, 2016). Recent counterparts of *Clypeaster* and *Echinolampas*, however, are now live in shallow and warm waters regions including the Red Sea (Ali, 2014). Medium-sized disarticulated oysters, gastropods, and celestite corals (Figure 17b) are subordinate and normally thrive in shallow and warm waters. The common occurrence of these body fossils concerning the lower part of the formation probably reveals a gradual change of sedimentation from a continental clastic to transitional estuarine, lagoon, and beaches to the proximal offshore (NRF5). This facies, though, has been interpreted by Selly (1966) to deposit in the offshore bar.

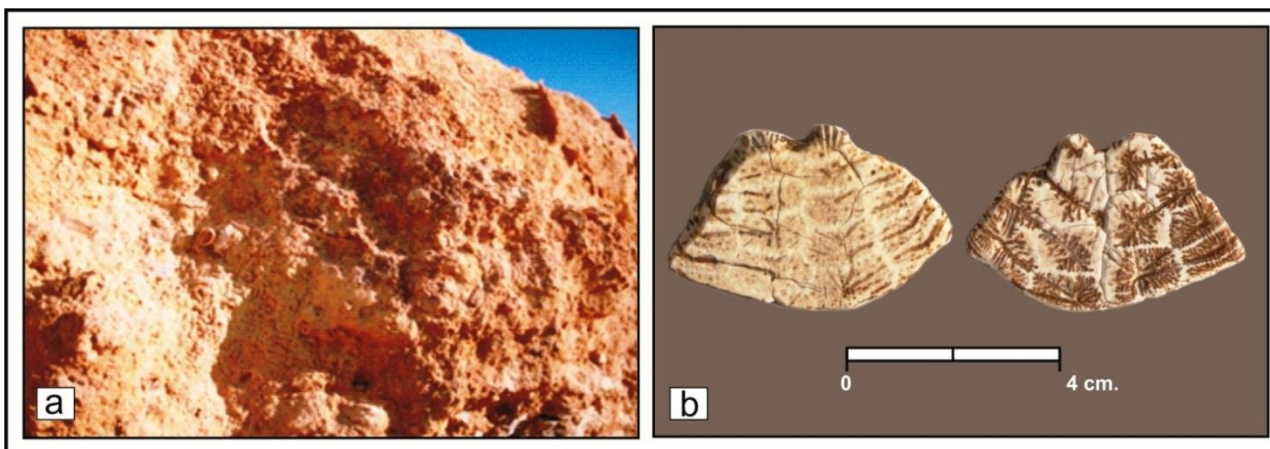


Figure 17. Views of whitish-yellowish calcarenites of facies five (NRF5) of the Ar R ʿġlah Member (a), with fragments of celestite corals (b) recovered from section three (S3)

Up-levels, the Ar R ʿġlah Member is terminated by facies six (NRF6) at section four (S4) that is represented by a rather hard dolomitic limestone unit (see Figure 12). Here, the lithoclasts are commonly re-crystallized, whereas the bioclasts are entirely leached-out. Only abraded pelecypods were recovered at the outcrop-scale and may indicate a nearshore or shoreface environment.

Facies seven (NRF7), however, is present in section three (S3) only and primarily consists of rather soft dolomitic marly limestone. Petrographic thin-sections associated with this level, show mud-supported wackestone texture with infrequent particles of clay and fine silt-size (Plate 3, figure 6). This facies is considered here as the last deposited unit of the Ar



Rāḥlah Member of the Marāḥlah Formation since it has been found under the contact with the overlying Wadi Yunis Member of the Al Khums Formation near Sidi Tahabit as previously mentioned. It is also developed along the road to Al Brega (Figure 18a) but the overlying Wadi Yunis Member of the Al Khums Formation is missing. This facies in this locality is combined with in situ Ostreidae community including *Ostrea digitalina* Fuchs, along the road to Al Brega (Figure 18b). The recent relatives of this species, however, are typical in shallow coastal waters down to the 10 m water depth (Milisic, 1991; Mandic & Harzhauser, 2003). Commonly, these oysters may indicate a relatively low salinity possibly due to a local and temporary influence of freshwater supply, which also caused the contamination by terrigenous quartz grains (see Abdulsamad & El Zanati, 2013).

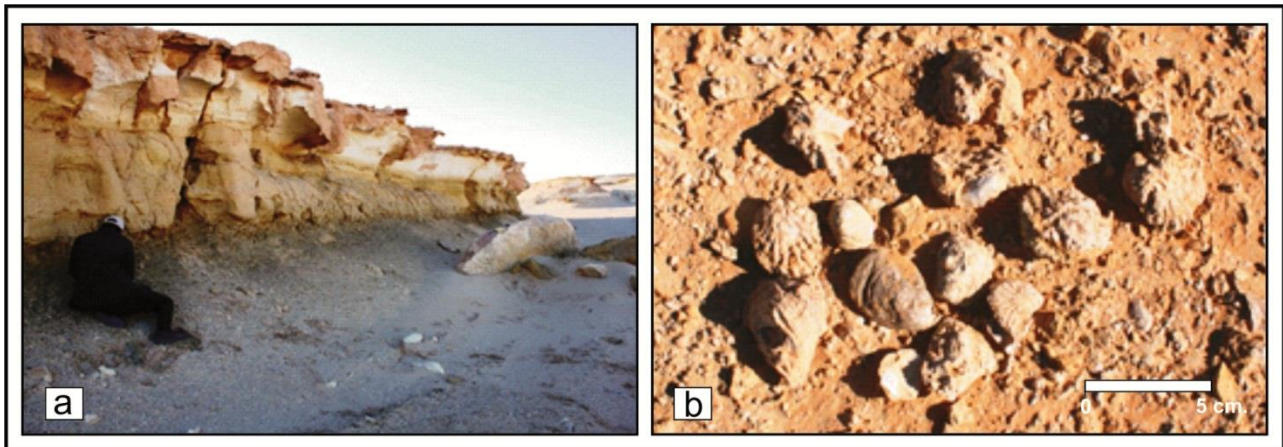


Figure 18. Views shows a quite soft dolomitic marly limestone stone of facies seven (NRF7) (a), and a collection of disarticulated oysters from the same lithological unit exposed along the road to Al Brega (b)

In section three (S3), however, large-sized oysters including *Crassostrea gryphoides* are associated with disarticulated pectinid bivalves at the top of the studied section (Figure 19) which display shallow-marine towards estuarine intertidal (littoral) environments (Harzhauser et al., 2016). The recovery of poorly preserved miliolids including *Quinquoluculina* and alveolinids (*Borelis*) from the washed residue, however, may suggest a deeper sublittoral condition (see Abdulsamad & El Zanati, 2013) for facies seven (NRF7).

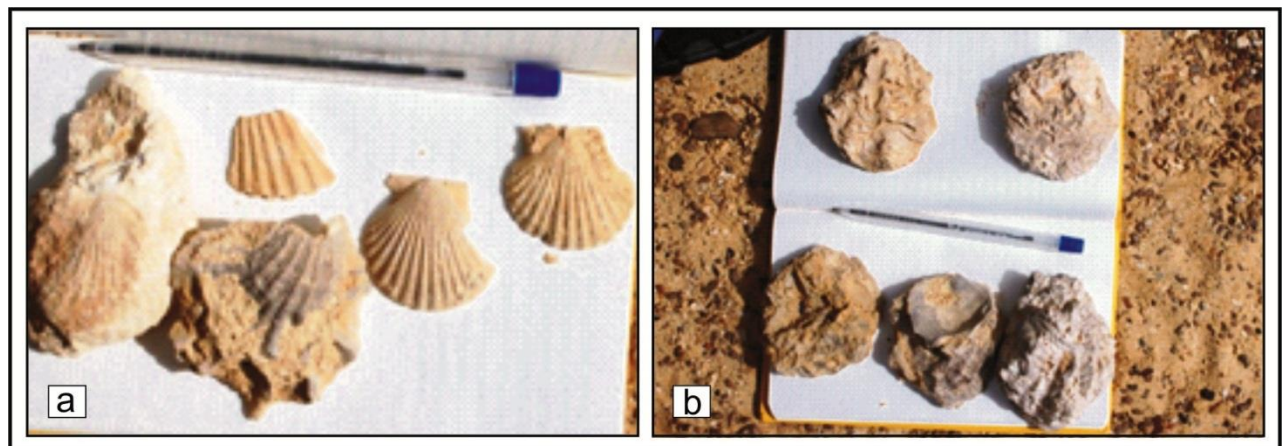


Figure 19. Views of pectinid bivalves (a), and large-sized oysters collected at the top of facies seven (NRF7) of the Ar Rāḥlah Member at section (S3)

### PLATE 3

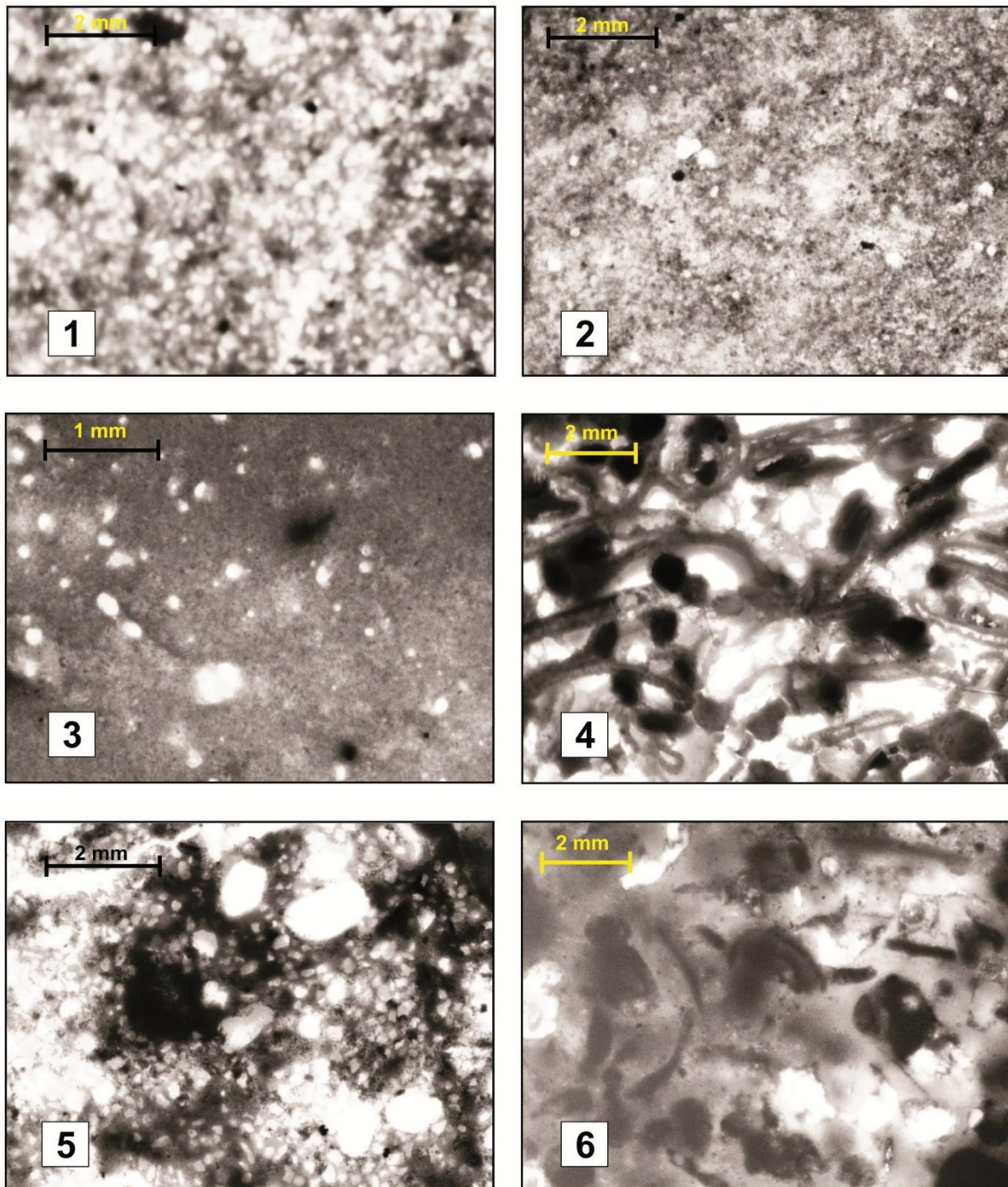


Plate 3. Figure 1. Photomicrograph showing facies one (NRF1) of the Ar Rahlah Member of the Mar álah Formation, which is represented by fine calcareous sands with mutual micrite-clasts and sparsely shell-fragments of bivalves. Black areas are representing iron-oxide impregnation. Figure 2. Photomicrograph showing facies two (NRF2) of the Ar Rahlah Member of the Mar álah Formation, which is denoted by fine-grained sand texture, common quartz, and rare skeletal grains. Figure 3. Photomicrograph showing facies three (NRF3) of the Ar Rahlah Member of the Mar álah Formation, which consists of fine-grained claystone with common sub-rounded detrital quartz sand grains. Figures 4; 5. Photomicrographs showing facies five (NRF5) of the Ar Rahlah Member of the Mar álah Formation, which is represented



mostly by skeletal limestone (notably, bivalves) with common detrital sand-size (calcarenites) carbonate grains (Figure 4). Particles of clay and fine silt-size are also present (Figure 5). Figure 6. Photomicrograph showing facies seven (NRF7) of the Ar Rahlah Member of the Mar álah Formation, which is represented by mud-supported wackestone texture with occasional particles of clay and fine silt-size. Shell-fragments of bivalves are also present.

## 5. Summary and Conclusions

Four stratigraphic sections of the Lower-Middle Miocene Mar álah Formation were measured and systematically sampled. The first and second sections (S1 and S2) are up to 100 m in thickness and were measured at the southwestern side of the Mar álah Oasis. The majority of the sequence in this locality is considered here to represent the Qarat Jahannam Member which corresponds to the continental-dominated facies reported in the earlier studies. Both sections (S1 and S2), however, encompass four different facies (SJF1-SJF4) at the outcrop-scale. In stratigraphic order, their lithology is dominated by fine-grained calcareous sands interbedded with cross-bedded sandstone grading to gypsified claystone at the lower and middle levels and by bioturbated calcareous sandstone and laminated calcareous shale at the upper levels. Their depositional environment, though, is ranging from the fluvial environment (SJF1), low-energy shoreline or lagoon setting (SJF2), high-energy sandy shoreline (SJF3) and river-floodplain, or low-energy shoreline (SJF4) respectively.

The remaining sediments of the S1 and S2 are considered here to represent the Ar Rahlah Member which corresponds to the marine-dominated facies described in the previous studies. Herein, three different facies have been recognized at the outcrop-scale (SRF1-SRF3). The associated macrofauna at the base is mostly represented by common high-spined turreted and subordinate biconical and trochiform gastropods. They are often abraded because of transport and sorting and may suggest that the accumulation was in high-energy environments like beaches or raised banks (SRF1). The overlying facies, though, is represented by a bioclastic limestone unit rich in thick and disarticulated oysters (notably, *Crassostrea gryphoides* (Schlottheim)) which infer transportation under high-energy conditions in a sandy shore environment (SRF2). Up-section, the studied sequence of the Ar Rahlah Member is terminated by limestone unit rich in tiny shell-fragments of bryozoans and pelecypods and indicates a nearshore environment (SRF3) with similar water energy seen in the underlying facies.

The third and fourth sections (S3 and S4) are representing by two different residual hills located in the northern part of the Mar álah Oasis. The total thickness of the studied sequence in this locality is about 80 m. and the Mar álah Formation is represented here only by the upper member namely, Ar Rahlah Member. Herein, the studied sequence includes seven different facies (NRF1-NRF7). At the base, lithology is representing mostly by fine calcareous sands but includes some remains of marine organisms including abraded undersized pelecypods at outcrop-level which infer free connection with the open sea and indicates deposition in an estuarine environment (NRF1). Up-levels, the sequence is considerably consisting of highly bioturbated laminated-shale which represents about 50% of the total sequence. Herein, a vertical trace fossil assemblage (*Ophiomorpha*, *Skolithos*) shows *Skolithos* ichnofacies which correspond to the beach, foreshore, and shoreface zone. Microfacies associated with this interval, however, are mostly showing fine-grained sand texture with common quartz and rare skeletal grains and indicate that the overall deposition was in the sublittoral zone with high-energy (NRF2). Up-sequence, the laminated calcareous shale is intercalated by a thick-bedded of fine-grained and gypsiferous claystone. The texture of the rock show quite sub-rounded detrital quartz sand grains, which display deposition in the low-energy shoreline or lagoonal setting (NRF3). The overlying interval is regularly represented by a detrital limestone unit rich in turritelline gastropods which are often found abraded and suggesting accumulation in high-energy environments like beaches (NRF4). Up-sequence, the member is principally consisting of thick-bedded of calcarenites (NRF5). Fossils, at the outcrop-scale, are common and diverse throughout this interval and include disarticulated oysters, gastropods, echinoids, bryozoans, and celestite corals. The common occurrence of these fossils with respect to the lower part of the Mar álah Formation probably reveals a gradual change of sedimentation from a continental clastic witness in southwestern outcrops (S1 and S2) to transitional estuarine, lagoonal and beaches to the proximal offshore in the northern outcrops (S3 and S4). The sequence of the Ar Rahlah Member is terminated by quite a hard dolomitic limestone unit (NRF6) at S4 and by soft dolomitic marly limestone (NRF7) at S3. Both facies, however, are combined with medium-sized oysters (including *Ostrea digitalina* Fuchs) and pectinid bivalves, which display a warm, shallow, marginal marine environment of deposition.

Biostratigraphic calibration for the age of the studied formation is difficult due to the lack of identified age-diagnostic microfossils. The fact that much of the studied deposits consist of siliciclastic intervals which have no age-constraining microfossils is a further complication. Our age assessment for the Mar álah Formation around the Mar álah Oasis supports the age valuation of Maštera (1985). The later author assigned a Lower-Middle Miocene age to the deposits of the Mar álah Formation. He considered the lithological boundary between the lower Qarat Jahannam Member and the upper Ar Rahlah Member as diachronous as a reflection of the change of facies due to the deposition in the Sirt Basin.

In the current research, the Mar álah Formation at the southwestern outcrops (S1 and S2) is represented by the lower Qarat

Jahannam Member and the upper Ar R ʿġlah Member. Both units, however, are representing the so-called continental and the carbonate phases mentioned in earlier studies. The lower Q ʿġrat Jahannam Member is interpreted to deposit in the Lower Miocene (Aquitania-Burdigalia) based on its stratigraphic position. It rests on an erosional surface of submarine origin in S1 above a 0.5 m. thick of a nummulitic unit of the Oligocene Bu Hashish Formation. The boundary between the lower Q ʿġrat Jahannam Member and the upper Ar R ʿġlah Member has been set based on a major facies change and supports by the recovery of the first aberrance of the larger benthic foraminifera *Borelis melo melo* (Fichtel & Moll). The recovery of this subspecies from the washed residue of SRF1 and in thin-section from SRF3 indicates that the upper Ar R ʿġlah Member is Middle Miocene (Langhian and Serravallian) in age.

The Mar ʿġlah Formation at the northern outcrops (S3 and S4), however, is represented only by the upper Ar R ʿġlah Member and the lower and upper contacts with the underlying Q ʿġrat Jahannam Member and the overlying Wadi Yunis Member of the Al Khums Formation are not recognized in these localities. Herein, the lower part of Ar R ʿġlah Member is denoted by NRF1-NRF3, which primarily resembles the continental-dominated phase mentioned above, and consequentially the sediments have been assigned to the Lower Miocene (Aquitania-Burdigalia). The overlying facies (NRF4-NRF7), nevertheless, are corresponding to the carbonate-dominated phase in the region, and the deposits have been ascribed to the Middle Miocene (Langhian and Serravallian) based on the total-stratigraphic range of *Borelis melo melo* (Fichtel & Moll) which recovered from the washed residues of NRF4 at both sections (S3 and S4) and NRF7 at section three (S3).

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