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Stratigraphic styles of the Upper Paleocene-Lower Eocene rocks along the escarpment of Jabal Waddan, NW Libya

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Highlights

- **Based on stratigraphic and foraminiferal evidence, two major sedimentary cycles have been recognized along the escarpment of Jabal Waddan of NW Libya.**
- **The first cycle is representing by a regressive-transgressive sequence and is attributed to the Shurfah Formation (Upper Paleocene).**
- **The second cycle is showing a transgressive-regressive sequence and is ascribed to the Bishimah Formation (Lower Eocene).**
- **The boundary between the Shurfah Formation and the overlying Bishimah Formation is erosional everywhere and sets the contact between the first and second sedimentary cycles. It has been considered here to represent the Upper Paleocene/Lower Eocene boundary.**

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ABSTRACT

Upper Paleocene-Lower Eocene carbonate rocks along the escarpment of Jabal Waddan of NW Libya are displaying two major sedimentary cycles based on stratigraphic and foraminiferal attributes.

The first one is representing by a regressive-transgressive sequence and is attributed to the Shurfah Formation. It indicates that during the Thanetian (Upper Paleocene) the deposition of the lower part (the Bú Rá's Member) was in shallow water depths of the subtidal environment under low energy conditions and is represented primarily by Dasycladacean and Codiacean green algae. Their association up-levels with small shallow benthic foraminifera such as miliolids and nonionids, however, may indicate a broad nearshore environment of deposition. The decline of the green algae and the prevalence of small-sized (<1 cm) and thick operculinids witnesses in the middle and upper parts (i.e. the Qaltah and Ammúr members) are characteristic of an open-shelf setting down to a water depth of a few dozen meters and typify warm-water habitats. Evidence of further deepening is indicated up-section by the existence of common shallow shark-teeth in a water depth limited to the photic zone (<120 m).

The second sedimentary cycle is showing a transgressive-regressive sequence and is ascribed to the Bishimah Formation. It shows that during the Ypresian (Lower Eocene) the deposition of the lower, middle and upper parts (i.e. Khayir, Wadi Zakim and Rawaghah members) of the Bishimah Formation was in the shallow marine neritic environment. The association of alveolinids with common textulariids in the lower and middle members points to a shallow inner shelf with water depth up to 60 m whereas their association with miliolids, nonionids and elphidiids seen at the upper levels indicate innermost shelf or restricted platform conditions. Evidence of further shallowing, however, is indicated up-section (the Rawaghah Member) by the presence of cross-bedded dolomitic limestone and chert nodules which delineate an advanced episode of the second sedimentary cycle. The closing part for the second cycle, however, is attributed to the overlying Al Jir Formation, elsewhere from the study area, in which a thick sequence of evaporates and chalky dolomites is reported to include a rich *Spirolina*-miliolid assemblage with globular alveolinids similar to those recovered from the studied deposits. Consequently, we recommend considering the Al Jir Formation as the upper member of the Bishimah Formation as originally described in the local literature.

The boundary between the Ammúr Member of Shurfah Formation and the overlying khayir Member of the Bishimah Formation, however, is erosional everywhere in the study area and sets the contact between the first and second sedimentary cycles. It has been considered here to represent the Upper Paleocene/Lower Eocene boundary. Based on planktonic foraminiferal evidence, described from the subsurface of the Sirt Basin, the lower part of the khayir Member has been considered in the current study to represent a Ypresian (Lower Eocene) rather than Thanetian (Upper Paleocene) in age as previously thought.

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1. Introduction

The Jabal Waddan of NW Libya represents a wide hilly terrain terminated at their western margin by a steep escarpment which extends for about 100 km along the road between the southern village of Waddan and the northern village of Abu Qrain close to the Mediterranean coast (Fig. 1). The escarpment is mostly built-up of horizontal to subhorizontal strata of carbonate sedimentary rock units mostly ranging in age from Upper Paleocene to Lower Eocene and geologically belonging to the western part of the Sirt Basin (see Fig. 1). The escarpment exhibits a SE-NW trend and is dissected by several wadis coming down from an elevation ranges from 300 m at the northern areas to 600 m in the southern region. Wadi ar Rawaghah, Wadi Ammúr, Wadi Marzuq and Wadi al Qaltah, are representing the main wadis of the escarpment and roughly follow the NE-SW trend till they reach the Hun (Hon) Graben (Fig. 2). The wadis alignment, however, is structurally controlled either by a complex joint system or following a particular fault trend. The faults display generally the downthrown blocks towards the Hun Graben. According to Shakoor and Shagroni (1984) faults are the dominant structural features affecting the sedimentary rock complex from Cretaceous to Eocene. The evolution of the fault systems responsible for the observed deformation in northwest Libya, Hun Graben and western Sirt Basin have been well documented by Westaway (1996), Abdunaser (2015) and Abdunaser and McCaffrey (2015). The regional geology mapping of the study area and nearby region, however, is studied by Shakoor and Shagroni (1984).

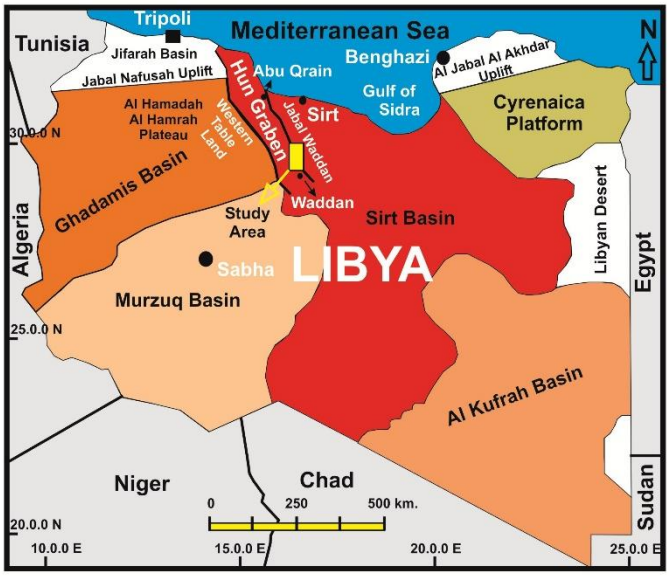

Fig. 1. Index map of Libya showing the major sedimentary basins of the country and the location of the study area, modified after Abdunaser and McCaffrey (2015).

In the current study, two stratigraphic sections from Wadi ar Rawaghah and Wadi Marzuq have been measured and systematically sampled (see Fig. 2). Spot samples, from Wadi Ammúr and Wadi al Qaltah, were also collected to understand the lateral continuity of the studied deposited. All wadis are located broadly between latitudes 15°.45' and 16°.15' E and longitudes 29°.00' and 30°.00' N (see Fig. 2). The field investigations led to the recognition of two formations, they are, from oldest to youngest, the Shurfah Formation and the Bishimah Formation. Several authors including Burollet (1960); Jordi and Lonfat (1963); Fürst (1964); Gohrbandt (1966); Gohrbandt and Hottinger (1967); Barr and Weegar (1972); Gourdarzi (1970); Berggren (1969; 1974); Mijalkovic (1977); Zivanovic (1977); Salaj (1979); Čepek (1979); Salaj and Nairn (1987); Woller (1978; 1984), Tmalla (1996) and more recently Shiref and Salaj (2007) have contributed to the stratigraphy and depositional history of these rock units and their coeval deposits, both in outcrop and in the subsurface from different parts of the region.

The stratigraphical subdivisions introduced for the study region by Jordi and Lonfat (1963) and the modification established by Shakoor and Shagroni (1984) have been adopted in the current work. Here, the Upper Paleocene-Lower Eocene rocks along the escarpment of the Jabal Waddan are described and discussed in terms of litho-biostratigraphical attributes. The study aims to improve the stratigraphy of the region and to provide a reasonable palaeoenvironmental assessment to the studied sediments based on information derived from the studied microfacies, foraminiferal parameters and the associated micro and macrofauna reported on earlier studies.

2. Materials and methods

Outcrops samples of predominantly carbonate limestone and dolomitic limestone and subordinately mixed siliciclastic-carbonates (marls and marly limestone), were collected from two stratigraphic sections from Wadi ar Rawaghah and Wadi Marzuq (Fig. 3). Other samples, however, were collected from the entrance of Wadi Ammúr, Wadi al Qaltah and along the asphaltic road of Wadi ar Rawaghah (see Fig. 2). All samples were collected at a maximum interval of ever 5 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 limestone 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 were crushed and disaggregated in a hydrogen peroxide solution and washed through a 63-µm sieve. Although some samples were barren of microfossils, several samples from critical levels are containing foraminifera, ostracods and shell fragments of molluscs and echinoids. The recovered specimens (mostly foraminifera), however, were examined based on the overall morphology under a stereoscopic microscope and stored in reference slides. All laboratory analyses were undertaken at the Micropalaeontology Laboratory of the Earth Sciences Department of the Benghazi University. Thin-section preparation, however, was taken at the Geological Laboratory of the Sirt Oil Company. The study material will have a final repository in the Geological Museum of the University of Benghazi (Benghazi, Libya).

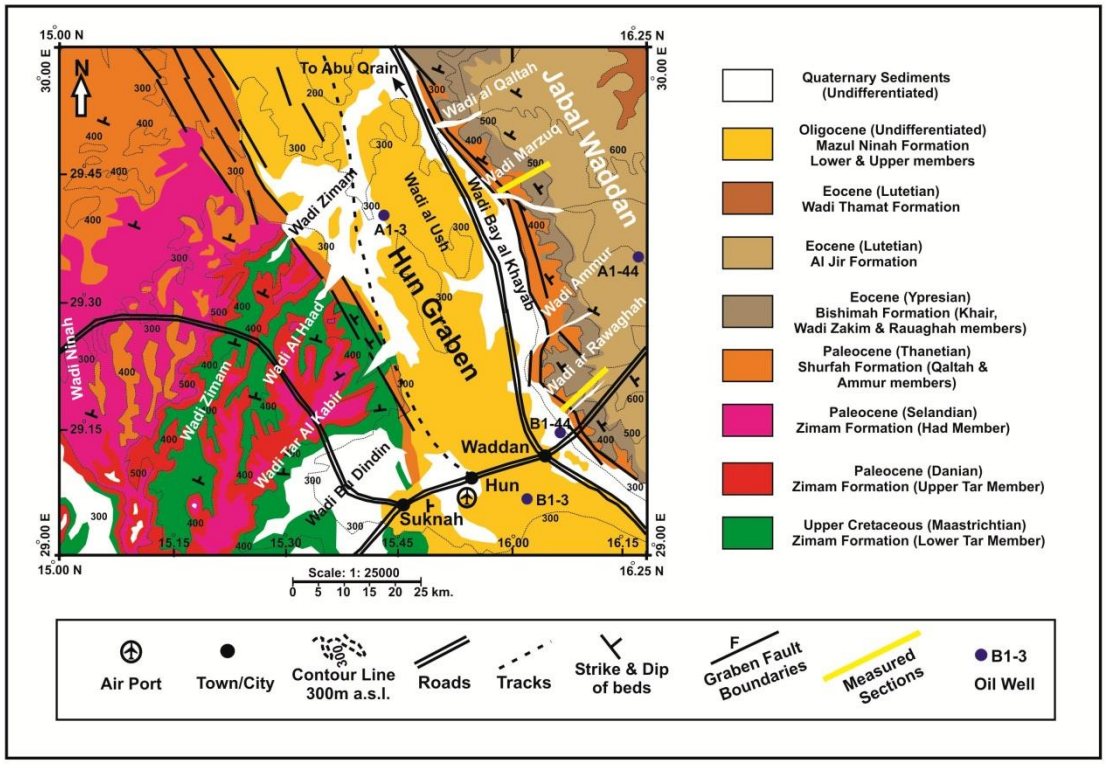

Fig. 2. Geological map of the study region showing the location of the measured sections at Wadi ar Rawaghah and Wadi Marzuq (modified after Shakoor and Shagroni, 1984).

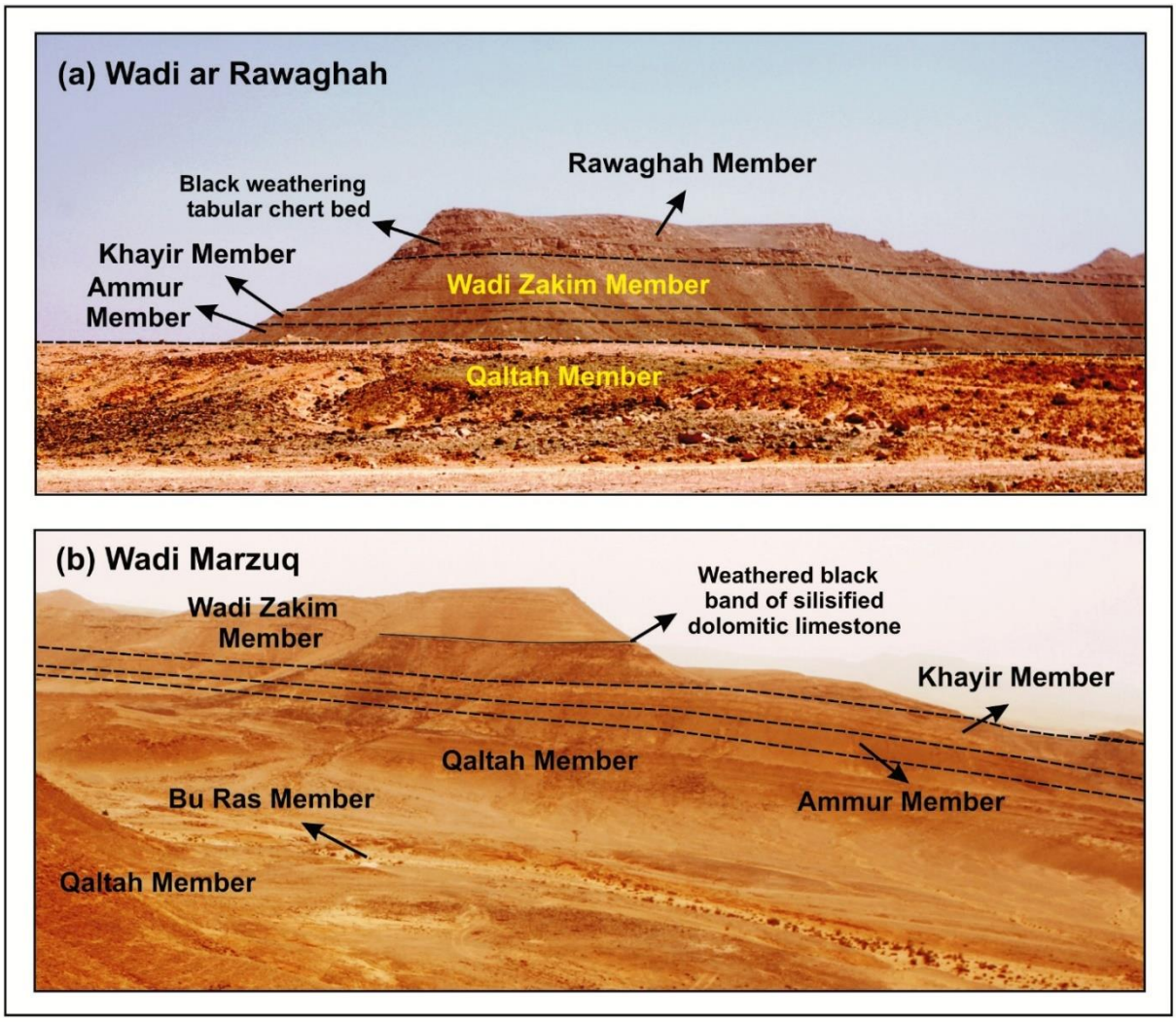

Fig. 3. Views of the studied outcrops showing the studied rock units at Wadi ar Rawaghah (a), and Wadi Marzuq (b).

3. Background and stratigraphy

The studied Upper Paleocene to Lower Eocene rocks of Jabal Waddan of NW Libya belongs to Jabal Waddan Group. The term was introduced by Chiesa (1940) as "Gebel Uaddan Series" and he described the type section from Wadi Ammúr (see Fig. 2). Burollet (1960), however, introduced the term "Gebel Uaddan Formation" to include all the Paleocene and Lower Eocene rocks of the region. As the base is not exposed in the type section of Chiesa (1940), Burollet (1960) described the type section from Wadi Zimam (also Zmam) and Wadi Tar al Kabir (see Fig. 2) where the base is found lying locally disconformably on the Upper Cretaceous-Paleocene. Later Jordi and Lonfat (1963) introduced the term 'Waddan Group' overlies conformably the Upper Cretaceous-Paleocene 'Hamada Group' of Jordi and Lonfat (1963). According to Banerjee (1980), they described type representative sections of this group from the Wadi Tar al Kabir and Wadi Zimam. Gourdarzi (1970) introduced the term 'Jabal Waddan Group' for the same rock sequence of Jordi and Lonfat (1963). Later on, Barr and Weegar (1972) divided the same rock sequence with slight modification in correlation with their subsurface formations in the Sirt Basin. The regional geological mapping project of Libya adopted with slight modification, the classification and nomenclature of Jordi and Lonfat (1963) for describing the Paleocene-Lower Eocene rocks (the Shurfah and the Bishimah formations). The "Gir Gypsum" Member of Jordi and Lonfat (1963), however, was upgraded to the rank of a formation named 'Al Jir Formation' following Barr and Weegar (1972). The stratigraphical subdivisions introduced for the study region by Jordi and Lonfat (1963) and the modification established by Shakoor and Shagroni (1984), however, have been adopted in the current work.

Fig. 4 represents the different characteristics of the Upper Paleocene/Lower Eocene stratigraphy in the study area. It shows three main lithostratigraphic units. They are, from oldest to youngest, the Shurfah Formation, Bishimah Formation, and Al Jir Formation. The first two formations, though, are further subdivided into several members and will be discussed in further detail in the following sections. Little, attention, however, has been attributed to the Al Jir Formation as it is not present in the studied outcrops.

To demonstrate the lateral variation of the studied deposits, a correlation of these outcrops, based on stratigraphic criteria, is summarized in Fig. 5. Here, the stratigraphic successions are generally similar, the difference being only in the thickness variations of the Qaltah Member of Shurfah Formation and the absence of the Rawaghah Member of Bishimah Formation at Wadi Marzuq section. Based on field and faunal evidence, the Paleocene/Eocene contact which has been chosen as a datum for our correlation has been placed between the top of Shurfah Formation and the base of the Bishimah Formation. The boundary is interpreted as an erosional surface of submarine origin which may be related to carbonate dissolution and clastic influx on a carbonate shelf.

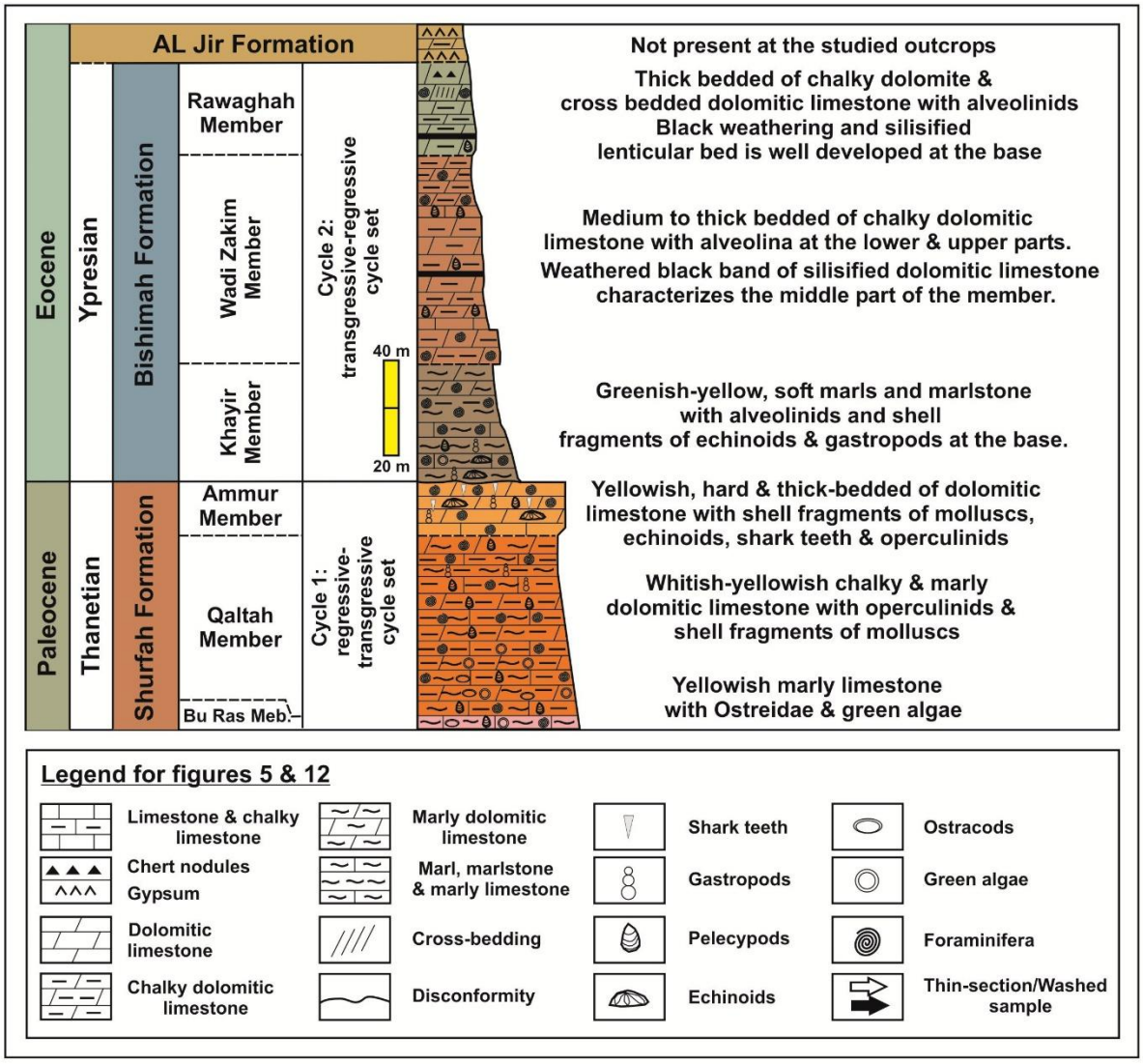

Fig. 4. Composite stratigraphic column of the study area showing the different characteristics of the Upper Paleocene/Lower Eocene stratigraphy in the study area and the main sedimentary cycles.

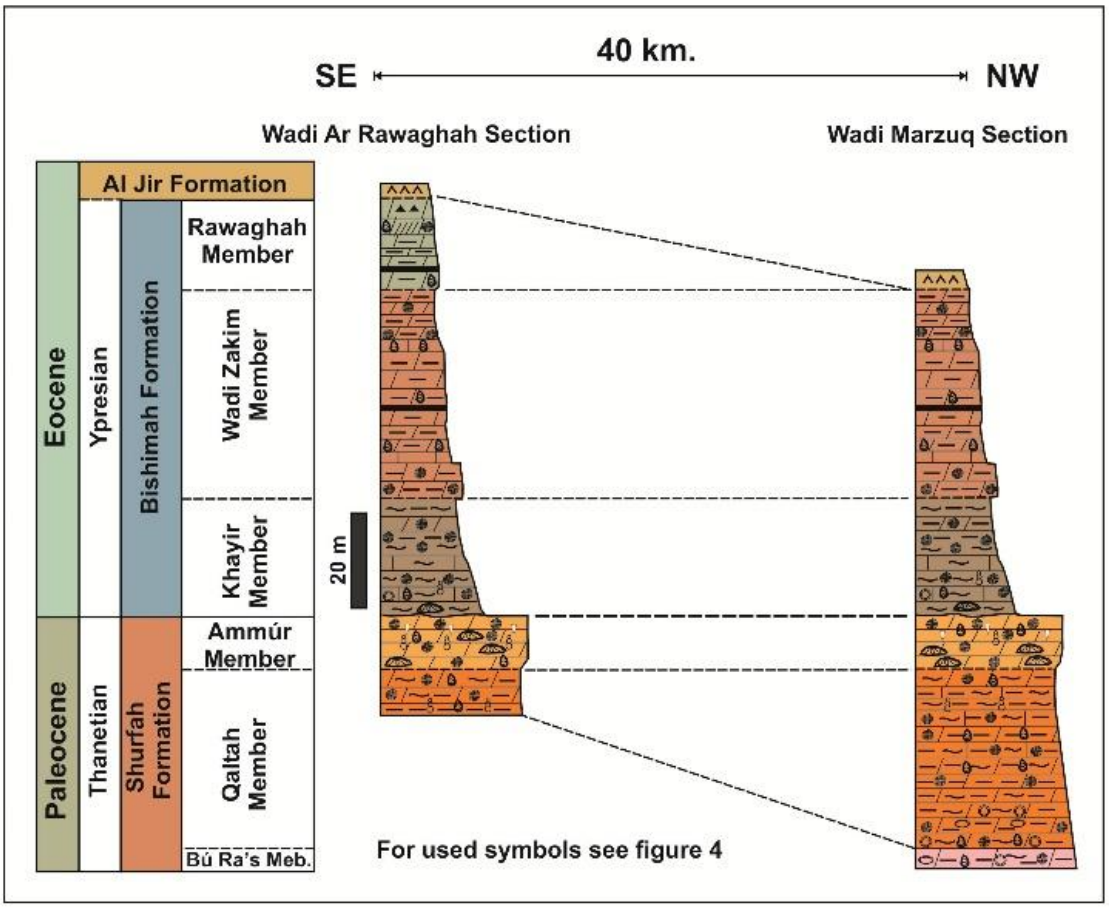

Fig. 5. Correlation chart showing the measured sections at Wadi ar Rawaghah and Wadi Marzuq. The correlation is based on all documented stratigraphical criteria.

3.1 Shurfah Formation (Upper Paleocene)

The Shurfah Formation (Jordi and Lonfat, 1963) comprises three members, from oldest to youngest, Bú Rá's, Qaltah and Ammúr (see Fig. 4). The Bú Rá's Member is represented by 30 m at the type locality in the eastern side of Hun Graben, along the escarpment of Jabal Waddan. It is found at the base of wadis in the thin strip along the fault scarp and the lower and upper boundaries are not exposed. In the study area, the Bú Rá's Member is represented by the uppermost part and is encountered only in the mouth of Wadi Marzuq (see Fig. 3b). Herein, up to 2 m of medium-bedded of yellowish marly limestone with undersized and disarticulated Ostreidae including *Ostrea cellae* de Stefani, as identified by Shakoor and Shagroni (1984), is capped by slightly gypsiferous calcareous marl at the top and covered by a few meters of wadi deposits. At microfacies level, the principal lithology is mud-supported wackestone-packstone and consists entirely of Dasycladacean and Codiacean green algae (Fig. 6). The washed residue, however, contains fairly preserved species of ostracods (mostly belonging to Bairdiacea and Cypridacea) and shallow-water benthic foraminifera (notably *Operculina* spp., *Lenticulina sp. Bolivina* sp., *Triloculina* sp.1 and *Spiroloculina* sp.).

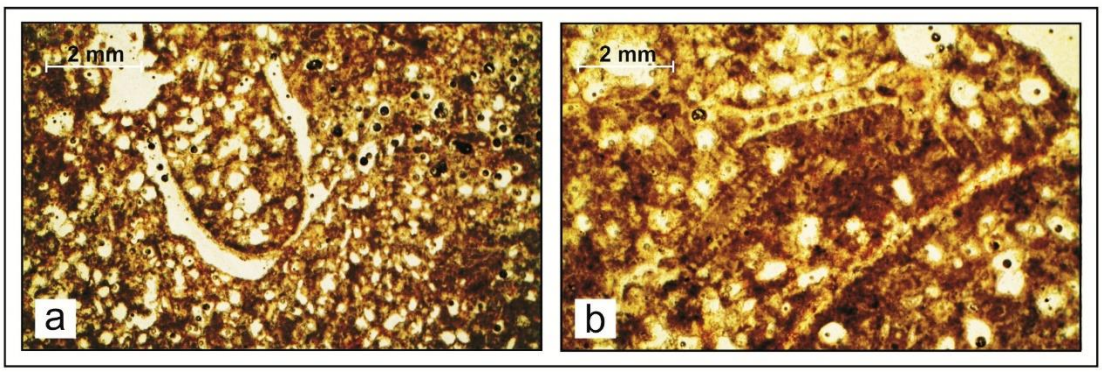

Fig. 6. Photomicrographs showing mostly mud-supported wackestone-packstone texture with abundant micrite-clasts (tiny brown pellets). Both microfacies are representing the typical lithology of the Upper Paleocene Bú Rá's Member, lower member of the Shurfah Formation, at Wadi Marzuq section. The sediments are completely made-up of tiny circular (white circles) including U-shape (at the middle) Dasycladacean and Codiacean green algae (a). Longitudinal sections (yellowish-brown) with a characteristic internal structure of Dasycladacean and Codiacean green algae are also present (b).

Up-sequence, the Qaltah Member attains a reduced thickness of about 10 m at Wadi ar Rawaghah section and about 40 m along the road-cut of Wadi ar Rawaghah. The type section of this member has been designated by Shakoor and Shagroni (1984) from Wadi al Qaltah (see Fig. 2) where over 50 m of chalky and marly dolomitic limestones rests overlying an eroded surface of the Bú Rá's Member. The sedimentological characters of the member are quasi-similar everywhere in the region and the difference being only in the thickness variations. The Qaltah Member is capped by the Ammúr Member, in both studied sections, and the lower contact with the underlying Bú Rá's Member is conformable elsewhere from the study area (see Fig. 5).

At the Wadi Marzuq section, the Qaltah Member is representing by a sequence with total thickness of about 40 m. The sequence, however, is made of poorly thick-bedded of whitish to yellowish chalky and marly limestone enriched locally with macrofauna, notably shell fragments of pelecypods and operculinids. At microfacies level, the lithology of the Qaltah Member largely consists of bioclastic and mud-supported wackestone with Dasycladacean and Codiacean green algae at the lower levels (Fig. 7a). At the upper levels, however, the lithology is mainly wackestone grading to packstone with indistinguishable shell fragments (Fig. 7b). The washed residue, however, contains fairly preserved species of shallow-water benthic foraminifera similar to those recovered from the underlying Bú Rá's Member with rather common *Operculina* spp., *Bolivina* sp. and *Textularia* sp. and few *Quinqueloculina* sp. 1.

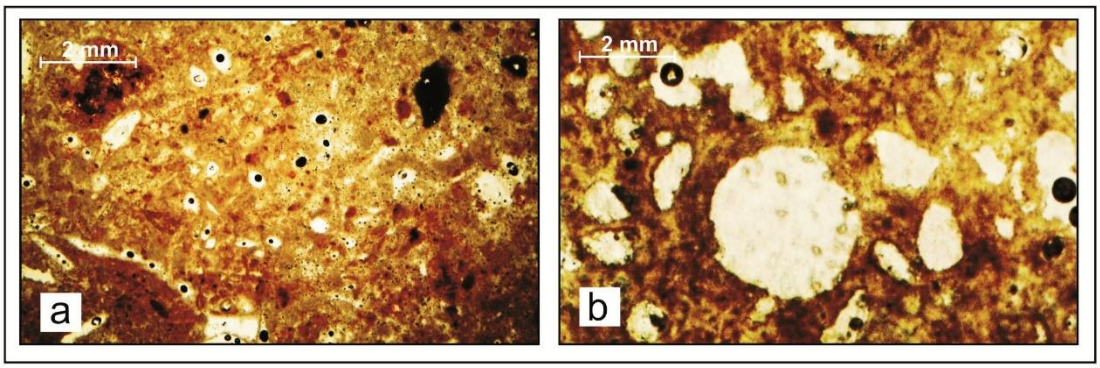

Fig. 7. Photomicrographs showing mostly mud-supported wackestone-packstone texture with common micrite-clasts (tiny brown pellets). The sediments in both microfacies are belonging to the Qaltah Member, the middle member of the Shurfah Formation (Upper Paleocene), at the Wadi Marzuq section. Longitudinal and circular sections (white colors) of Dasycladacean and Codiacean green algae are quite evident at the lower levels (a). Indistinguishable shell fragments (white colors) with micrite envelopes, micrite-clasts (brown colors) and scares grains of green algae (white tiny disks) are major contributors to the sediments at the upper levels (b).

The uppermost part of the studied Shurfah Formation is representing in both studied sections by hard lithology of about 10 m thick of the Ammúr Member (see Fig. 5). The type section of the Ammúr Member has been designated by Shakoor and Shagroni (1984) from Wadi Ammúr (see Fig. 2). Being hard and resistant and aided by the softer sediments of the underlying Qaltah Member of the Shurfah Formation and overlying khayir Member of the Bishimah Formation, the Ammúr Member can be easy distinguished in the field. The contact between the Ammúr Member and the overlying khayir Member of the Bishimah Formation is erosional everywhere in the study area and has been considered here to represent the Upper Paleocene/Lower Eocene boundary (see Fig. 5). The deposits of the Ammúr Member, however, are generally characterized by hard, yellowish thick-bedded of dolomitic limestone. Limestone, however, is also present and frequently augmented with rather large-sized shell fragments of pelecypods, echinoids, operculinids and common shark-teeth. At microfacies level, the limestones are representing in the lower and upper levels by wackestone to packstone enriched with quite small fragments of Dasycladacean and Codiacean green algae and by small-sized shallow benthic foraminifera (Fig. 8). The washed residues encompass common small-sized shallow benthic foraminifera including *Cibicides libycus* and *Operculina* spp.

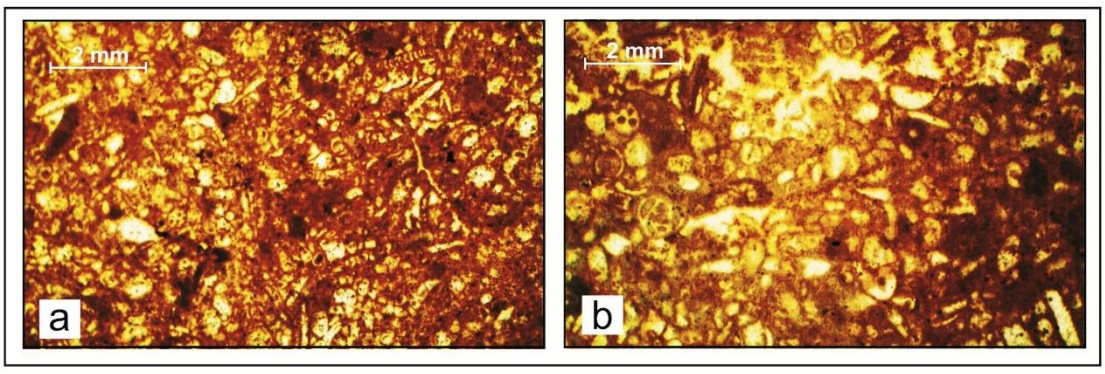

Fig. 8. Photomicrographs showing mostly bioclastic and mud-supported wackestone-packstone. Both microfacies are belonging to the Ammúr Member, the upper member of the Shurfah Formation (Upper Paleocene). Tiny circular (white colors) and longitudinal sections (tiny needle-shaped) of Dasycladacean and Codiacean green algae and unrecognized small-sized shallow benthic foraminifera are quite common in the lower levels at Wadi Marzuq section (a). Shallow small benthic foraminifera (left side); other shell fragments (dispersed) and bladed crystals of calcite (dispersed) are major constituents to the study sediments in the upper levels at Wadi ar Rawaghah section (b).

3.2 Bishimah Formation (Lower Eocene)

The Bishimah Formation (Shakoor and Shagroni, 1984) is subdivided also into three members, from base to top, the Khayir, Wadi Zakim and Rawaghah (see Fig. 4). The type section of Khayir Member has been described by Jordi and Lonfat (1963) from Wadi Khayir (see Fig. 2). It's represented in the lower part by 15 m thick of soft greenish-yellow slightly gypsiferous marl to marlstone containing poorly preserved pelecypods, gastropods, and few small-sized flattened echinoids. The upper part is about 15 m also and principally made of greenish-yellow chalky marls and marlstone intercalated by fossiliferous dolomitic marly limestone containing casts of small-sized *Operculina* and miliolids (Shakoor and Shagroni, 1984). The Khayir Member in the study area rests conformably over the Ammúr Member of Shurfah Formation and is representing by about 25 m thick of soft yellowish marls and marly limestone with small Fe-oxide concretions grading to dolomitic marly limestone and soft marls at the top (see Fig. 4). The upper boundary of the member is conformable with the overlying dolomitic chalky limestone of the Wadi Zákim Member. At microfacies level, the soft lithologies of the studied sequence of the Khayir Member are representing by fine-grained, mud-supported and fossiliferous wackestone (Fig. 9a). The hard lithologies of the sequence, however, are chiefly made of gypsiferous dolomitic marly limestone enriched by shell fragments of pelecypods and small shallow benthic foraminifera (Fig. 9b). The washed residues, though, contain rather common specimens of small-sized shallow benthic foraminifera including poorly preserved globular forms of *Alveolina* spp., *Textularia* sp., *Rotalia* sp.2, *Textularia* sp. 2, and *Cancris* sp. Scarce specimens of ostracods are also present and dominated by *Bairdia* sp.

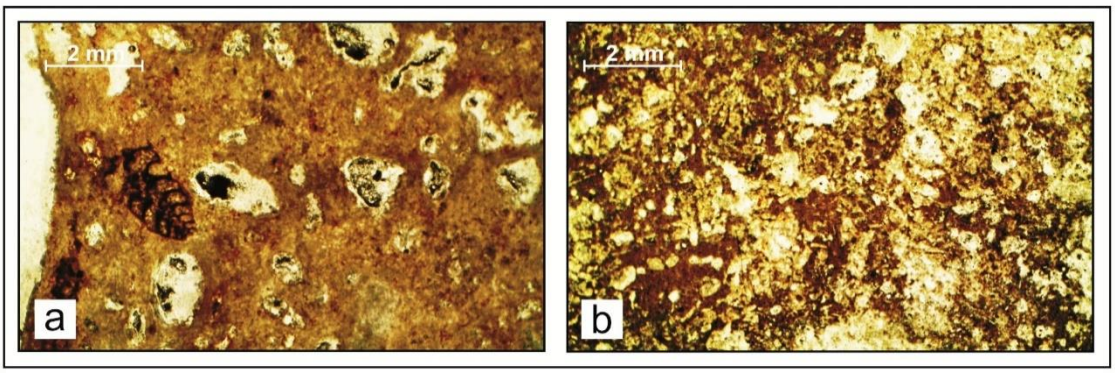

Fig. 9. Photomicrograph showing mostly mud-supported wackestone with undifferentiated shell fragments of pelecypods (white colors) and biserial (left side) small benthic foraminifera (a). Photomicrograph showing gypsiferous dolomitic marly limestone enriched mostly by shell fragments of pelecypods (white colors) (b). Both microfacies are belonging to the Khayir Member, lower member of the Bishimah Formation (Lower Eocene), at the Wadi Marzuq section.

Up-sequence, the deposits of the Wadi Zákim Member is prevailed and attained a thickness of about 45 m. in both studied sections (see Fig. 5). It is worth noting, that the type section of the Wadi Zákim Member has been introduced by Woller (1978) after Wadi Zakim for the "Flosculina Limestone Member" of Burollet (1960). It's attaining a thickness of about 50 m of medium to thick-bedded of dolomitic chalky limestone. At the studied area, the Wadi Zakim Member, nevertheless, shows similar lithology and the lower and upper boundaries with the underlying Khayir and the overlying Rawaghah Members are conformable (see Fig. 5). The lower and upper parts of the member are recognized in the field by the presence of a weathered black band of silicified dolomitic limestone (see Fig. 3b). At microfacies level, the lower part of the member is representing by mud-supported wackestone with *Alveolina* spp. (Fig. 10a). The upper part is principally made of wackestone to packstone and enriched with quite large fragments of pelecypoda (Fig. 10b). The washed residues contain small-sized shallow benthic foraminifera including common poorly preserved globular forms of *Alveolina* spp., *Nonionella* sp., *Sprioplectammina* sp. and *Textularia* sp. 2.

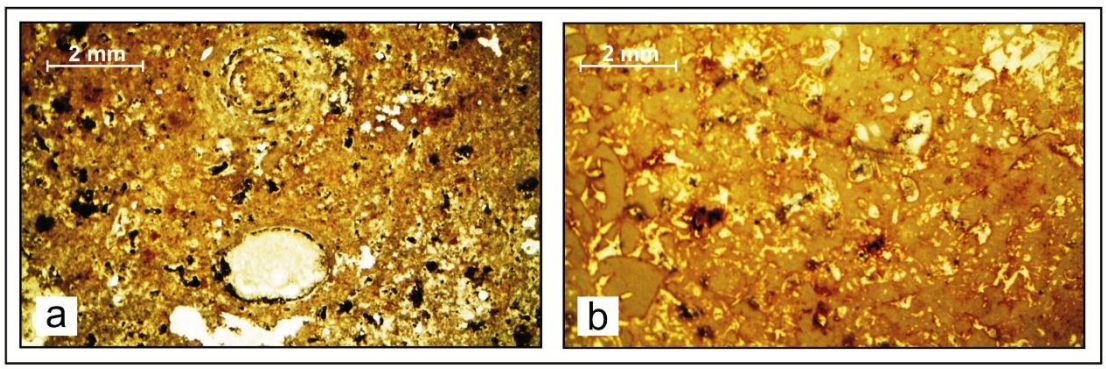

Fig. 10. Photomicrographs showing limestone with mud-supported wackestone-packstone texture. Both microfacies are belonging to the Wadi Zakim Member, the middle member of the Bishimah Formation (Lower Eocene), at Wadi ar Rawaghah section. *Alveolina* sp. (at the top) and leached bioclasts of larger benthic foraminifera (at the bottom) are quite characteristic at the lower part (a). Large fragments of pelecypods (gray color) are the main bioclastic components in the upper part (b).

The last rock unit of the Bishimah Formation is represented by the Rawaghah Member which is conformably overlying the previous rock unit at Wadi ar Rawaghah section (see Fig. 5). Herein, the member is about 20 m thick and developed as a fairly steep vertical cliff. It's composed of thickly bedded, white to grayish-white dolomitic limestone grading to dolomitic marly limestone. It is recognized in the field by the presence of black weathering tabular chert bed at the lower part whereas irregular lenticular chert nodules characterize the upper levels (see Fig. 3a). The macrofauna is limited to common casts and molds of pelecypods. Apart from the dolomitic intervals, the lithology at microfacies level shows nearly

similar texture throughout the study section and is principally made up of mud-supported wackestone to packstone with rather large-sized *Alveolina* spp. and *Quinqueloculina* sp. 2 (Fig. 11). The washed residues of the limited soft intervals, however, contain rare and poorly preserved specimens of *Quinqueloculina* sp.2, *Triloculina* sp.2, *Nonion* sp., *Sigmolina* sp. and *Elphidium* sp.

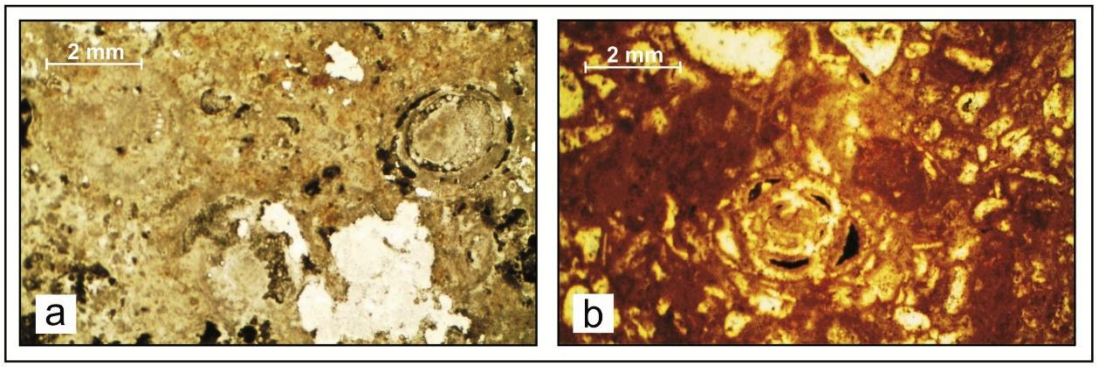

Fig. 11. Photomicrographs showing limestone with mud-supported wackestone-packstone texture. Both microfacies are belonging to the Rawaghah Member, the upper member of the Bishimah Formation (Lower Eocene), at Wadi ar Rawaghah section. Large-sized and globular forms of *Alveolina* sp. (right & left sides) (a) and large-sized *Quinqueloculina* sp.2 (at the middle) with scattered shell fragments of pelecypods (yellowish color) (b) are representing the main bioclasts components.

4. Discussions

4.1 Bio-Chronostratigraphy

A composite stratigraphic occurrence chart of the studied foraminifera from Wadi ar Rawaghah and Wadi Marzuq is shown in Fig. 12. The studied foraminifera was recovered both in thin-sections and from the washed residues and the results, however, were analyzed to provide the age/stage boundaries were possible based on the first and last occurrences of particular taxa. Generally, the examined sediments are containing rather rich assemblages of relatively few foraminiferal species of poor to adequate preservation. Each examined sample contains up to 20 individuals per species. The limited number of the recovered species (about 25 species), though, is attributed to the facies control on the fossil range which hinders the acquisition of complete biostratigraphic data. It similarly restricts the application of a formal zonal scheme and the use of quantitative or semi-quantitative methods of biostratigraphic correlation. Although no biostratigraphic scheme is presented in the current study due to complications arising from dolomitizing and recrystallization, which have led to the poor preservation and leaching of a considerable part of microfauna, biostratigraphic analyses of the studied foraminifera were based on two taxa of larger benthic foraminifera (namely, *Operculina* spp. and *Alveolina* spp.). The remaining species, however, were shallow small benthic foraminifera and their preservation does not allow a good specific determination. They are identified mostly up to the generic level and unfortunately none of them good enough to illustrate. Badly preserved species, which were recovered from below and above the Paleocene/Eocene boundary without any noticeable variation, have been excluded from our occurrence chart in Fig. 12.

It is worth noting, that, the Paleocene/Eocene boundary in the subsurface of Sirt Basin has been placed by Barr and Weegar (1972) within the "Kheir Formation" (equivalent to the Khayir Member of Shurfah Formation) based on the recovery of planktonic foraminifera namely, *Morozovella velascoensis* (Cushman) and *Morozovella subbotinae* (Morozova). In fact, these two species have been recovered recently from the Upper Paleocene by Abdulsamad *et al.* (2019) in Concession 65, SE Sirt Basin with several planktic foraminiferal species including *Morozovella angulata* (White), *Igorina pusilla* (Bolli), *Globanomalina ehrenbergi* (Bolli), *Morozovella apanthesma* (Loeblich & Tappan), *Globanomalina chapmani* (Parr), *Morozovella parva* (Ray), *Morozovella aequa* (Cushman & Renz), *Acarinina soldadoensis* (Brönnimann) and *Subbotina triangularis* (White). This assemblage indicates broad Upper Paleocene age (Selandian-Thanetian). The Selandian Stage is equivalent to P3: *Morozovella angulata-Globanomalina pseudomenardii* Interval Zone of Berggren *et al.* (1995). The Thanetian Stage, however, corresponds to the P4: *Globanomalina pseudomenardii* Total Range Zone and P5: *Morozovella velascoensis* Interval Zone of Berggren *et al.* (1995). The last occurrence of *Morozovella velascoensis* and associated planktic taxa has been used to establish the upper limit of the Upper Paleocene in Concession 65, SE Sirt Basin (see Abdulsamad *et al.*, 2019, p.49).

Based on the above information, the Paleocene/Eocene boundary has been located in the current study between the top of the Shurfah Formation and the base of the overlying Bishimah Formation (i.e. the base of Khayir Member). This choice is consistent with the last occurrence of *Operculina* spp. and the first appearance of the *Alveolina* spp. (see Fig. 12). The *Operculina* recovered from the lower member of the Shurfah Formation; however, it was identified by Salaj (1979) as *Operculina* aff. *heberti* Munier-Chalmas, whereas those recovered by Shakoor and Shagroni (1984) from the lower, middle and upper members were identified as *Operculina canalifera sindensis* (Davies). The former species is similar to *Operculina ammonea* Leymerie, but lacks granules and has less curved septa (see also Haynes *et al.*, 2010). It was previously known from the Upper Paleocene of Pyrenees (Hottinger, 1977) and Oman (Racey, 1995). The *Operculina canalifera sindensis* (Davies) has been included under the *Nummulitoides* by Haynes *et al.*, (2010) despite its operculine coiling which led him previously to describe it as *Operculina canalifera sindensis* (see Haynes, 1962). It was described by Davies (1927) and by Davies and Pinfold (1937) from the Upper Paleocene (Thanetian) of the Sind region (now Pakistan) and the Punjab province respectively. Adams (1970; 1987), however, considered the *Operculina canalifera sindensis* as two distinct species (namely, *Operculina sindensis* and *Operculina canalifera*) and regarded them with other larger benthic foraminifera as the diagnostic fauna for Upper Paleocene in Indian areas. Racey (1995), though, recovered this species from the Lower Eocene of Oman as *Operculina canalifera* d'Archiac & Haime. It is obvious that this species is ranging in age from Upper Paleocene to Lower Eocene. But the recovery of *Lochkartia haimei* (Davies) from the Ammúr Member, from the nearby region of the study area by Woller (1984), restricts the age of the Shurfah Formation to the Upper Paleocene. This species is well known from the sediments of the Upper Paleocene in Pakistan (Afzal *et al.*, 2005; Sameeni *et al.*, 2009) and in the Arabian Peninsula (Jones and Racey, 1994). As we have recognized some morphological variation (notably, in test shape and chamber form) among the individuals of this species in our material, Thus, for the time being, we have grouped these individuals under the genus *Operculina* as previously described in the local literature (e.g. Shakoor and Shagroni, 1984) and we have been assigned the deposits of the Shurfah Formation to the Thanetian in age (Upper Paleocene).

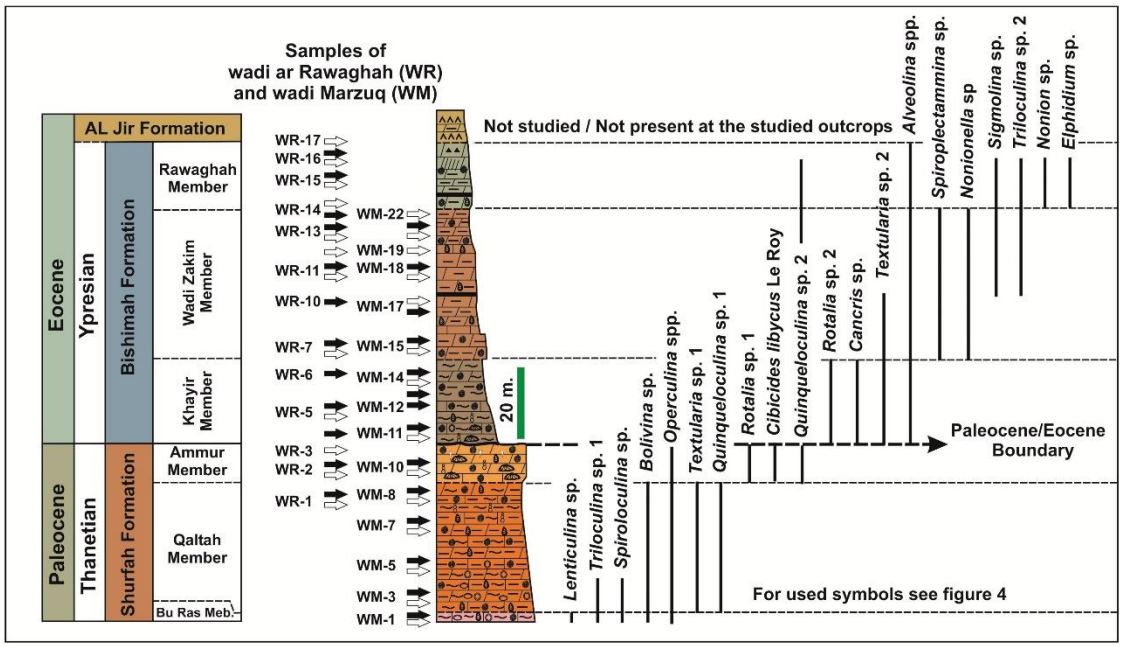

Fig. 12. Composite stratigraphic occurrences chart of the studied foraminifera in the study area.

The deposits of the overlying Bishimah Formation with its lower and middle and upper members are characterized by a fairly common occurrence of *Alveolina* spp. (see Fig. 12). These species are recorded by Jordi and Lonfat (1963) from the neighboring region as *Alveolina* (*Flosculina*) sp. but Gohrbandt and Hottinger (1967) have described these forms from the Wadi ar Rawaghah section and their profile have been designated by Shakoor and Shagroni (1984) as the type section for the Rawaghah Member. Here, Gohrbandt and Hottinger (1967) have recognized two species of *Alveolina*, from the so-called "Flosculina Limestone Bed" (red-brown weathering white chalky limestone which is representing a limited part of the middle member of the Bishimah Formation), namely, *Alveolina decipiens* Schwager and *Alveolina* cf. *solida* Hottinger. Based on this recovery, the middle part of the Bishimah Formation has been dated by Gohrbandt and Hottinger (1967) as Upper Paleocene and they correlated this rock unit roughly with the Farafrah Limestone in western Egypt. Previously, however, these two species were described by Hottinger (1960) from the Lower Eocene sediments of southern France. In fact, these species were found in the Lower Eocene in Turkey by Sirel (1976) and by Özgen-Erdem *et al.* (2007). Only *Alveolina decipiens*, however, was found in the Lower Eocene in Southern Apennines of Italy by Vecchio *et al.* (2007), in the South-Central Pyrenees of Spain by Gaemers (1978) and in the Sistan Suture Zone of eastern Iran by Hadi *et al.* (2018). Supporting evidence from the nearby region (Al Washkah area) is provided by Woller (1978) who considered all representatives of the alveolines of the Bishimah Formation are belonging to the *Alveolina oblonga* Zone (see Salaj, 2003; Shiref and Salaj, 2007). In fact, all these taxa were reported by Serra-Kiel *et al.*, (1998) from the lower and upper parts of the Lower Eocene. As the alveolines in our material show some morphological variation, we have chosen to describe them for the time being as *Alveolina* spp. They will be taxonomically discussed with the genus *Operculina*, which is recovered from the underlying Shurfah Formation, somewhere else. The age of the Bishimah Formation, however, has been assigned to the Ypresian (Lower Eocene) based on the total range of the recovered globular forms of *Alveolina* spp. (see Fig. 12).

4.2 Palaeoenvironment and palaeoecology

The sediments of the Shurfah Formation exhibit lithological variations indicative of shallow warm-water, nearshore to offshore in the littoral zone. The common occurrence of Dasycladacean and Codiacean green algae which generally live in shallow depths down to a range from 10-20 m (Wilson, 1975; Wray, 1977) in the lower member (the Bú Rá's Member) indicate that the deposition was in shallow depths of the subtidal environment under low energy conditions. Their association with small-sized benthic foraminifera such as miliolids and nonionids, however, may indicate the broad nearshore environment of deposition. The occurrence of Ostreidae at the upper levels, which is widely distributed in deposits representing shelf habitats at water depths of less than 50 m (Reiss and Hottinger, 1984), may, however, indicate the offshore environment below the low tide. Additionally, the presence of such oysters may indicate a relatively low salinity, possibly due to a local and temporary influence of a fresh water supply, which also caused contamination by terrigenous quartz grains (e.g. Abdulsamad *et al.*, 2018). This is may also explain the sporadic occurrence of operculinids at the top of the lower member (the Bú Rá's Member). The decline of the green algae, nonionids and miliolids and the prevalence of small-sized (<1 cm) and thick specimens of *Operculina* spp. witnesses up-sequence (i.e. the Qaltah and Ammúr members) is characteristic of an open-shelf setting down to a water depth of a few dozen meters water with a vegetated soft substrate (see also Hottinger, 1983; Abdulsamad *et al.*, 2018) and typify warm-water habitats (Murray, 1973; 1991). Normally, thick-walled larger foraminifera built more robust shells in high energy environments whereas thin-walled shells dominated in quiet environments (see Murray, 1991; Renema *et al.*, 2001; Kovács, 2005).

Taken together, the observed conditions confirm that the entire sediments of the Shurfah Formation are indicating a fining-upward sequence representing a regression-transgression cycle. Evidence of further deepening is indicated up-section by the existence of common shark-teeth which delineates the final episode of the first sedimentary cycle (see Fig. 4). Although reworking cannot be excluded, the association of shark-teeth with molluscan and echinoid fragments at the top of the Ammúr Member restricts the water depth to the photic zone (<120 m). Normally, shallow shark-teeth thrive in water depth between 100-300 m (see Carlsen and Cuny, 2014). The occasional occurrence of gypsiferous and arenaceaous materials in the middle part of the Shurfah Formation, however, is attributed to continental and local brackish influence during the deposition.

Up-sequence, the nature of the sediments of the lower, middle and upper parts of the Bishimah Formation (Khayir, Wadi Zakim

and Rawaghah members) indicates a shallow marine neritic environment. The dolomites of the uppermost part of the Rawaghah Members, however, may suggest deposition in the intertidal zone (see Woller, 1984). The sporadic occurrence of alveolinids throughout the study sediments of the Bishimah Formation indicates that the sedimentation was in the shallow inner shelf. According to Drobne *et al.* (2011), the alveolinids are very compatible with a broad tolerance of salinity and temperature fluctuation. Therefore, they can have a common distribution in various parts of the shallow inner shelf. Normally, they thrive in depth less than 35 m (Langer and Hottinger, 2000), though Yordanova and Hohenegger (2002) reported that the recent alveolinids occur in a wide range of habitats, from deep lagoons to fore-reef settings, down to a depth of 60 m. Their distributions, however, can be influenced by the substrate type (see Zamagni *et al.*, 2008). The association of alveolinids with miliolids is quite evident in our samples and indicates that they lived within a vegetated substrate. Today, however, recent miliolids and alveolinids thrive in sea-grass areas (Hottinger, 1997; Beavington-Penny and Racey, 2004). The association of alveolinids with common textulariids (notably, *Textularia* sp. 2) and *Nonionella* sp. in the lower and middle members of the studied rock unit point to a shallow inner shelf with water depth up to 60 m (as suggested above) whereas their association with miliolids, nonionids and elphidiids seen at the upper member indicates innermost shelf (see Fig. 12). This assemblage is considered by Murray (1991) to indicate restricted platform conditions. The entire sediments of the Bishimah Formation, however, are indicating a coarsening-upward sequence representing a transgression-regression cycle. Evidence of further shallowing is indicated up-section (Rawaghah Member) by the existence of large scale cross-bedded dolomitic limestone and chert nodules that delineate the ultimate episode of the second sedimentary cycle (see Fig. 4). The deposition of a thick sequence of chalky dolomites enriched by *Spirolina*-miliolid assemblage, dolomites and evaporates (notably, marly gypsum and anhydrite) of the overlying Al Jir Formation (not present in studied out-crops) may be attributed to the influence of the previous sedimentary cycle. Therefore, we recommend maintaining the original stratigraphical status of this rock unit which considered it as the upper member of the Bishimah Formation (see Burollet, 1960; Jordi and Lonfat, 1963).

5. Summary and conclusions

The Upper Paleocene to Lower Eocene carbonate rocks along the escarpment of Jabal Waddan of NW Libya have been stratigraphically investigated from two stratigraphical sections in Wadi ar Rawaghah and Wadi Marzuq. The field investigations led to the recognition of two formations, the Shurfah Formation (Upper Paleocene) and the Bishimah Formation (Lower Eocene). The variation in lithology at out-crops scale and the recognition of several microfacies and the associated foraminifera recovered from the washed residues indicate that the deposition of studied rock units is corresponding to two sedimentary cycles separated by an erosional contact considered here as the Upper Paleocene/Lower Eocene boundary.

The first cycle is representing by a regressive-transgressive sequence and attributed to the Shurfah Formation. Herein soft yellowish marly limestone with undersized and disarticulated Ostreidae is capped by slightly gypsiferous calcareous marl at the top of the lower member (the Bú Rá's Member). The principal lithology, however, is mostly mud-supported wackestone and consists typically of Dasycladacean and Codiacean green algae with fairly preserved species of ostracods and shallow-water benthic foraminifera. The middle member (the Qaltah Member), however, is representing mostly by soft whitish to yellowish chalky and marly limestone enriched locally by shell fragments of pelecypods and operculinids. The lithology largely consists of bioclastic and mud-supported wackestone with Dasycladacean and Codiacean green algae grading up-sequence to packstone with fairly preserved species of shallow water small benthic foraminifera similar to those recovered from the underlying member. The closing part of the first cycle is belonging to the Ammúr Member in which hard, yellowish thick-bedded of dolomitic limestone and limestones enriched in large-sized shell fragments of molluscs, echinoids, operculinids and common shark-teeth. Here, the primary microfacies are representing in the lower and upper levels by wackestone to packstone augmented with quite small fragments of Dasycladacean and Codiacean green algae and by small-sized shallow benthic foraminifera (notably, *Cibicides libycus* and *Operculina* spp.).

The second cycle is showing a transgressive-regressive sequence and ascribed to the Bishimah Formation. Herein, the lower part of Khayir Member is representing by soft lithology in which fine-grained, mud-supported and fossiliferous wackestone whereas the upper levels are locally representing by hard lithology and are chiefly made of gypsiferous dolomitic marly limestone enriched by shell fragments of pelecypods and contain rather common specimens of poorly preserved globular forms of *Alveolina* spp. Up-sequence, the deposits of the Wadi Zákim Member prevails and the lower and upper parts of the member are recognized in the field by the presence of a weathered black band of silicified dolomitic limestone. The lithology is chiefly mud-supported wackestone grading up-sequence to packstone and enriched with quite large fragments of pelecypods and contains small-sized shallow benthic foraminifera including *Alveolina* spp. The upper depositional section of the second cycle, however, is belonging to the Rawaghah Member which is composed of thickly bedded of dolomitic limestone grading at the top to dolomitic marly limestone. Here, the lithology is principally made up of mud-supported wackestone to packstone with poorly preserved miliolids including *Alveolina* spp.

Elsewhere of the study area, the Bishimah Formation is overlying by the Al Jir Formation. The deposits of later rock unit are representing by a thick sequence of evaporates and chalky dolomites enriched by *Spirolina*-miliolid assemblage and locally by globular alveolinids similar to those recovered from the underlying deposits. These deposits are considered here to represent the final segment of the second sedimentary cycle and accordingly, we recommend considering the Al Jir Formation as the upper member of the Bishimah Formation as originally described in the local literature.

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