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Contribution to the stratigraphy and sedimentology of the Upper Jurassic – lower Eocene succession of the Mitla–El Giddi stretches, west Central Sinai, Egypt

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ABSTRACT

The present study deals with the stratigraphy, petrography and facies analysis of the stratigraphic succession of Mitla-El Giddi stretches (west Central Sinai, Egypt). Lithostratigraphically, the study area is covered by a thick succession extending from Late Jurassic to early Eocene time. This succession is subdivided into the Masajid Formation (Upper Jurassic (Oxfordian) at the base followed upwardly by the Risan Aneiza Formation (Lower Cretaceous (? Aptian- Albian), the Galala Fm. (Cenomanian), the Abu Qada Formation (lower Turonian), the Buttum Formation (middle Turonian), the Wata Formation (middle–upper Turonian), the Themed Formation (Coniacian–Santonian), the Sudr Chalk (Campanian–Maastrichtian), the Mitla Formation (= Esna Shale) (Paleocene–lower Eocene), the Thebes Formation (lower Ypresian) and the Minia Formation (upper Ypresian) at top. The Aptian – Albian Risan Aneiza Formation is first recorded at G. El Hamra in the study area. As well, a new formational name (the Mitla Formation) is used to describe the Paleocene – lower Eocene unit equivalent to the Esna Shale due to variation in lithology mainly represented by chalky limestone and argillaceous limestone. Many unconformities, represented by variable sedimentologic features, i.e., red paleosols, conglomerates, crustified laminated limestone and glauconitic facies were investigated and mostly attributed to the Syrian Arc System.

The petrographic investigations especially for the lithified rocks revealed eighteen limestone microfacies, three dolostone microfacies and four sandstone microfacies, besides the non-lithified shale, sandy shale, clay and marl lithofacies. The recognized facies and their related paleoenvironments document lateral and common vertical transition between inner, middle and outer ramp setting. These facies could be subdivided into eight associations that are related to six depositional environments: peritidal flat/beach clastics, peritidal flat carbonates, lagoonal clastics, lagoonal carbonates, high energy shoal of ooids and patch reefs (oolitic shoal), intertidal-subtidal open marine, storm influenced subtidal open marine (mid-ramp) and hemipelagic outer ramp facies.

The study indicates that, the area was controlled by a long-term transgressive phase and several higher order sea level fluctuations during the deposition of the studied succession. The main factors controlling the ramp deposition and the described events are; structure control mainly Syrian Arc deformation, eustatic sea level fluctuations combined with environmental influences such as autochthonous carbonate productivity-siliciclastic supply and paleorelief conditions.

1. Introduction and geologic setting

A good knowledge of various aspects of Mesozoic and Paleogene stratigraphy and sedimentology of Sinai Peninsula is very important in understanding the geologic history of an area apart from the Mediterranean realm. The area of Mitla and El Giddi passes is located in west Central Sinai about 35 km east of Suez Canal (Fig. 1). The area is covered by a thick succession spanning Late Jurassic to early Eocene. The Sinai Peninsula was a broad shallow shelf situated on the southern passive margin of the Neo-Tethys, where a carbonate platform with siliciclastic intercalations was established during the Cretaceous (Kuss and Bachmann, 1996; Bauer et al., 2001). In the Mid and Late Cretaceous times, the main phase of compressive tectonic activities is related to the Syrian Arc System that was initiated at the late Cenomanian time

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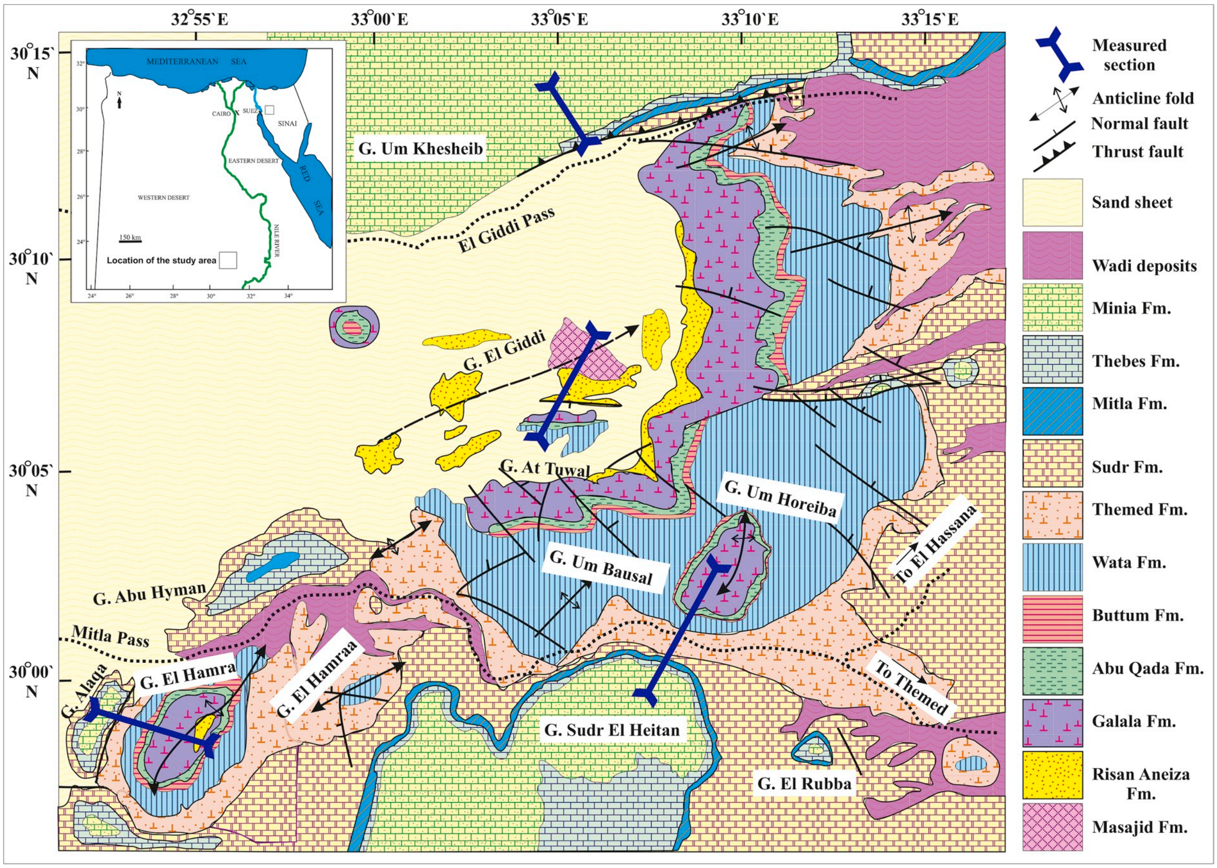

Fig. 1. Geologic map of the study area showing the studied sections (modified after Noweir et al., 2006).

(Bartov and Steinitz, 1977; Kuss and Bachmann, 1996). Therefore, Sinai is believed to have remained tectonically rather quiet throughout the Cenomanian time (Kuss and Bachmann, 1996). According to Issawi et al. (1999a), the trans- African seaway connecting the Tethys and the Gulf of Guinea, initiated in the early Cenomanian by a highstand sea level, started to close together with the Neotethys during the Turonian. Their exposures can be traced along the Tih to Egma Plateaux (Central Sinai), in the folded belt of northern Sinai, and along the Gulf of Suez and Gulf of Aqaba. Their distribution is controlled by two principal factors, namely global or local eustatic changes of sea level and tectonic deformation.

Several studies were done on the Upper Cretaceous stratigraphic successions of west central Sinai such as those of Lewy (1975), Bartov and Steinitz (1977), Abdel-Gawad and Zalat (1992), El-Sheikh et al. (1998, 2010), Bauer et al. (2001, 2003), Abdallah et al. (2001), El Hedeny (2002) and Wanas (2008). While the works which were carried on the sedimentology of Mitla Pass and its environs are those of Zalat and Eweda (1998), Zalat (1999), Saber (2001), Saber et al. (2002) and Abu El-Hassan, 2006. Accordingly, the present study aims to shed the light on an integrated lithostratigraphic and sedimentologic framework for the stratigraphic succession of Mitla and El Giddi Passes, west central Sinai. The biostratigraphy of this stratigraphic succession, especially those of the Upper Cretaceous, was studied by El Qot and Afify (2010) and Orabi et al. (2012).

2. Material and methods

Several field trips were achieved to measure the stratigraphic succession of the Mitla-El Giddi stretches (Latitudes 29° 57′ N and 30° 15′ N and Longitudes 32° 52′ E and 33° 10′ E; Fig. 1). Five sections representing the entire studied rock units were studied in detail. Landsat images were used for field investigations. About 860 rock samples were collected to cover all possible rock varieties representing clastic and carbonate sediments. The sections were studied at G. Um Horeiba, G. El Hamra, G. Sudr El Heitan, G. Alaqa, G. Um Khesheib and G. El Giddi (Fig. 1). The macro-invertebrates were carefully collected bed by bed and identified. Some index macrofossils such as ammonites as well as some diagnostic oysters, gastropods, brachiopods and echinoids, which used for age-dating are photographed. About 380 thin sections were prepared for petrographic studies using transmitted light microscope. Staining methods using Alizarin Red S combined with Potassium Ferricyanide were used to differentiate between the dolomite and calcite carbonate facies. The lithified and non-lithified samples as well as the collected fauna are housed in the Geology Department of the Faculty of Science, Benha University, Egypt.

3. Stratigraphy

The studied succession is subdivided lithostratigraphically into eleven formations, from base to top are the Masajid, Risan Aneiza, Galala, Abu Qada, Buttum, Wata, Themed, Sudr Chalk, Mitla, Thebes, and Minia formations. These rock units are briefly described in the following.

3.1. The Masajid Formation (Upper Jurassic "Oxfordian")

The term Masajid Formation was introduced by Al-Far (1966) for describing marine Bathonian-Kimmeridgian sediments that represent the top unit of the Jurassic at its type locality in Wadi Masajid, Maghara area. In the study area, the exposed part of the Masajid Formation was recorded only at the core of El Giddi large anticline (Fig. 1). It measures 33 m thick, composed of highly fossiliferous light-colored limestones and marl beds (Fig. 2). Its base is unexposed, nonetheless about 805 m thick succession of clastic-carbonate sequence of Middle Jurassic was

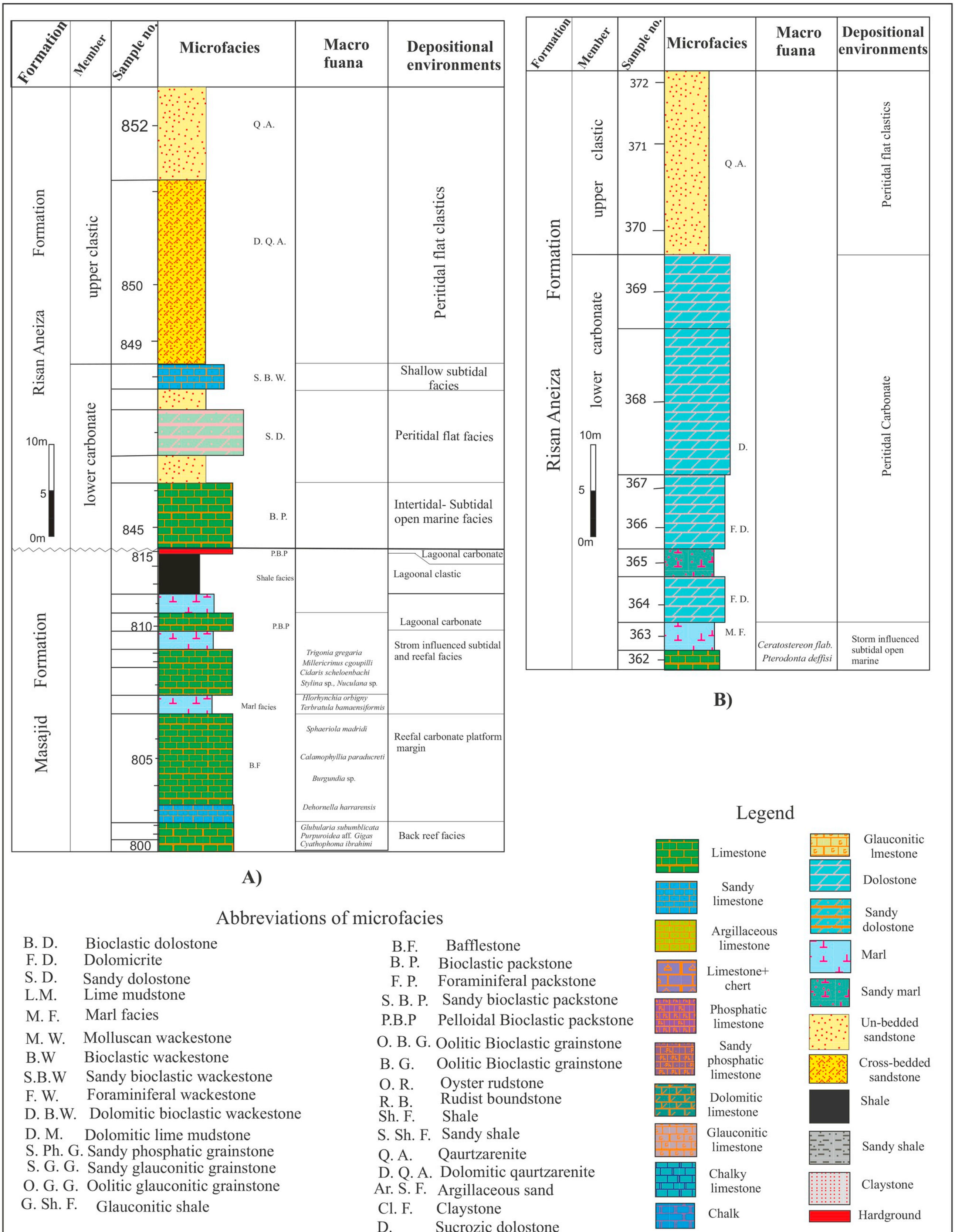

Fig. 2. Lithostratigraphy of the Masajid and Risan Aneiza formations at G. El Giddi (section A) and G. El Hamra (section B).

recorded in El Giddi-1 well borehole (Aboul Ela and El Shamma, 1997). The upper contact of the Masajid Formation is outlined by 50 cm red ferruginous duricrust as a marker horizon separating the whitish-colored carbonates of the Masajid Formation from the overlying dark-colored sandstones/carbonates of the Risan Aneiza Formation.

Lithology and faunal content of this rock unit is similar to the middle part of the Masajid Formation at its type locality at Gebel Maghara area.

The studied section of the Masajid Formation is highly fossiliferous with coralline sponges, corals, brachiopods, bivalves, gastropods, echinoids and crinoids (Plates 1-3). Saber et al. (2002) described twenty species from the Upper Jurassic rocks of Gebel El Giddi area. Barakat (1970) considered the exposed Jurassic rocks at El Giddi anticline to be Oxfordian and the subsurface Jurassic is of Bajocian–Callovian age. Whereas, Kerdany and Marzouk (1971) mentioned that the surface Jurassic at El Giddi anticline contain foraminiferal assemblages of Oxfordian age, meanwhile, the subsurface section is of Callovian age. Aboul Ela and El Shamma (1997) stated that the subsurface Jurassic at El Giddi borehole 1 ranges from late Bathonian? to early Oxfordian age based on the stratigraphic distribution of dinocysts. Accordingly, the Masajid Formation of the present study is considered Oxfordian in age.

3.2. The Risan Aneiza Formation (? Aptian- Albian)

The term Risan Aneiza Formation was introduced by Said (1971) at its type locality at Risan Aneiza area, North Sinai. In the area studied, the Risan Aneiza Formation is exposed above the Masajid Formation at G. El Giddi and forming the core of El Hamra domal structure (Fig. 1) which is described herein for the first time (Fig. 3B). It shows slight variations in lithology in the two sections and can be subdivided into two informal members; a lower carbonate-clastic member and an upper clastic member (Fig. 2). Eastward at El Giddi Pass, the Risan Aneiza Formation measures 50 m thick of yellowish white to grayish white limestone and grey shale at base and brown thinly laminated dolomitic sandstone at top (Fig. 3C). At G. El Hamra (Fig. 3B), the exposed thickness of the Risan Aneiza Formation is 75 m thick, grayish green to grey dolostone as well as sandy marl at base and highly ferruginous, fine-to medium-grained brown quartzitic sandstone at top. This rock unit is highly impregnated with black-colored iron oxides, where ironstone pockets reaching up to 3–4 m in diameter were imbedded in the dolostones of the Risan Aneiza Formation. At G. El Giddi, the lower contact of the Risan Aneiza Formation with the underlying Masajid Formation is represented by a red limestone bed forming hardground. The upper contact with the overlying Galala Formation is marked by a massive and dark colored sandstone bed representing the uppermost part of the formation. On the other, at Gebel El Hamra, the base of the Risan Aneiza Formation is unexposed, while its upper contact with the overlying Galala Formation is easily recognized by the presence of dark-colored, large hematite pockets that were scattered in the sandstone and dolostone beds at the uppermost part of the formation. The Risan Aneiza Formation is barren of macrofauna except a marl bed in its lower part at Gebel El Hamra that yields the oyster *Ceratostreon flabellatum* (Goldfuss). It contains the gastropods *Pterocera incerta* d'Orbigny, *Colombellina* (*C.*) *fusiformis* Douvill, and *Pyrazus* (*P.*) *valeriae* (Verneuil and Lorière), in addition to the ammonite *Engonoceras serpentinum* (Cragin) that is considered an upper Albian species and was recorded from the upper Albian rocks of Sinai by Aly et al. (2005) and El Qot (2018). The Risan Aneiza Formation is considered to be ?Aptian-Albian age according to its faunal content and to its stratigraphic position being enclosed between the Oxfordian Masajid Formation and the Cenomanian Galala Formation.

3.3. The Galala Formation (Cenomanian)

The term Galala Formation was first introduced by Abdallah and El Adindani (1963) in northern Galala Plateau. It has been subdivided by Awad and Abdallah (1966) into two informal members; a lower marly and shaly member and an upper limestone member. In Sinai, the Cenomanian sediments show a lateral facies change from the carbonate-dominated facies (Halal Formation) in North Sinai covering G. Halal, Yelleg, El Maghara, Lebni and Areif El Naga to clastic-carbonate facies (Galala Formation) in Central Sinai at El Giddi – Mitla Passes and clastic-dominated facies (Raha Formation) in Southern Sinai.

In the studied sections, the Galala Formation represents the core of G. Um Horeiba where its base is un-exposed, and it underlies the lower Turonian Abu Qada Formation, while at G. El Hamra (Fig. 3D), the Galala Formation overlies unconformably the Risan Aneiza Formation. It measures about 310 m thick at G. Um Horeiba and 345 m thick at G. El Hamra. In both sections, the Galala Formation can be subdivided into two informal members (Fig. 4). The lower member is made up of shales, siltstone and claystone with marl and limestone intercalations. The occurrence of clastic sediments increases to the south west of the area studied at G. El Hamra. This lower member is equivalent to the lower marly shaly member of Awad and Abdallah (1966). The upper member in both sections studied consists mainly of thick carbonate sequence of limestone, dolomitic limestone and dolostone beds which is also equivalent to the upper limestone member of Awad and Abdallah (1966). The Galala Formation is very rich in macrofossils especially the oysters *Ceratostreon flabellatum* (Goldfuss), *Rhynchostreon suborbiculatum* (Lamarck), *Gyrostrea deletteri* (Coquand), *Ilymatogyra africana* (Lamarck) and *Costagyra olisiponensis* (Sharpe), and the rudists *Eoradiolites liratus* (Conrad) and *Praeradiolites biskraensis* (Coquand). It yields also the echinoids *Heterodiadema libycum* (Desor), *Mecaster batnensis* (Coquand), *Mecaster cubicus* (Desor) (Plates 1-3) in addition to the larger benthic foraminifera *Orbitolina* (*Conicorbitolina*) *conica* (d'Archiac), *Sellialveolina viallii* Colalongo, *Praealveolina cretacea* (d'Archiac). Based on the above-mentioned fauna, the Galala Formation is Cenomanian in age (El Qot and Afify, 2010).

3.4. The Abu Qada Formation (lower Turonian)

The Abu Qada Formation was first described by Ghorab (1961) from Wadi Abu Qada, an extension of Wadi Gharandal in west Central Sinai. In the present study, the formation measures 70 m-thick at Gebel Um Horeiba and 60 m at Gebel El Hamra (Fig. 3D). It overlies unconformably the Cenomanian Galala Formation and unconformably underlies the middle Turonian Buttum Formation. The formation is formed of white, thinly-bedded limestone, grey and very hard dolostone and marl interbeds. The Abu Qada Formation is rich in early Turonian ammonites as *Choffaticeras securiforme* (Eck), *Choffaticeras segne* (Solger), *Choffaticeras luciae* (Pervinquiére) and *Thomasites rollandi* (Thomas and Peron) (Plates 1-3). Accordingly, the Abu Qada Formation is early Turonian in age.

3.5. The Buttum Formation (middle Turonian)

The Buttum Formation was proposed by Issawi et al. (1999b), for the 15.0 m thick crystalline gypsum alternating with shale and sandy siltstone beds in Wadi El-Buttum, east Central Sinai. In the study area, the Buttum Formation is characterized by change from carbonate lithofacies in the east to clastics in the west. It is unconformably overlying the Abu Qada Formation and unconformably overlain by the Wata Formation. The Buttum Formation is well developed forming 15 m thick succession of red ferruginous dolostone, dolomitic limestone (Fig. 3E) and limonitic sandstone beds at Gebel Um Horeiba, Gebel El Giddi and Gebel At Tuwal. The ferruginous carbonate beds are bioturbated, red, hard, thalathnoidus measuring about 8 m thick forming calcretes and dolocrete facies (Fig. 3E) and overlain by laminated and limonitic sandstone of 7 m thick. To the west of the study area, at G. El Hamra, the Buttum Formation consists of up to 48 m thick clastic succession of kaolinitic clay, gypsiferous shales and red sandstone (Fig. 3F).

The Buttum Formation in general is barren of fossils except some

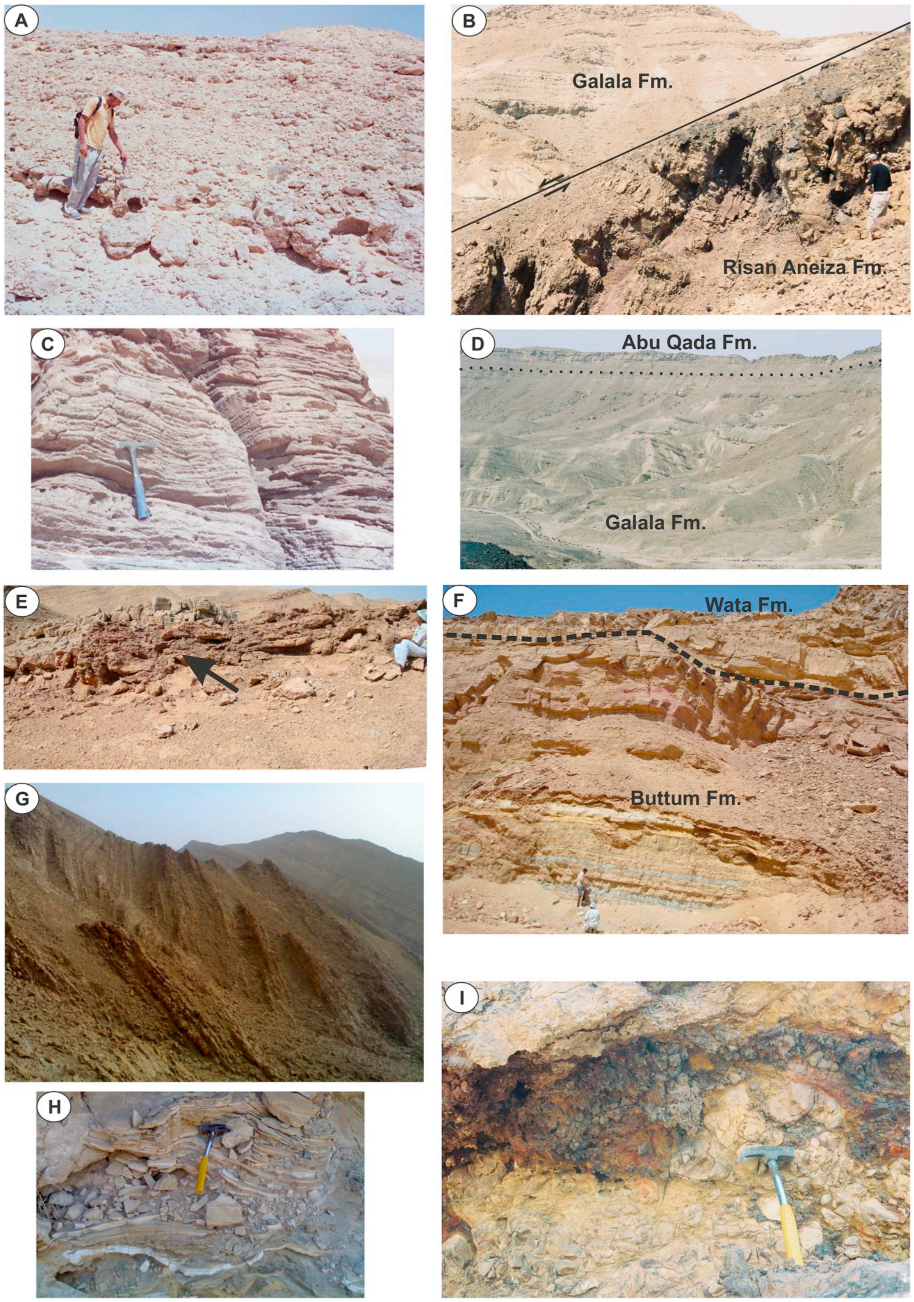

Fig. 3. Field photographs showing A-reworked and cavernous limestone in the lower part of the Masajid Fm. at the core of G. El Giddi. B- the Risan Aneiza forming the core of G. El Hamra and upthrown in front of the overlying Galala Formation. C- thinly-laminated, coarse-grained sandstone of the Risan Aneiza Fm. at G. El Giddi. D-panoramic view of the Galala and the overlying Abu Qada formations at G. El Hamra. E – red and thalathnoidus dolostone facies of the Buttum Fm. at G. Um Horeiba. F- kaolinitic clay, gypsiferous shale and red sandstone of the Buttum Formation at G. El Hamra. G-nearly vertical carbonate strata of the Wata Fm. G. El Hamra. H, I-close-up views of laminated calcite (H) and thin irregular ironstone bed (I) at the contact between the Wata and the Themed formations at G. El Hamra. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

plant remains and few small-sized bivalves and gastropods. According to its stratigraphic position between the lower Turonian Abu Qada Formation and the upper Turonian Wata Formation, the Buttum Formation is middle Turonian in age.

3.6. The Wata Formation (middle – upper Turonian)

This formation was first introduced by Ghorab (1961) at Wadi Wata in west Central Sinai. In all sections studied, the Wata Formation overlies the Buttum Formation and underlies the Themed Formation measuring about 350 m–400 m thick (Fig. 5). The Wata Formation crops out in most of the domal areas either representing their cores as in El Hamraa and Um Bausal anticlines (Fig. 1) or making their limbs showing steeply dipping strata such as in Gebel El Hamra (Fig. 3G) and El Giddi anticlines. It consists mainly of carbonate sequence of limestone, chalky limestone, dolomitic limestone and thick bedded dolostone with lenticular and thin-bedded chert at its upper part. The upper contact with the overlying Themed Formations is characterized by the presence of calcite laminae forming crust (Fig. 3H), black manganese oxide (Fig. 3I) and/or chert band indicating subaerial exposure and/or an unconformity surface.

The Wata Formation is relatively less fossiliferous than the Galala Formation and yields *Curvostrea rouvillei* (Coquand), *Plicatula auressensis* Coquand, *Cucullaea trigona* (Seguenza), *Volutomorpha* sp., *Phymosoma abbatei* (Gauthier), *petalobrissus pygmeaus* (Fourtau) and *Coenholectypus turonensis* (Desor) in addition to *Durania arnaudi* (Choffat), *Nerinea requieniana* d'Orbigny (Plates 1-3) and corals being replaced by silica and iron oxides (Fig. 6A). The Wata Formation yields the late middle-early late Turonian ammonite *Coilopoceras requienianum* (d'Orbigny) (Plate 1). The above-mentioned macrofossils suggest a late middle-late Turonian age for this rock unit (El Qot and Afify, 2010).

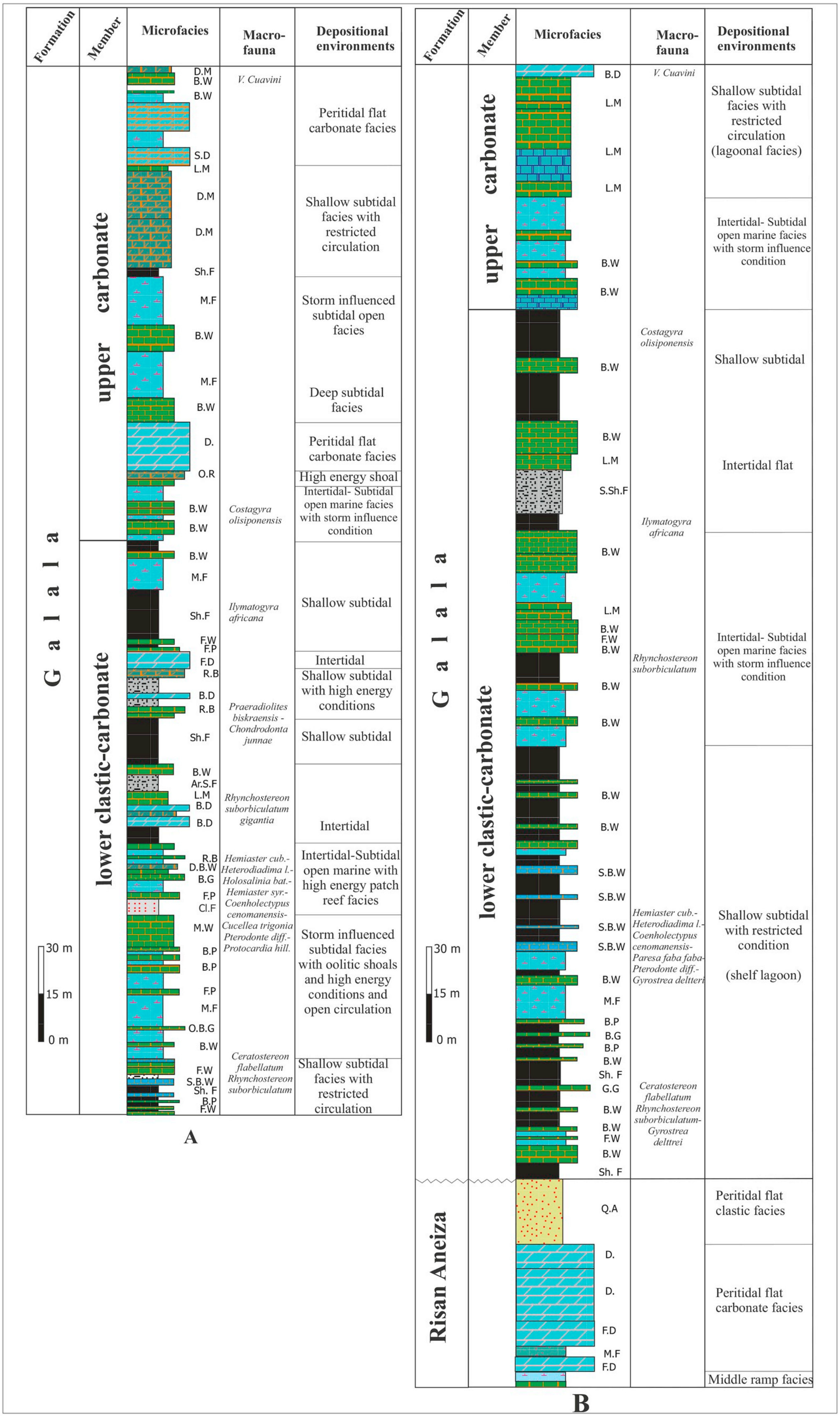

Fig. 4. Lithostratigraphy of the Galala Fm. at G. Um Horeiba (A) and G. El Hamra (B).

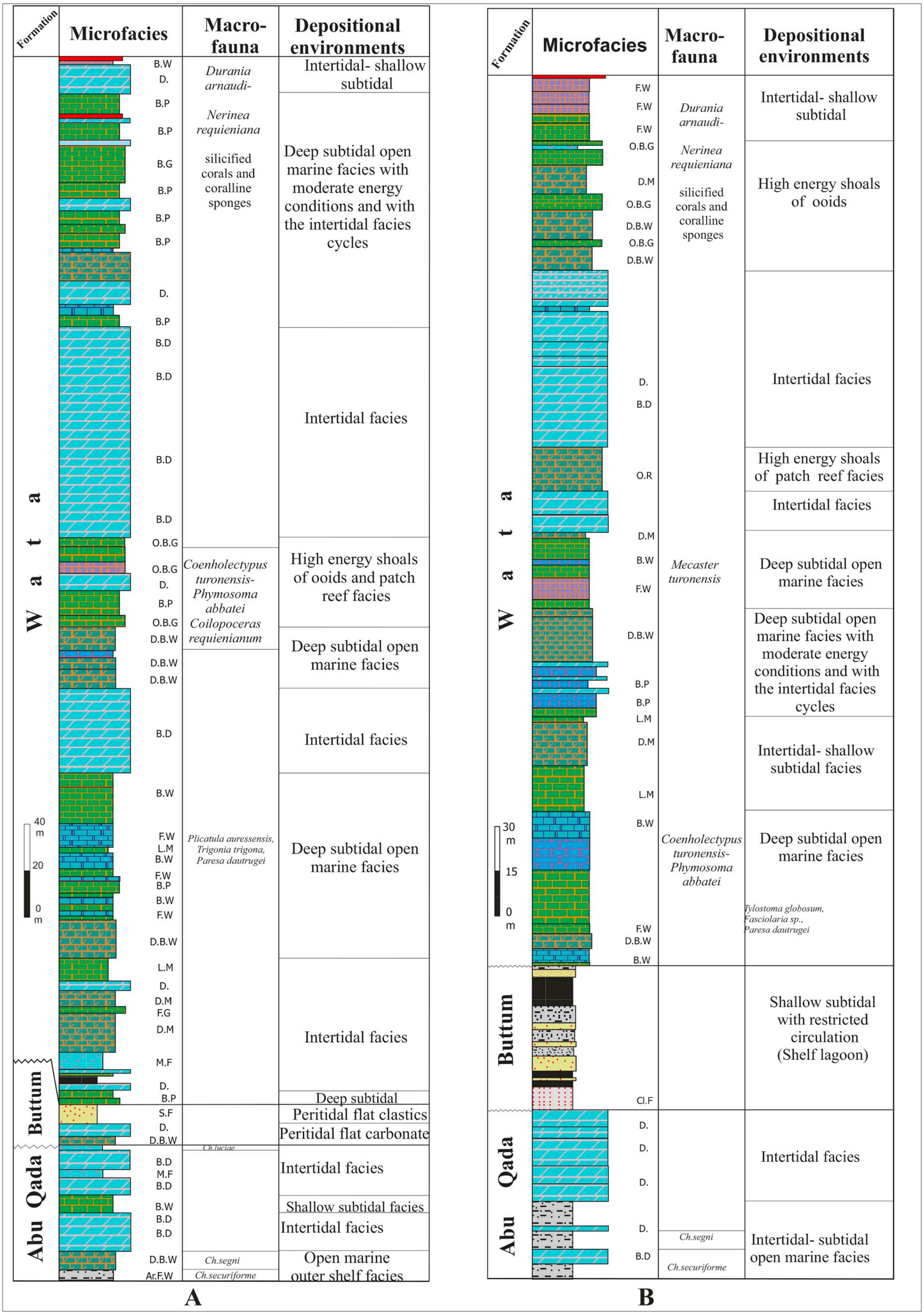

Fig. 5. Lithostratigraphy of the Turonian rock units (Abu Qada, Buttum and Wata formations) at G. Um Horeiba (A) and G. El Hamra (B).

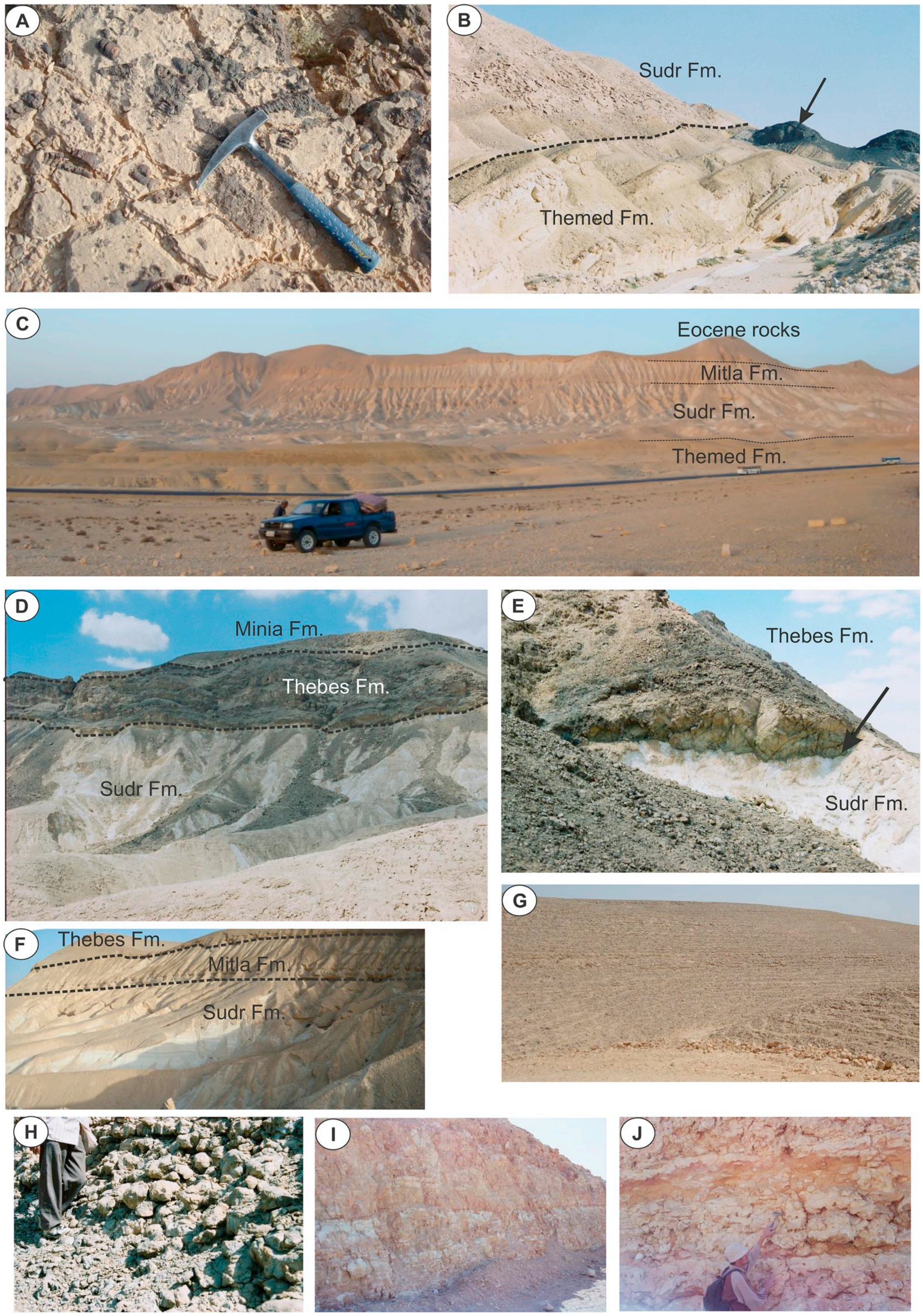

Fig. 6. Field photographs showing A-close-up view of *Nerinea requieniana* d'Orbigny and *Durania arnaudi* (Choffat) replaced by iron oxide imbedded in dolostone bed at the upper part of the Wata Fm. at G. Um Horeiba. B- the Themed Fm. and the overlying Sudr Chalk at G. El Hamra. The field photo show basaltic dyke cutting through the two units C- general up view of Gebel Sudr El Heitan showing the Themed, Sudr, Mitla, Thebes and Minia formations. Sudr Chalk unconformably overlain by the Thebes Fm. at G. Alaqa near G. El Hamra. E – close-up view of wavy irregular surface of glauconitic limestone at the contact between the Sudr Chalk and Thebes Fm. at G. Alaqa. F- the Mitla Formation above the scarps of the Sudr Chalk and below the Eocene sediments at Gebel Sudr El Heitan. G-unbedded limestone of the Thebes Fm. at G. Sudr El Heitan. H- reworked, conglomeratic limestone of the Thebes Fm. at G. Alaqa. I- reddish white highly brecciated limestone beds of the Minia Fm. at G. Um Khesheib. J- Highly brecciated, reworked limestone with sand infill in the Minia Fm.

3.7. The Themed Formation (Coniacian- Santonian)

The Themed Formation was introduced by Ziko et al. (1993) at Garf El Themed area, Central Sinai to designate the strata between the Wata and the Sudr formations and it is equivalent to the more clastic Matulla Formation of Ghorab (1961). The formation measures 139 m at G. Um Horeiba and 130 m at G. El Hamra (Fig. 7). It consists of highly fossiliferous marl and phosphatic limestone intercalation with glauconitic shale and glauconitic sandstone interbeds that increase in G. El Hamra section (Fig. 7). The Themed Formation is easily distinguished from the overlying Sudr Formation and the underlying Wata Formation by its yellow, greenish yellow color forming a prominent horizon (Fig. 6B and C).

This rock unit is rich in macrofossils and yields *Pycnodonte (costeina) costei* (Coquand), *Oscillopha dichotoma* (Bayle), *Pholadomya pedernalis* Roemer, *Mecaster fourneli* (Deshayes), *Aporrhias fourneli* (Coquand) (Plates 2-3). Based on these macrofossils, the Themed Formation is of Coniacian- Santonian age.

3.8. The Sudr Chalk (Campanian- Maastrichtian)

This term was first introduced by Ghorab (1961) to describe the chalk sequence exposed at Wadi Sudr area, west Central Sinai. He subdivided it into two members; the Markha Member at base and Abu Zenima Member at top. The Sudr Chalk is easily recognized in the field by its lithology of snow-white chalk (Fig. 6C–F) that can be separated

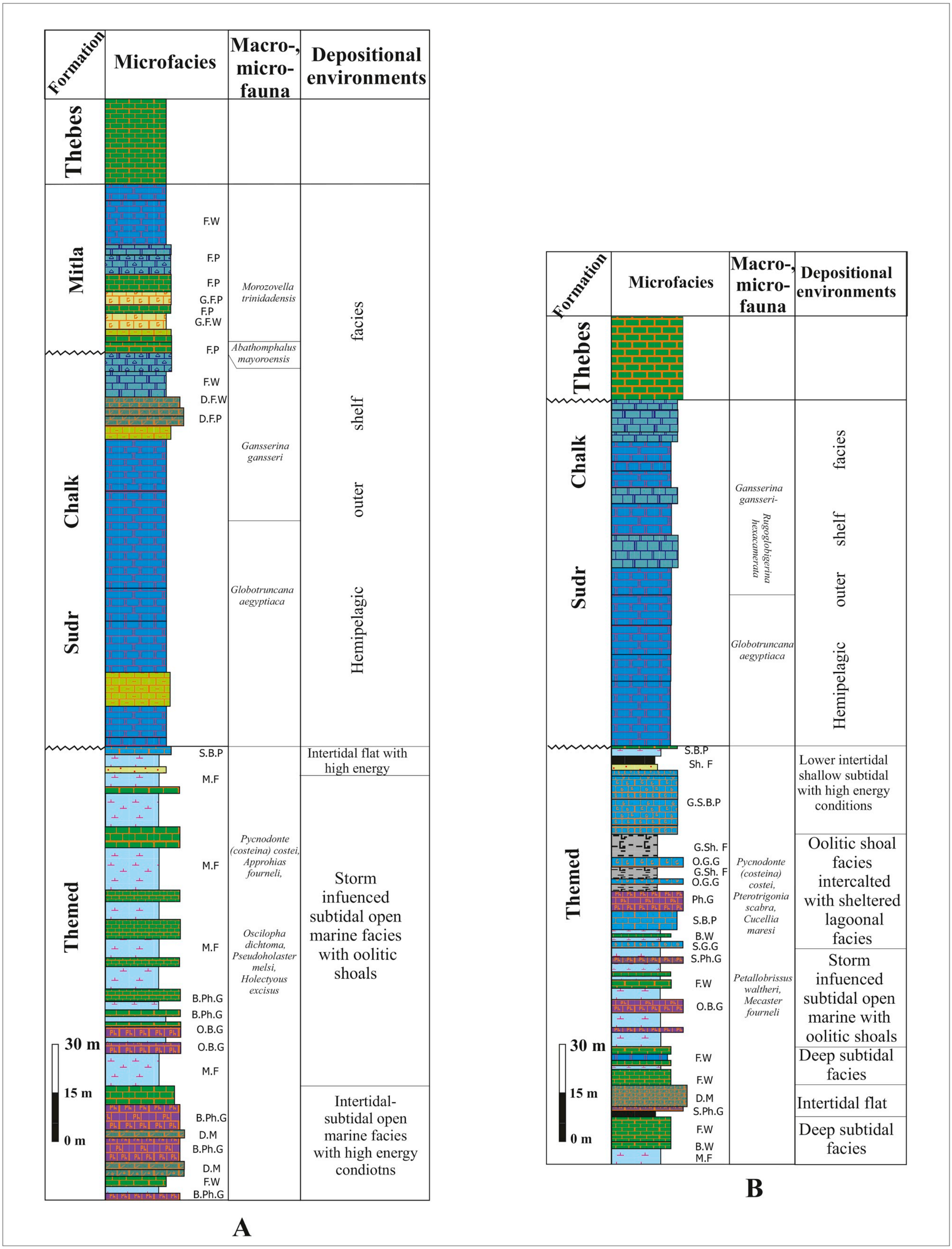

Fig. 7. Lithostratigraphic section of the Upper Cretaceous-Lower Paleogene succession (Themed, Sudr, Mitla formations) at G. Um Horeiba-Sudr El Heitan (A) and G. El Hamra (B).

from the underlying brownish to faint yellow marl, and phosphatic limestone of the Themed Formation (Fig. 6B and C). The formation measures 114 m at G. Sudr El Heitan and 107 m at G. El Hamra (Fig. 7). It is composed mainly of white, hard and highly jointed chalk at base and chalky, argillitic limestone at top. At G. El Hamra, a basaltic dyke traverses the Sudr Chalk and Themed Formation (Fig. 6B). The formation overlies unconformably the Themed Formation at both sections, while it underlies unconformably either the Mitla Formation at G. Sudr El Heitan or the Thebes Formation at G. El Hamra. At the latter, the unconformity surface is marked by presence of green glauconitic limestone bed and occasional conglomerate lenses and chert pebbles with absence of Paleocene deposits (Fig. 6D and E). The Sudr Chalk is relatively poor in macrofossils, yields only *Pycnodonte (Phygraea) vesicularis vesicularis* (Lamarck). In contrast, the formation is very rich in microfossils especially planktic foraminifera as *Globotruncanella havanensis* (Voorwijk), *Globotruncana aegyptiaca* Nakkady and *Gansserina gansseri* (Bolli). The above-mentioned planktic foraminifera suggest a late Campanian – Maastrichtian age (El Sheikh et al., 2010).

3.9. The Mitla Formation (here emended) (Paleocene – lower Eocene)

For the first time, at Mitla Pass, the present authors preferred not to use the term Esna Shale Formation for the rock unit above the Sudr Chalk and below the Thebes Formation at G. Sudr El Heitan which is equivalent to the Esna Shale Formation. The latter unit is easily recognized in the field by its lithologic characteristics of dark grey and slope forming shales (Beadnell, 1905). Accordingly, a new term (Mitla Formation) was used to describe about 60 m thick succession of chalky and argillitic limestone (Fig. 6F). At its type locality, the Mitla Formation overlies unconformably the Sudr Chalk and underlies conformably the Thebes Formation (Fig. 6C, F). It is represented by wall-forming, grayish white, medium hard limestone at base which is followed upwardly by chalky, grayish white, flakey and slope-forming limestone with chert nodules and calcite-filling fractures. It is topped by grey, hard, thinly bedded, argillitic, wall-forming limestone. Due to intermittent rising Gebel Alaqa, in the west, the Mitla Formation was not recorded to the west of the study area.

The present rock unit is highly fossiliferous with planktic foraminiferal assemblages as *Morozovella pseudobulloides* (Plummer), *Morozovella trinidadensis* Bolli *Morozovella angulata* (White), *Morozovella uncinata* (Bolli) *Morozovella edgari* (Premoli Silva & Bolli), *Morozovella subbotinae* (Morozova). The above-mentioned planktic foraminifera suggest a Paleocene – early Eocene age.

3.10. The Thebes Formation (lower Ypresian)

The term Thebes Formation was introduced by Said (1962) to describe about 290 m thick succession of bedded limestone with chert bands, cropping out at Gebel Gurnah, behind the famous temple of El Deir El Bahari, West Luxor. There is an agreement among many authors to use the term Thebes Formation to describe the lower Eocene rocks in Southern Egypt and Central Sinai. The terms Egma Formation ntroduced by Beadnell (1927) at Egma Plateau, the Waseiyit Formation introduced by Barakat et al. (1988) for the lower Eocene rocks at Hammam Faraun and Tanka area are equivalent to the Thebes Formation.

The formation is well represented in the study area forming the plateau surface above the Upper Cretaceous rocks and below Minia Formation at Gebel Heitan, Gebel Um Khesheib and Gebel Alaqa. The Thebes Formation is well developed along Sudr El Heitan and Gebel Um Khesheib measuring about 44 m thick, while at the southwestern part of the area at Gebel El Hamra, Gebel Alaqa and Gebel Abu Hyman, this rock unit measures about 108 m thick. Lithologically, the Thebes Formation is characterized by ledge forming, bedded and wall forming limestone, nummulitic and chalky limestone and glauconitic limestone beds. At Gebel Sudr Heitan and Gebel Um Khesheib (Fig. 8), this rock unit is made up of thin-bedded, pinkish white, hard nummulitic limestone with brecciated chalky limestone interbeds (Fig. 6G) that changes to conglomeratic, nodular and glauconitic limestone (Fig. 6H) at Gebel Alaqa and Gebel Abu Hyman (Fig. 1). Chert in the form either of nodules or rare thin layers occurs but rare.

The Thebes Formation is rich in larger foraminifera such as alveoliniids, operculinids, and nummulitids in addition to planktic foraminifera such as *Morozovella formosa formosa* (Bolli) and *Acarinina angulosa* (Bolli). The pre-mentioned foraminifera suggest an early Eocene (early Ypresian) age for the Thebes Formation.

3.11. The Minia Formation (upper Ypresian)

The term Minia Formation was first introduced by Said (1960) to describe about 35 m thick of snow white alveoliniid limestone at Zawiet El Saada opposite El Minia that overlies the Thebes Formation. The Formation was thought to be of middle Eocene age but the work of Boukhary and Abedelmalik (1983) on the faunal assemblages identified from the Minia Formation puts this formation within the late early Eocene time. Rod El Awad Formation that was introduced at central Sinai by Zalat and Eweda (1998) and the upper part of Waseiyit Formation that was introduced by Barakat et al. (1988) at Hammam Faraun-Tanka area is equivalent to the studied Minia Formation.

The studied Minia Formation is exposed on the plateau surface of G. Sudr El Heitan, G. Alaqa, G. Abu Hyman and G. Um Khesheib (Fig. 1) measuring up to 45 m-thick succession of thin bedded to massive, white, hard, ledge forming limestones. At Gebel Um Khesheib, this rock unit becomes more reddish in color, with reworked and highly brecciated limestone and with sand fill (Fig. 6I and J). This rock unit is rich in larger benthic foraminifera as alveoliniids and nummulitids. According to its stratigraphic position above the lower Ypresian Thebes Formation, the Minia Formation is considered as late Ypresian age.

4. Facies associations and interpretation

Twenty-seven facies of both lithified and non-lithified clastic and carbonate rocks were recorded in the stratigraphic succession from the Masajid Formation to the Minia Formation. These facies include: siliceous quartzarenite, dolomitic quartzarenite, fossiliferous and/or phosphatic quartzarenite, quartz wacke, dolomicrite, medium to coarse-crystalline dolostone (sucrozic dolostone), fossiliferous dolostone, lime mudstone, dolomitic lime mudstone, moluscan wackestone, foraminiferal wackestone (planktonic/benthonic), bioclastic wackestone, foraminiferal packstone (planktonic/benthonic), bioclastic packstone, oolitic bioclastic packstone, peloidal bioclastic packstone, bafflestone, oolitic bioclastic grainstone, oyster rudstone, oolitic phosphatic packstone/grainstone, rudist boundstone, greensand, glauconitic shale, sandy shale, gypseferous shale and marl lithofacies. These facies are grouped into eight associations that are assigned to six depositional environments. The distribution of the different facies and their interpretation are described in the following subchapters.

4.1. Pretidal flat/beach clastics

This facies association was recorded in the Risan Aneiza, Buttum, Themed and Minia formations (Figs. 2, 5, 7 and 8). It is represented by thinly laminated and/or massive sandstones that are fine to medium-grained, yellowish red to dark brown and rarely fossiliferous and phosphatic. The petrographic investigation of these sandstones revealed siliceous quartzarenite (Risan Aneiza and Buttum formations) (Fig. 9A), dolomitic quartzarenite (Risan Aneiza Formation) (Fig. 9B), phosphatic calcareous quartzarenite (Themed Formation) (Fig. 9C) and quartz wacke (Minia Formation) (Fig. 9D). The quartz grains are well rounded, well sorted and monocrystalline with high maturity. The cement is either of silica overgrowths, calcite and/or dolomite (Fig. 9A–D).

Interpretation: the high maturity of quartzarenite indicates

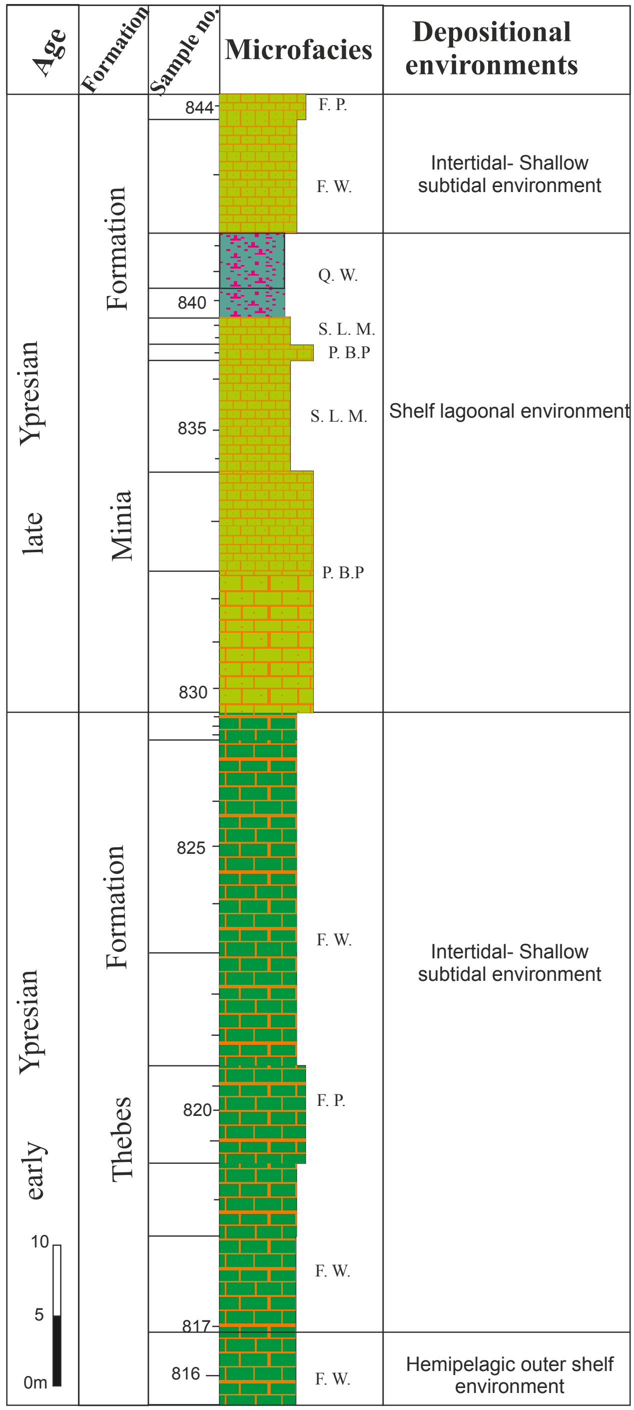

Fig. 8. Lithostratigraphic section of the Thebes and Minia formations at G. Um Khesheib, El Giddi Pass, west Central Sinai.

deposition in high energy shallow water at passive continental margin (Pettijhon et al., 1987). Also, the rounded nature of quartz grains indicates prolonged transport. The horizontal lamination of the dolomitic quartzarenite facies of the Risan Aneiza Formation at G. El Giddi may reflect deposition of sand from suspension nearby the clastic source where the storm action decreases (Read, 1985). On the other hand, the massive sandstones are formed in supra tidal-inter tidal zone with storm conditions. This in turn indicates a more proximal source and suggests that this quartzarenite facies was developed close to the shore/beach where the quartz grains could be supplied either by rivers or erosion of the coastal area. As well, occurrence of phosphatic grains along with the bivalve shells and quartz grains can be interpreted as a storm terrigenous material reworked and transported from shallow and more energetic sites.

4.2. Pretidal flat carbonates

This facies association was recorded in the Risan Aneiza, Galala, Buttum, Wata, and Themed formations (Figs. 4, 5 and 7). It is represented by fine grained dolostone, sucrozic dolostone and bioclastic dolostone. The petrographic investigations revealed that, this lithofacies is made up of dolomite rhombs of ferroan core and distinctly zoned of iodiotopic to xenotopic fabrics (Fig. 9E, F, G). The main bioclasts are of echinoid fragments and bivalve shells. The bioclastic

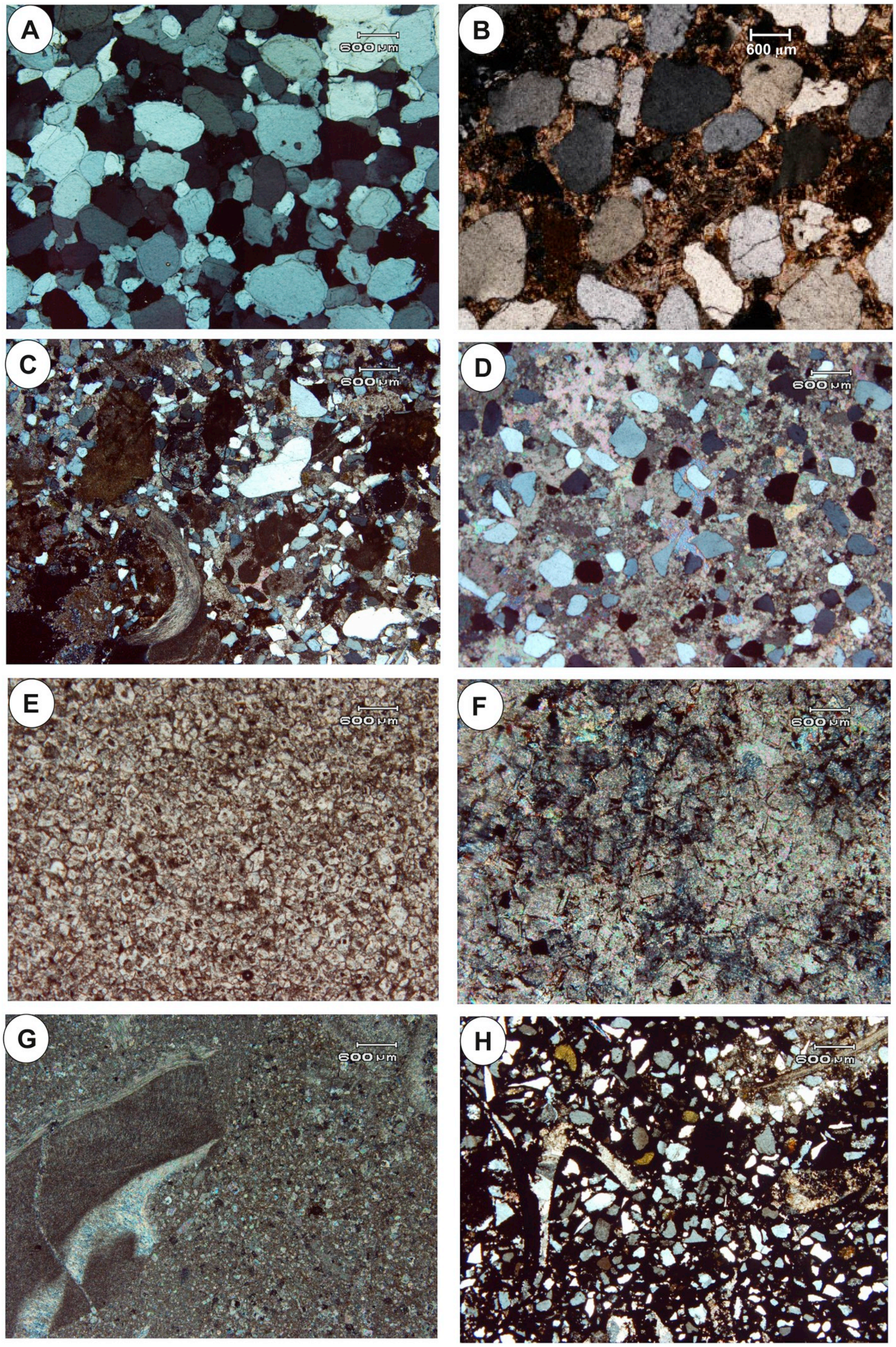

Fig. 9. Photomicrographs showing A-coarse grained quartzarenite microfacies with well-sorted and rounded quartz grains and silica overgrowth. B- dolomitic quartzarenite with coarse quartz grains and medium-grained dolomite rhombs forming the cement. C- fossiliferous and phosphatic quartzarenite microfacies. The main bioclasts are of bivalve shells, echinoids and bryozoans. D-quartz wacke lithofacies that exhibits medium-sized quartz grains that are subrounded and ill-sorted and cemented together by a drusy calcite cement. E – fine-grained dolostone microfacies (dolomicrite) with dolomite rhombs of equigranular texture. F- sucrozic dolostone microfacies that made up of medium-to coarse-grained dolomite rhombs with ferroan core and clear outer rim. The dolomite rhombs are equigranular in texture and iodiotopic in nature and distinctly zoned. G-bioclastic dolostone microfacies mainly of coarse-grained dolomite rhombs account about 90% of the rock and the main bioclasts are of echinoid plates and bivalve shells. H- fossiliferous ferruginous quartzarenite microfacies with fine quartz grains and glauconitic grains cemented together by ferruginous cement. The main bioclasts are of bivalve and gastropod shells.

dolostone replace the bioclastic wackestone lithofacies by dolomitization.

Interpretation: the dolomicirtes are of supratidal-intertidal facies formed because of penecontemporaneous dolomitization of precursor micrite during regressive phase (Warren, 2000). Also, the presence of coarse dolomite facies refers to late diagenetic process of subtidal carbonates during sea-level fall in lower intertidal zone. Accordingly, we can deduce that the dolomicrites are of supratidal-intertidal facies and the bioclastic dolostone facies are of lower intertidal – shallow subtidal facies of areas in mixing with meteoric water.

4.3. Lagoonal clastics

The lagoonal clastic facies were recorded in the Masajid, Galala, Um Horeiba, Buttum and Themed formations (Figs. 2, 5 and 7) where it is represented by glauconitic shale, sandy shale, gypsiferous shale, fossiliferous ferruginous sandstone and green sand lithofacies. The petrographic studies of the lithified rocks of this facies association show ferruginous quartzarenite (Fig. 9H) and green sand microfacies (Fig. 10A). The green sand facies exhibit green glauconitic pelloids of sand size that are highly compacted and fossiliferous with little bivalve shells (Fig. 10A). Shale lithofacies are fissile, green, highly fossiliferous with oyster banks and dissected with gypsum veinlets.

Interpretation: the lagoonal area is lower intertidal-shallow subtidal area protected from sea (with low energy conditions). The fine-grained size and lamination of shale indicates deposition out of suspension in a low energy environment. Also, the occurrence of gypsum filled desiccation cracks in shale facies can be related to arid climate in supratidal conditions (Shinn, 1983; Bauer et al., 2001). The presence of sand in shale lithofacies indicates a sand-mud tidal flat deposition (Reineck

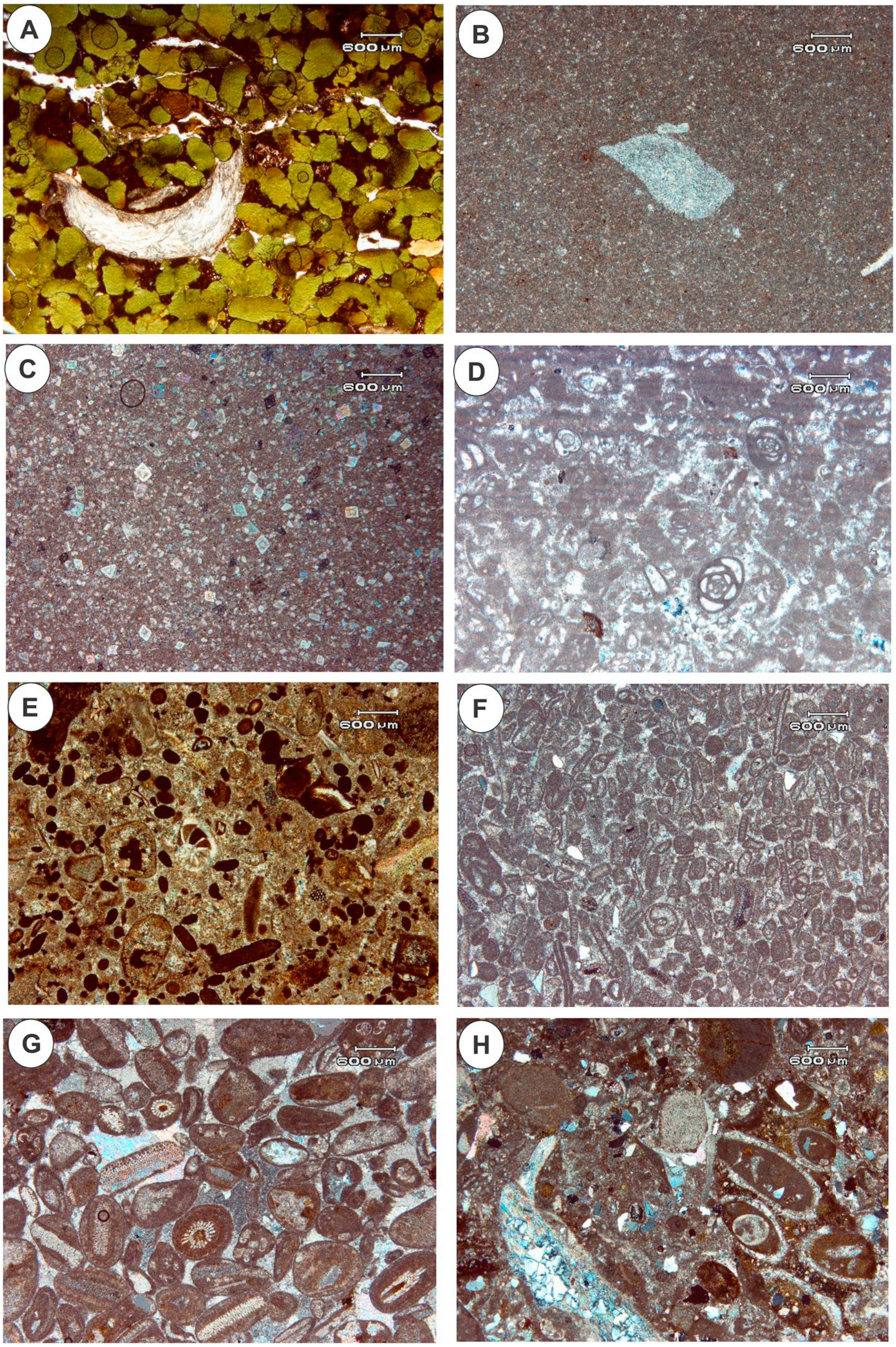

Fig. 10. Photomicrographs showing A-green sand facies, with closely-packed glauconitic grains of sand size. Calcite fills the voids and the main bioclasts are of oyster shells. B- lime mudstone microfacies with dense and dark grey microcrystalline calcite. C- dolomitic lime mudstone microfacies with clear dolomite rhombs scattered in the dense micrite. D-foraminiferal wackestone microfacies with benthic foraminifera of miliolids (*Quinqueloculina* sp. and *Triloculina* sp.) and textulariids scattered in the dense micrite. E – pelloidal bioclastic packstone microfacies with benthic foraminifera, gastropods, bivalve shells and rare echinoid plates closely packed together. The pellets are mostly of glauconitic grains that are completely oxidized into iron oxide. F- pelloidal bioclastic packstone microfacies that exhibits small sized pelloids that are affected by micritization. The main bioclasts are of benthic foraminifera and gastropods and rare bivalve shells. G-oolitic bioclastic grainstone microfacies that exhibits ooids of superficial type. Notice the nucleus of fossil grains of echinoid spines in the ooids that act as the main bioclasts besides the bivalve shells and echinoid plates. H- glauconitic bioclastic phosphatic packstone microfacies which exhibits different types of skeletal particles closely packed together. The main bioclasts are of bivalves that are affected by silicification of spherulitic quartz besides the echinoid plates that are affected by micritization and with phosphatic and quartz grains. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

and Singh, 1975). Also, the green mottling of shale indicates low sedimentation rates of areas sheltered from open sea. So, we can deduce that, shales, glauconitic, sandy and fossiliferous shales are of shallow subtidal facies with restricted circulation and with normal salinity.

4.4. Lagoonal carbonates

The lagoonal carbonate facies association was represented in the Masajid, Galala, Themed, Thebes and Minia formations (Figs. 2, 4, 7 and 8). Rocks of this facies association were recorded in the upper part of the Galala Formation forming thick sequence of lime mudstone and dolomitic lime mudstone and in the lower part of this rock unit as well forming thin limestone ledges of foraminiferal wackestone (Fig. 4). It was recorded in the lower part of the Themed Formation as well (Fig. 7). Petrographically, the lagoonal carbonates composed mainly of lime mudstone (Fig. 10B), dolomitic lime mudstone (Fig. 10C), miliolid bioclastic wackestone (Fig. 10D) and pelloidal bioclastic packstone microfacies (Fig. 10E and F). The lime mudstone exhibits dense micrite with rare bioclasts, that when contains dolomitic rhombs less than 50% of the rock it is named dolomitic lime mudstone. The benthic foraminiferal wackestone exhibits miliolids and textularids float in the dense micrite. The peloidal bioclastic packstone also consists of dense peloids scattered in micritic matrix with gastropods, bivalves and miliolids.

Interpretation: The scarce fossils in lime mud reflect restricted shallow subtidal quiet water of high salinity (Flügel, 1982; Pitter et al., 1995). Also, absence of wave current structure and low diversity of fossils denote that, the lime mudstone and dolomitic lime mudstone were deposited in low energy zone below the normal wave base and below the storm wave base. Also, presence of diverse miliolids and textularids indicates restricted shallow-deep subtidal quiet water conditions (Pitter et al., 1995). Abundance of peloids with gastropods and benthic foraminifera indicates restricted shallow subtidal and low sedimentation rates.

4.5. High energy shoals of ooids and patch reefs (reefal and back reef facies association)

The platform margin is an area of high energy conditions and low sedimentation rate that separates the shelf lagoons from the open marine environment (Burchette and Wright, 1992). This facies association is represented in the Masajid, Galala, Wata, and Themed formations (Figs. 2, 4, 5 and 7) by thin-to thick-bedded, fossiliferous and mostly oolitic limestone and phosphatic limestone, oyster rudstone and boundstone facies. The oolitic bioclastic limestones were recorded in the lower part of the Galala Formation at G. Um Horeiba forming thin, hard limestone ledge and in the middle and upper part of the Wata Formation in G. Um Horeiba and G. El Hamra. The oolitic phosphatic limestones were recorded in the Themed Formation intercalating with marl and shale lithofacies. The rudstone lithofacies was recorded in the Galala Formation at its upper part at G. Um Horeiba and in the middle part of the Wata Formation in G. Um Horeiba and G. El Hamra and the boundstone facies were recorded in the lower and middle part of the Galala Formation at G. Um Horeiba.

The petrographic studies of these limestones are represented by oolitic bioclastic grainstone (Fig. 10G), oolitic phosphatic grainstone (Figs. 10H and 11A), oyster rudstone (Fig. 11B), rudist boundstone (Fig. 11C) and bafflestone microfacies (Fig. 11D). The main bioclasts of these microfacies are of coralline sponges, crinoids, echinoid spines and plates, bivalves of oysters and rudists with non-skeletal ooid grains (Fig. 10G and H, Fig. 11A–D). The ooids are rounded to sub-rounded and some are elongate affected by compaction and with nuclei of fossil grains. The petrographic investigations revealed also that, the bafflestone microfacies were recorded in the Masajid Formation and made up of bioclasts of rod-like shape (corals, sponges and crinoids). Subordinate occurrence of benthic foraminifers and bivalve shells are also observed. The bioclasts and matrix are partially silicified by chalcedony. The back-reef facies were recorded at the lower part of this rock unit and represented by reworked limestone that is fossiliferous with large sized gastropods, corals, sponges and benthic foraminifers.

Interpretation: The presence of corals, coralline sponges and crinoids with the ooids indicates shallow subtidal environment with high energy conditions of warm tropical to subtropical areas, where they act as wave resistant rocks of rod-like shape in water depth of few 10 m (Wilson, 1975). The oolitic bioclastic and phosphatic grainstone are interpreted as high energy carbonate shoals (Harris et al., 1997) and occurrence of ooids and phosphatic grains indicates deposition in an intertidal zone of highly agitated shallow water conditions with upwelling current (Strasser, 1986). The boundstone microfacies are formed in high energy water with significant autochthonous carbonate production in well oxygenated environment above the wave base as well (Flügel, 1982). Whereas, oyster rudstone reflect lower intertidal shallow subtidal area of moderate to high energy conditions.

4.6. Intertidal-subtidal open marine (shelf basin environment)

The open marine environment is an area of deposition that lies in the lee side of islands and shoals toward open marine (Tucker, 1990). The intertidal-subtidal open marine facies are dominant in the studied succession especially in the Risan Aneiza, Galala, Abu Qada, Wata, Thebes and Minia formations (Figs. 4, 5 and 8). Rocks of this facies association are dominant in the Galala Formation at its lower, middle and upper parts intercalating with the high energy shoal, peritidal and storm influenced subtidal environments. This facies association is represented by thin-bedded limestones, dolomitic limestone that are highly fossiliferous, especially with ammonites in the Galala, Abu Qada and Wata formations.

These open marine facies associations include wackestone and packstone facies (molluscan wackestone (Fig. 11E), ostracodal wackestone/packstone (Fig. 11F), echinoidal bioclastic wackestone (Fig. 11G and H) alveolinid (Fig. 12A and B) and nummulitic wackestone/packstone (Fig. 12C and D), oolitic bioclastic packstone (Fig. 12E and F) and bioclastic wackestone/packstone microfacies (Fig. 12G). The petrographic study revealed that the main bioclasts are of echinoid spines and plates, bivalves, planktonic foraminifera, filaments of planktonic bivalves and larger foraminifera and with non-skeletal grains of ooids. Fine to medium-grained quartz and rare glauconitic grains (Fig. 12E and F) are scattered with the bioclasts in the micritic groundmass.

Interpretation: The wackestone and packstone lithofacies reflects deposition in a shallow subtidal-lower intertidal environment (Wilson, 1975). The abundance of bivalves in micrite matrix suggests deposition in a shallow subtidal environment with open circulation (Wilson, 1975; Flügel, 1982). Accordingly, the molluscan bioclastic wackestone lithofacies are of shallow subtidal environment ensured also by abundance of benthic foraminifera. Occurrence of clear dolomite rhombs in bioclastic wackestone lithofacies may also suggest intertidal-shallow subtidal environments and mixing with meteoric water. On the other hand, the echinoidal and bioclastic wackestone microfacies with the dominance of planktic foraminifera, filaments of planktic bivalves and ammonites indicates a deep subtidal environment with open circulation. The abundance of dense lime mud indicates a quiet water condition. Accordingly, the bioclastic wackestone/packstone facies associations are of shallow-deep subtidal with open circulations and quiet water conditions below normal wave base with low-to moderate-energy conditions (Wilson, 1975; Tucker and Wright, 1990; Harris et al., 1997). As well, lack of bioturbations and any internal sedimentary structures in the thin bedded limestone ledges refer to deposition in quiet-water deep subtidal environment (Tucker and Wright, 1990). Presence of quartz and glauconitic grains indicates low sedimentation rates and deposition from suspension nearby source of clastic erosion. As well, presence of larger foraminifera suggests an intertidal/shallow subtidal environment with depth of few meters to 20 m.

4.7. Storm influenced subtidal open marine environment

Storm influenced subtidal marine environment refers to a deep-water area that is influenced by storm action and lies above the storm wave base (Burchette and Wright, 1992). This facies association is mainly represented by nodular marl facies that were intercalated with the reworked or thinly bedded limestone lithofacies in the Masajid, Risan Aneiza, Galala, Wata and Themed formations (Figs. 2, 4, 5 and 7). The marl facies are yellowish white, moderately hard, slope forming and highly fossiliferous.

Interpretation: Nodular marls and limestones are storm deposits formed after early lithification on the sea floor (Bàdenas and Aurell, 2001). Burchette and Wright (1992) stated that, the occurrence of carbonate nodules within a carbonate mud matrix is a common feature of deposits that were formed above storm wave base in mid-ramp settings. Abundance of brachiopods with the corals, sponges, echinoid and bivalves in the Masajid Formation indicates a deposition in shallow subtidal environment in the middle ramp setting and the nodular marl facies are formed in open circulation. So, the recognized nodular marls reflect a deposition below fair-weather wave base and above storm wave base in a mid-ramp setting.

4.8. Hemipelagic outer shelf facies

The term pelagic means the open sea and refers to marine nektons or planktic organisms whose environment commonly is the open ocean. Biogenic deep-sea sediments are formed by the remains of pelagic organisms contributing to the formation of carbonate or siliceous oozes and muds. Rocks of this facies association are dominant in the latest

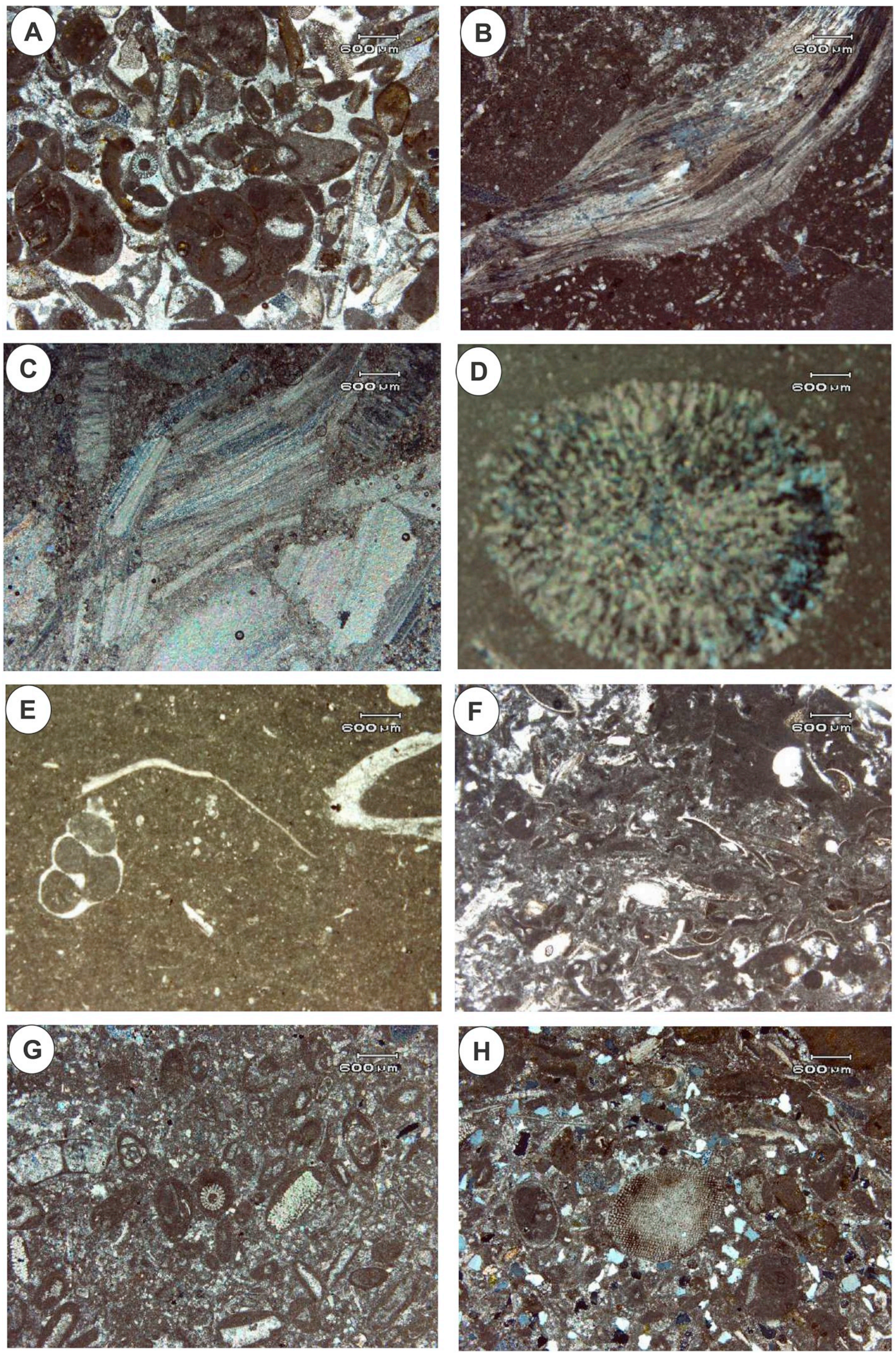

Fig. 11. Photomicrographs showing A-oolitic phosphatic grainstone microfacies with ooids, echinoid spines, echinoid plates and bivalve shells packed in the spiritic calcite. Note the glauconitic grains scattered with the echinoid plates and echinoid spines in glauconitic phosphatic grainstone microfacies. B-oyster rudstone microfacies with abundant large bivalve shells that exhibits original fibrous internal structure. C- rudist boundstone microfacies with parallel-imbricate rudist shell fragment. D-the coralline sponge in transverse section in bafflestone microfacies. E – molluscan wackestone microfacies with bivalves and gastropod shells scattered in the dense micrite. F- ostracodal packstone microfacies with ostracodal thin valves that are closely packed and associated with benthic foraminifera. G-bioclastic wackestone microfacies with bivalve shells, echinoid plates, benthic foraminifera of miliolid types and gastropods with rare oolitic grains. Notice the micrite envelope around the different types of skeletal particles. H- sandy bioclastic wackestone/packstone microfacies with micritized echinoid plates and few glauconitic and phosphatic grains.

Cretaceous and earliest Paleogene deposits of the Sudr Chalk and Mitla formations. This facies association is mainly represented by chalk, chalky limestone and argillaceous limestone that are highly fossiliferous with planktic foraminifera. Rocks of this lithofacies is represented by thick-bedded to massive chalk forming thick sequence along Mitla Pass from G. El Hamra to G. Sudr El Heitan. Petrographically, this microfacies composed mainly of planktic foraminifers of globular shape compacted together with high diversity in the fine grained micrite (Fig. 12H).

Interpretation: Generally, the planktic organisms indicate deposition under open marine environment with water depth of 100–200 m in quiet water conditions due to the occurrence of micrite. Deposition and presence of glauconitic grains in argillaceous limestone beds reflect slow sedimentation rate. Occurrence of chert nodules with the chalk sequence in the Sudr Chalk is interpreted to have been associated with marine high productivity conditions leading to blooming of siliceous organisms such as radiolaria and diatoms (Moshkovitz et al., 1983; Reiss, 1988).

5. Paleoenvironments and geologic history

The recognized facies and their related paleoenvironments document lateral and common vertical transition between inner, middle to outer ramp setting. These facies were subdivided into eight associations that show a cyclic nature through the studied stratigraphic succession. The geologic history and paleoenvironments of the studied stratigraphic units are summarized in the following subchapters.

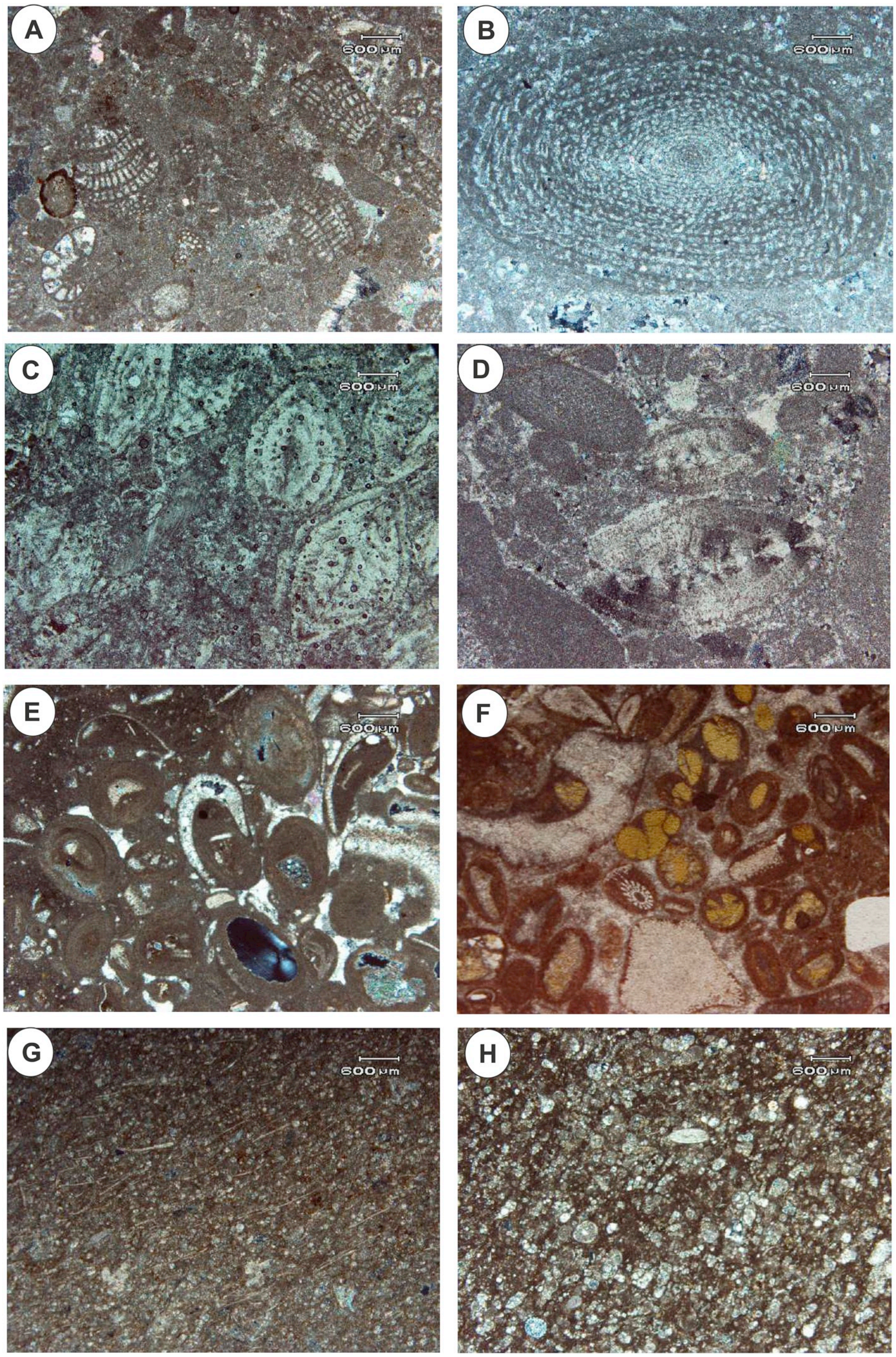

Fig. 12. Photomicrographs showing A-benthic larger foraminifera scattered in the dense micrite in foraminiferal wackestone microfacies. B- transverse section in larger foraminifera (*Praealveolina* sp.). C-nummulitic packstone lithofacies that exhibits *Nummulites* sp., that are closely packed together D-foraminiferal packstone lithofacies with nummulites and alveolinids pack-scattered in the micritic groundmass. E – oolitic phosphatic packstone microfacies with ooids and the nucleus of these ooids are of quartz grains or bivalve shell fragments. F-glauconitic grains scattered with the echinoid plates and echinoid spines in glauconitic phosphatic grainstone microfacies. G-bioclastic wackestone microfacies which declares planktic foraminifera (small-sized and rounded shape) and planktic bivalves (filaments of thin valve shells) floating in the dense micrite. H- planktic foraminiferal packstone lithofacies with planktic foraminifers closely packed together in the micritic matrix.

5.1. Jurassic time span

Through the northern part of the area, a reefal facies were deposited on a carbonate platform margin with the formation of reworked fossiliferous limestones. These limestones are rich in corals, coralline sponges, echinoid spines and plates, crinoid stems and large sized gastropods forming bafflestone of frame buildup of wave resistant rocks. This is followed upward by storm influenced subtidal facies of open marine circulations and moderate to high energy conditions represented by nodular marl being rich in corals, coralline sponges, bivalves and brachiopods. At the end of the Jurassic, the area was affected by a minor break in sedimentation or low sedimentation rate associated with a short term of sea level fall most probably due to structure event and lagoonal shales were overlain by red duricrust.

5.2. Early Cretaceous (? Aptian – Albian) time span

The Risan Aneiza Formation is unconformably overlies the Masajid Formation and starts with intertidal-subtidal open marine facies deposited in moderate to high energy conditions for the two sections studied. This facies association was followed upwardly by peritidal flat carbonate facies associations and peritidal flat beach clastics of dolostone, siliceous and dolomitic quartzarenite microfacies.

5.3. Cenomanian time span

During the Cenomanian, the clastics/carbonates of the Galala Formation were deposited in intertidal, subtidal, lagoonal and reefal environments that show deeper conditions to the northeast of the study

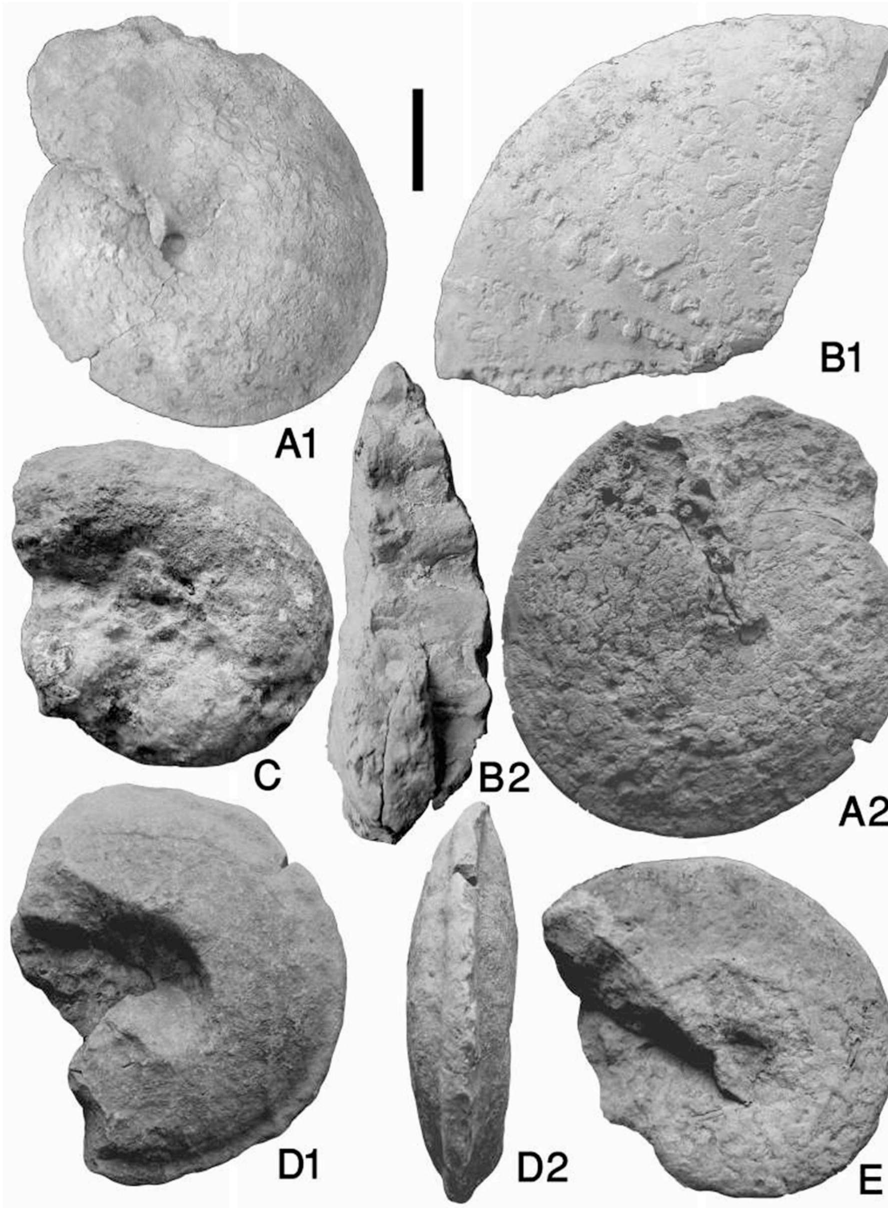

Plate 1. A1., A2. *Coilopoceras requinianum* (d'Orbigny, 1841); side views, Upper Turonian, Wata Formation, G. Um Horeiba. **B1., B2.** *Engonoceras serpentinum* (Cragin, 1900); B1., side view, B2: whorl section Upper Albian, Risan Aneiza Formation, G. El Hamra. **C.** *Vascoceras cauvini* Chudeau, 1909; side view, upper Upper Cenomanian, Galala Formation, G. Um Horeiba. **D1., D2.** *Choffaticeras securiforme* (Eck, 1909); D1: side view, D2: venter view, Lower Turonian, Abu Qada Formation, G. Um Horeiba. **E.** *Choffaticeras segne* (Solger, 1903); side view, Lower Turonian, Abu Qada Formation, G. Um Horeiba. Scale bar in mm: A: 60; B2: 20; B1, C, D, E: 25.

area. The main facies associations are of shallow subtidal facies with restricted circulation and normal salinity with the formation of shales and high diversity of fossil assemblages at the base of the Galala Formation. It shows a cyclic nature with storm influenced subtidal open marine facies and high energy shoals of patch reefs. The patch reef facies are represented by oolitic shoals, oyster rudstone and rudist boundstone microfacies. Upward, the marine transgression continued with deeper conditions and open circulation forming carbonate platform that are intercalated with pulses of regressive phase represented by formation of dolostone, lime mudstone and sandy shale lithofacies of intertidal environment. During late Cenomanian, intertidal flat carbonate and shallow subtidal facies associations being represented by lime mudstone and dolomitic lime mudstone are dominant. During latest Cenomanian, a major marine transgression continued, and deep subtidal open marine facies represented by argillaceous limestone rich in latest Cenomanian ammonites (*Vascoceras cauvini, Pseudaspedoceras pseudonodosoides*) are dominant in the study area.

5.4. Turonian time span

The marine transgression of the late Cenomanian continued in the early Turonian where the Abu Qada Formation was deposited in a shelf basin environment of intertidal-subtidal open marine environment with deeper outer shelf facies. These facies are rich in ammonites and planktic foraminifera. They show cyclicity with dolostone facies controlled probably by pulses of epi-orogenic movements (structure event).

During middle Turonian, a regressive phase occurred in the study area and coincides with the worldwide general drop in sea level of Haq et al. (1987) and to the constant movements which led to the close of Neotethys in the circum Mediterranean region of Lanphere and Pamic (1993) as well. The regressive phase in the studied area is represented by subaerial exposure and calcrete and red paleosols (Buttum Formation) were deposited at the eastern part of the area at Gebel Um Horeiba, Gebel At Tuwal and Gebel El Giddi. This facies association is changed clearly to southwest at Gebel El Hamra to shelf lagoonal facies of shale and red sandstone.

In late Turonian, thick limestone, dolostone sequences of peritidal flat carbonate, intertidal-subtidal open marine facies and high energy

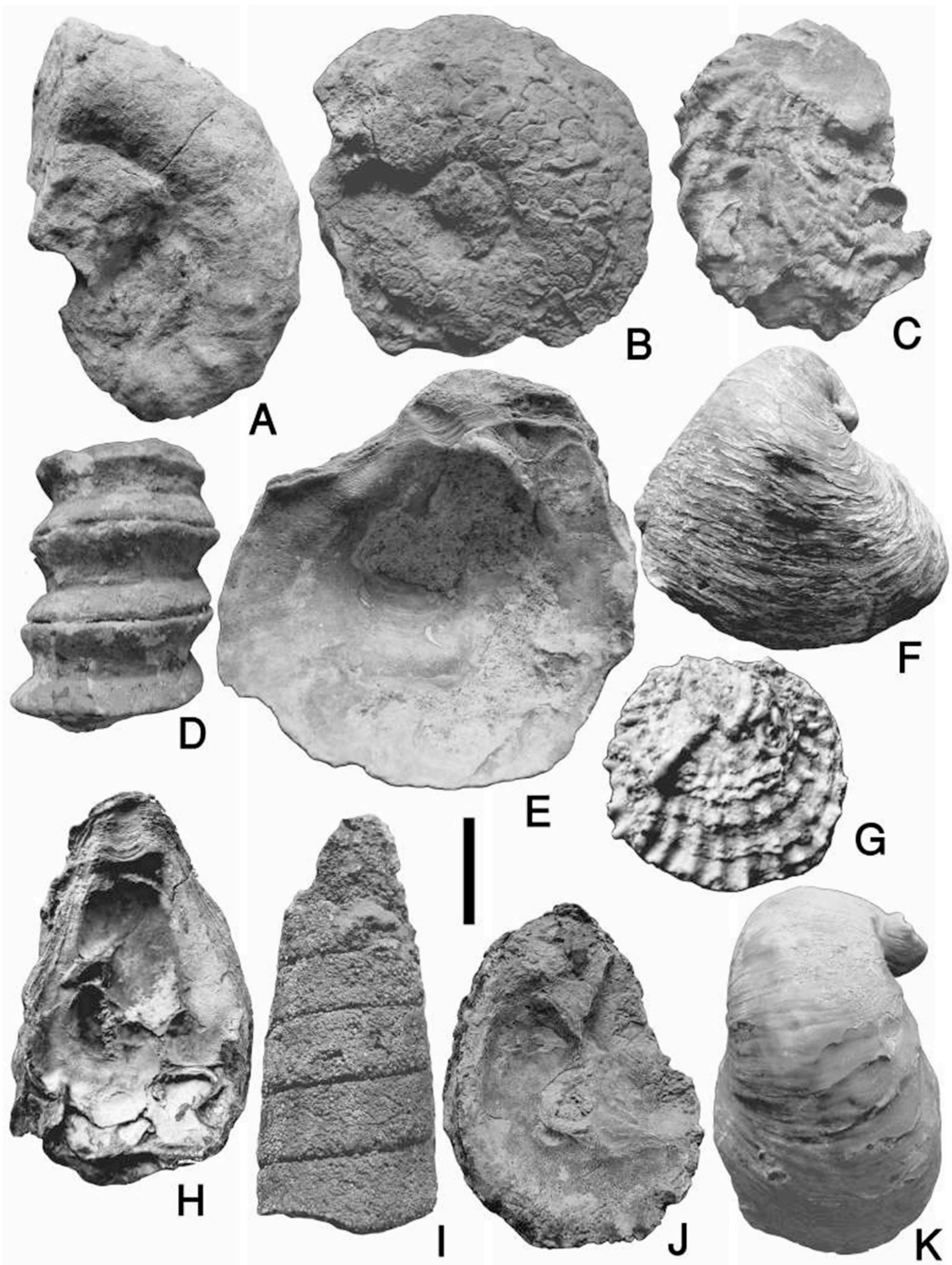

Plate 2. A. *Pseudaspidoceras pseudonodosoides* (Choffat, 1899); side view, upper Upper Cenomanian, Galala Formation, G. Um Horeiba. **B**. *Choffaticeras luciae* (Pervinquiére, 1907); side view, late Lower Turonian, Abu Qada Formation, G. Um Horeiba. **C**. *Ceratostreon flabellatum* (Goldfuss, 1833); left valve, exterior view, Cenomanian, Galala Formation, G. Um Horeiba. **D.** *Nerinea gimmifera*, Coquand, 1862; side view, Middle Cenomanian, Galala Formation, G. Um Horeiba. **E.** *Pycnodonte (Costeina) costei* (Coquand, 1869); left valve, interior view, Coniacian-Santonian, G. Um Horeiba. **F.** *Rhynchostreon suborbiculatum* (Lamarck, 1801); left valve, exterior view, Cenomanian, Galala Formation, G. Um Horeiba. **G.** *Plicatula ferryi* Coquand, 1862; articulated specimen, exterior views, Themed Formation, G. Um Horeiba. **H.** *Gyrostrea delettrei* (Coquand, 1862); left valve, interior view, Cenomanian, Galala Formation, G. Um Horeiba. **I.** *Nerinea requieniana* d'Orbigny, 1842; side view, Upper Turonian, Wata Formation, G. Um Horeiba. **J.** *Oscillopha dichotoma* (Bayle, 1849); left valve, interior view, Coniacian- Santonian, Themed Formation, G. Um Horeiba. **K.** *Ilymatogyra africana* (Lamarck, 1801); left valve, exterior view, Cenomanian, Galala Formation, G. Um Horeiba. Scale bar in mm: A, E, F, G, I: 20; B: 30; C, D, H: 15; J: 25; K: 13.

shoal facies associations were deposited. These facies associations are represented by lime mudstone (and dolomitic lime mudstone), dolomitic bioclastic wackestone, bioclastic packstone, oolitic bioclastic grainstone, oyster rudstone sucrozic and bioclastic dolostone microfacies (Wata Formation). At the lower and upper parts of the Wata Formation, deep subtidal open marine environment with shallowing upward cycles of intertidal flat environment occur. At the middle part of the formation, high energy oolitic shoals were recorded indicating a short term of sea level fall with high energy conditions.

5.5. Coniacian – Santonian time span

During late Turonian and Coniacian time, the area under investigation was oolitic shoal inner shelf environment (Lewy, 1975; Abdel-Gawad and Zalat, 1992). During late Coniacian, uplifting and tilting of North Sinai took place, which is followed by a transgression pulse during latest Coniacian and Santonian (Lewy, 1975). The Coniacian- Santonian is represented by peritidal flat, storm influenced deep subtidal and oolitic shoal facies. The oolitic shoal facies are represented by oolitic and phosphatic grainstone microfacies that are intercalated with the storm influenced deep subtidal marine marl facies. Lower intertidal-shallow subtidal facies with high energy conditions and restricted circulation are dominant at the upper part of the Themed Formation forming glauconitic shale and glauconitic limestone lithofacies at G. Hamra.

5.6. Campanian – Maastrichtian – Paleocene time span

A hemipelagic outer shelf facies were deposited and composed of chalk and chalky limestone which are highly fossiliferous with planktic foraminifera. These lithologies are dominant in the Sudr Chalk and the Mitla formations where the hemi-pelagic facies continued during the Paleocene. The latter unit is represented by chalky limestone, argillaceous limestone and marl intercalations. The Mitla Formation is

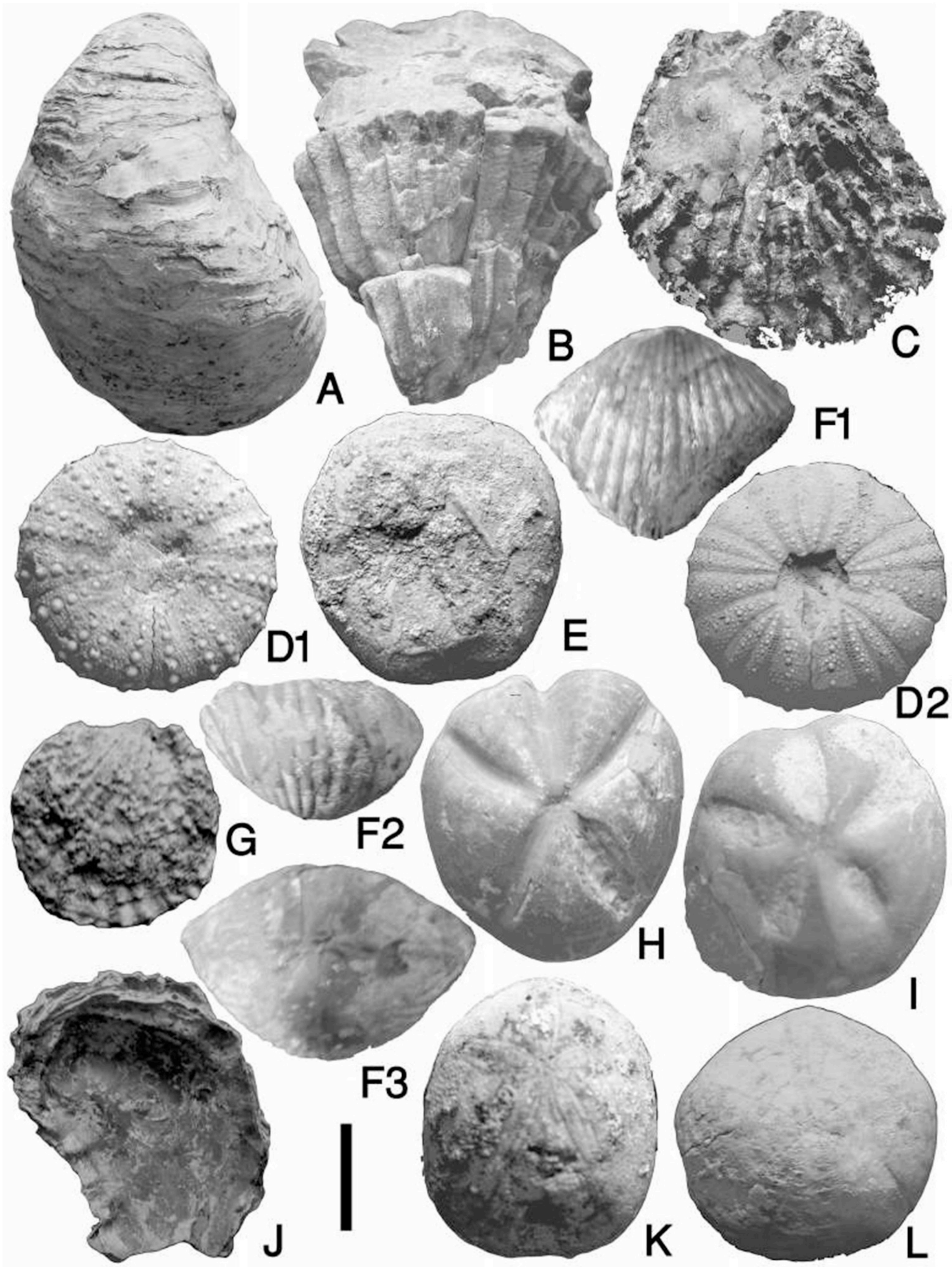

Plate 3. A. *Costagyra olisiponensis* (Sharpe, 1850); Left valve, exterior view, Upper Cenomanian, Galala Formation, Gabal Um Horeiba. **B**. *Praeradiolites biskraensis* (Coquand, 1880); attached valve, Upper Cenomanian, Galala Formation, G. Um Horeiba. **C.** *Oscillopha dichotoma* (Bayle, 1849); left valve, exterior view, Coniacian-Santonian, Themed Formation, G. Um Horeiba. **D1, D2.** *Heterodiadima libycum* (Desor, 1846); D1. adoral view, D2. adapical view, Cenomanian, Galala Formation, G. Um Horeiba. **E.** *Mecaster turonensis* (Fourtau, 1921), adoral view, Lower Turonian, Galala Formation, G. El Giddi. **F1-F3.** *Holorhynchia orbigni* (Oppel); F1. ventral view, F2. anterior view, F3. posterior view, Oxfordian, Masajid Formation, Gebel El Giddi **G.** *Plicatula ferryi* Coquand, 1862; articulated specimen, exterior views, Themed Formation, G. Um Horeiba. **H.** *Mecaster cubicus* (Desor, 1847); adapical view, Cenomanian, Galala Formation, G. Um Horeiba. **I.** *Mecaster fourneli* (Deshayes, 1847); adapical view, Coniacian- Santonian, Themed Formation, G. Um Horeiba. **J.** *Ceratostreon flabellatum* (Goldfuss, 1833); left valve, interior view, Cenomanian, Galala Formation, G. Um Horeiba. **K.** *Petalobrissus waltheri* (Gauthier, 1900); adapical view, Coniacian-Santonian, Themed Formation, G. Um Horeiba. **L.** *Coenholectypus turonensis* (Desor, 1847), adapical view, Turonian, Wata Formation, G. Um Horeiba. Scale bar in mm: A, B: 25; C, E, F2, G, H: 15; D1, D2, I, F3: 10; F1: 13; J: 20; K, L: 7.

missing to the western part of the area at Gebel El Hamra and Gebel Alaqa mostly due to structure control and uplift of that part of the area studied.

5.7. Early Eocene time span

During this time a carbonate sequence with 145 m maximum thickness is represented by Thebes and Minia formations. The Thebes Formation starts with open marine outer ramp facies at the eastern part of the area at Gebel Sudr El Heitan which changes to intertidal-subtidal facies of agitated and high energy environments at the west. During the deposition of the carbonates of the Thebes Formation, the western part of the study area was affected by tectonic activity that most probably started earlier than the Ypresian, mostly during the Paleocene time where the Mitla Formation was missed. In this part of the area, the Thebes Formation is represented by conglomeratic and nodular limestones. Upwards, this rock unit is represented mostly by nummulitic limestones of intertidal-shallow subtidal facies. The Thebes Formation shows shallowing upward cycles to form intertidal-shallow subtidal and lagoonal shelf facies of the Minia Formation where regressive and/or shallower facies were observed.

6. Conclusions

Five stratigraphic sections covering the Mitla- El Giddi Passes are described and interpreted on basis of field studies, petrographic and facies analysis to reconstruct the depositional environments and the geologic history of exposed stratigraphic succession. The area studied is covered by a thick succession of marine siliciclastic and carbonate deposits spanning from Jurassic to Early Paleogene time. This succession is subdivided into eleven formations are the Masajid Formation (Late Jurassic (Oxfordian), the Risan Aneiza Formation (? Aptian- Albian), the Galala Fm. (Cenomanian), Abu Qada Formation (early Turonian), the Buttum Formation (middle Turonian), the Wata Formation (middle–late Turonian), the Themed Formation (Coniacian–Santonian), the Sudr Chalk (Campanian–Maastrichtian), the Mitla Formation (Paleocene–early Eocene), the Thebes Formation (early Ypresian) and the Minia Formation (late Ypresian). The exposed succession shows lateral facies changes that are mostly attributed to paleorelief and tectonic activities. Hence, new formational name was introduced e.g., the Paleocene-early Eocene Mitla Formation which is coeval with the Esna Shale. The facies and their related depositional environments indicate that the studied rock units were deposited on a ramp setting. Different depositional environments were recognized in the studied succession including peritidal flat, lagoonal, high-energy shoals of ooids and rudist patch reef, back-reefal, intertidal–subtidal, storm-influenced open marine and hemipelagic environments. The recognized facies show a northeastern gradual transition from inner-to mid-ramp where the deeper facies of the same stratigraphic position in each rock unit were clearly encountered to the northeast of the study area whereas the siliciclastic facies increase to the southwest. The area was controlled by a long-term transgressive phase and several higher order sea level fluctuations.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jafrearsci.2019.01.013.

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