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SEDIMENTOLOGY OF THE PALEOCENE – EARLY EOCENE SEQUENCE, SOUTHWESTERN IRAQ

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ABSTRACT

Facies analysis, depositional environments and diagenesis of the Paleocene – early Eocene sequence at southwestern Iraq is studied in ten boreholes. The whole sequence is carbonate – evaporite bounded by unconformities and incorporates Umm Er Radhuma, Rus and Jil Formations. The sequence comprises grey clayey dolomite, dolomitic marl, nodular or bedded evaporites, and crystalline limestone representing vanished evaporites and dedolomite. Six lithofacies are recognized in the studied sequence extending from shore towards the basin, these lithofacies are: **1)** Evaporites Lithofacies; **2)** Laminated Dolomite Lithofacies; **3)** Non-laminated Dolomite Lithofacies; **4)** Sucrose Dolomite Lithofacies, **5)** Massive Fossiliferous Dolomite Lithofacies and **(6)** Phosphatic Arenite Lithofacies. The evaporites are formed in a lagoon as sabkha cycles and subaqueous shallow marine evaporite. Possibly the evaporite nodules grew under the sediment/water interface under the lagoon. The sulphate could have grown by mixing of waters of different salinities. The evaporitic basin seems to have shifted its geographic position with time. Several diagenetic processes affected the sequence, such as neomorphic replacement, dissolution, dolomitization, sulphate development, vanished evaporites and dedolomitization. Some of these processes obliterated the primary textures.

رسوبية تتابع الباليوسين – الأيوسين المتأخر في جنوب غربي العراق

مازن يوسف تمراغا

المستخلص

تم دراسة تحليل السحن وبيئات الترسيب وعمليات التحوير لتتابع الباليوسين – الأيوسين المبكر في عشرة آبار في جنوب غربي العراق. يتميز التتابع باحتوائه على المتبخرات ويضم تكوينات أم الرضومة والرص والجل. يتكون التتابع من دولومايت طيني رمادي وفتات عضوي ومارل دولوميتي رمادي ومتبخرات عقدية أو طبقية وحجر جيري بلوري يمثل المتبخرات المختفية والديدولومايت. يتكون التتابع من ست سحنات صخارية تمتد من الساحل الى الحوض و هي: **1)** سحنة المتبخرات الصخارية، **2)** سحنة الدولومايت المتصفح الصخارية، **3)** سحنة الدولومايت غير المتصفح الصخارية، **4)** سحنة الدولومايت السكري الصخارية، **5)** سحنة الدولومايت الحامل للمستحاثات الكتلي الصخارية و **(6)** سحنة الرمل الفوسفاتي الصخارية. تكونت المتبخرات في بيئة لاغونية شبه مغلقة عن البحر المفتوح. تعد بعض المتبخرات دورات سبخة وأخرى بحرية ضحلة ومن المحتمل بأن عقد المتبخرات نمت جراء اختلاطها بمياه ذات ملوحة مختلفة وقد تم تغير الموقع الجغرافي للحوض التبخيري مع الزمن. تأثر التتابع بالعديد من العمليات التحويرية مثل الإحلال التشكلي والإذابة والدلمتة وتكوين المتبخرات واختفاء المتبخرات وإزالة الدلمتة مما أدى أحياناً الى تشوه الأنسجة الأولية.

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INTRODUCTION

A comprehensive project was planned by the Desert Development Consortium of Iraq at the mid-seventies of the last Century concerning the hydrogeology of western Iraq. Iraq Geological Survey executed the southern part of the project (Blocks 1, 2 and 3). Eleven keyholes and two subsidiary boreholes were drilled to various depth (full-core drilling) ranging from 120 to 600 m deep (Fig.1). Ten of the wells penetrated Paleogene sequence, named the Jerishan Group, as it comprises primary evaporite sandwiched between two carbonate sequences free of primary evaporites and bounded by upper and lower unconformities (Tamar-Agha, 1984; Tamar-Agha and Al-Sagri, 2015; Tamar-Agha and Basi, 2021). Primary evaporite is a term used here to indicate nodular evaporites that are formed by replacement and displacement at very early stages of diagenesis (almost syngenetic to deposition). The Jerishan Group is introduced by Tamar-Agha in 1983 incorporating three formations namely Umm Er Radhuma (Paleocene), Rus (Lower Eocene) and Jil formations (Lower Eocene).

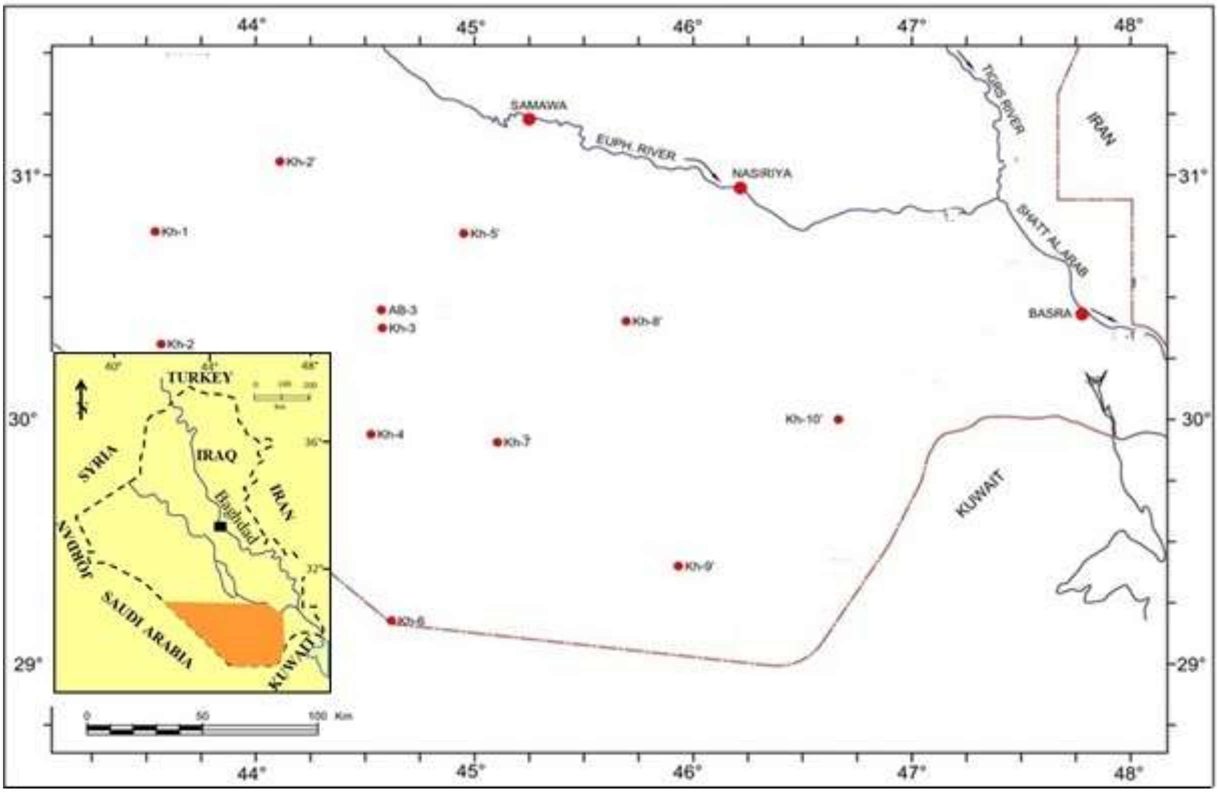

Fig.1: Location map of the studied area. KH-1 at Shbecha, KH-2 at Rijm Al-Thaydi, KH-2' at Umm Al-Hashim, KH-3 at Al-Salman Depression, KH-4 at Takhadid, KH-5 at Salhobiya village, KH-6 at Al-Ansab, KH-7 at Abu Radham, KH-8 at Shaib Al-Ghanimi and Ab-1 at Abou Allum

In some of these boreholes, the drilling penetrated the whole sequence whereas in others it was only partially penetrated. A total of 4707 m of core were described and about 4000 samples were collected (at a regular one meter interval or at change of lithology). A preliminary study was carried out on the collected samples at the laboratories of the Petrology, Paleontology and Geochemistry Labs of Iraq Geological Survey and presented as internal reports. Finally the work was compiled, discussed and interpreted in final reports (Tamar-Agha, 1983 and 1984).

A summary of the knowledge then about Iraq's stratigraphy including the southern region was compiled (Bellen *et al*., 1959; Al-Naqib, 1967) (Fig.3) and a series of isopach maps for the various formations from the Yamama to the Fatha (previously named Lower Fars) Formations were constructed by Al-Siddiki (1978). Subsequent to this work, the amount of works on the area increased during the mid-seventies to the early eighties of the last Century by Iraq Geological Survey (Al-Hadithi and Al-Mehaidi, 1982; Al-Mubarak and Ameen, 1983; Al-Ani and Ma'ala, 1983a and b; Al-Sharbati and Ma'ala, 1983a and b), as they produced maps (scale 1: 100 000) accompanied with unpublished reports.

The aim of this study is to investigate the facies and deduce the depositional environments of the Paleocene – early Eocene sequence. In addition to study the diagenesis, as the sequence suffered a high degree of diagenetic modification.

GEOLOGICAL SETTING

The study area represents part of the Southern Desert Subzone of the Arabian Inner Platform of the northern part of the Arabian Plate (Fouad, 2014). It has suffered remarkably little deformation. The structural elements are almost limited to very gently-lying sedimentary strata mostly of carbonates, mudrock and evaporite successions. The strata are gently inclined towards the Mesopotamian Alluvial Plain.

Some of the folds can be attributed to tectonic activities whereas most of them are expected to be secondary structures. They are solution collapse structures which might have been initiated by tectonic features, such as faults. The strata were then bent by flexuring and subsequent differential settlement and readjustment (Al-Hadithi and Al-Mehaidi, 1982).

The studied succession is equivalent to the lower part of Tectonostratigraphic Megasequence AP10 (TMS AP10) (Sharland *et al*., 2001; Jassim and Buday, 2006) incorporating the Umm Er Radhuma (Paleocene), Rus (Lower Eocene) and Jil (Lower Eocene) formations (Fig.2). Tamar-Agha and Al-Sagri (2015) gave the geological setting of this sequence.

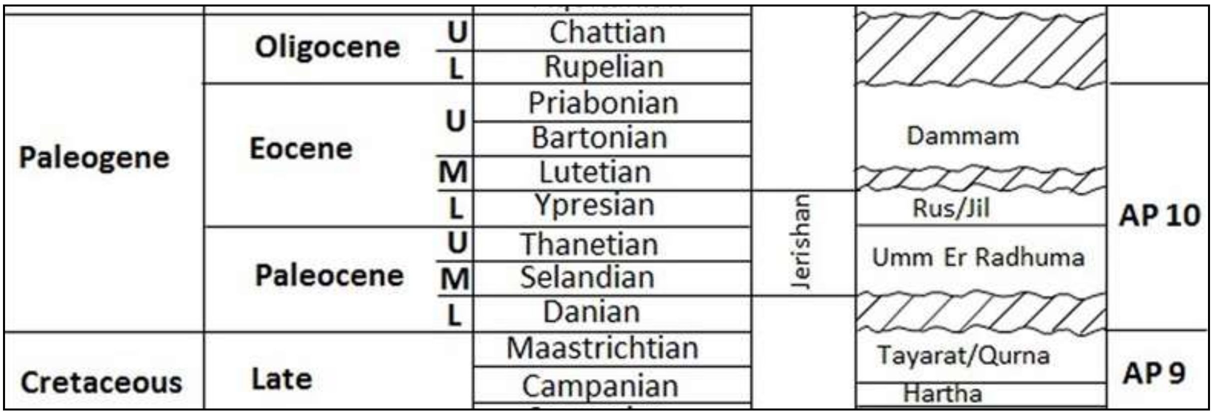

Fig.2: Stratigraphic column of the studied sequence

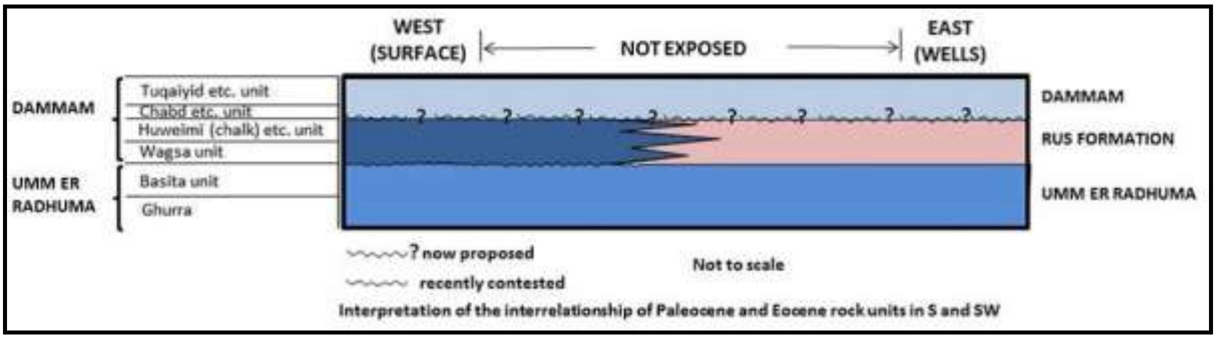

Fig.3: Bellen's proposal for the Paleocene – Eocene stratigraphy in the Southern Desert of Iraq (redrawn from Bellen *et al*., 1959)

MATERIALS AND METHODS

Ten of the boreholes drilled for the hydrogeology of the Southern Desert of Iraq project have partly penetrated the Paleocene-early Eocene sequence, namely KH-1 at Shbecha, KH-2 at Rijm Al-Thaydi, KH-2′ at Umm Al-HAshim, KH-3 at Al-Salman Depression, KH-4 at Takhadid, KH-5 at Salhobiya village, KH-6 at Al-Ansab, KH-7 at Abu Radham, KH-8 at Shaib Al-Ghanimi and Ab-1 at Abou Allum. The cores were described and sampled (about 2100 samples) at one meter interval or at change of lithology. The samples were examined and analysed at the Petrology, Paleontology and Geochemistry labs of Iraq Geological Survey. For petrographic studies all samples were thin sectioned and stained with Alizarin red S.

LITHOFACIES

Lithology of the three formations, as appeared in the studied boreholes, is essentially the same having distinct characteristics of a carbonate-evaporite system with subordinate terrigenous input i.e. dolomite (clayey on occasions) and subordinate dolomitic marl; with evaporite nodules and/or bedded nodular evaporites. The sequence is mostly fossil barren, with rare occurrence of gastropods, bivalves, ostracods, algae and some foraminifera. Thickness of the evaporite beds ranges from a fraction of a meter in the Umm Er Radhuma Formation (in general) to about ten meters in the Thaydi Beds. The thick beds are especially found in the Thaydi, Abu Radham and Salhobiya Beds (Fig.4), and the Rus Formation (Tamar-Agha and Al-Sagri, 2015). They all show rhythmic nature, i.e. asymmetric alternation of different lithologies. The most ubiquitous difference lies in the variation of beds thickness and clustering of the evaporite nodules. The three evaporite beds differ from the rest of the Umm Er Radhuma Formation by, first having thick evaporite beds and relatively thin carbonates, and second in having the evaporite clusters within relatively short intervals of depth. In the studied area (apart from Kh-3 in Al-Salman Depression), the Umm Er Radhuma Formation forms a rhythmic alternations. The complete rhythm is formed of the following attributes: pale grey, dolomitic marl (bottom); pale grey, fossiliferous, clayey dolomite; pale grey, terrigenous carbonate with gypsum nodules; evaporite bed (top). These rhythms are rarely complete.

In the petrographic study during this work Dunham's classification (1962) is adopted, though on few occasions reference is made to Folk's terminology (1959). Two main components are recognized throughout the studied sections: grains of various sizes and abundance, embedded in lime-mud matrix. The grains are both skeletal and non-skeletal. The skeletal are rare occurrence of a number of invertebrate fossils such as pelecypods, gastropods and some microfossils such as nummulites, operculina, miliolids, ostracods, a1gae, etc. The classification of the rock samples into microfacies was attempted but occasionally it was hindered by destruction by diagenesis. Instead, the rock samples were grouped into Crystalline Carbonates which are considered as a function of diagenesis rather than depositional environment and thus not included as lithofacies. The use of terminology and interpretations relied on several sources (Folk, 1959; Dunham, 1962; Tucker and Wright (1990); Scholle and Ulmer-Scholle (2003); Boggs (2009); Nichols (2009); Flügel, 2010 and many others).

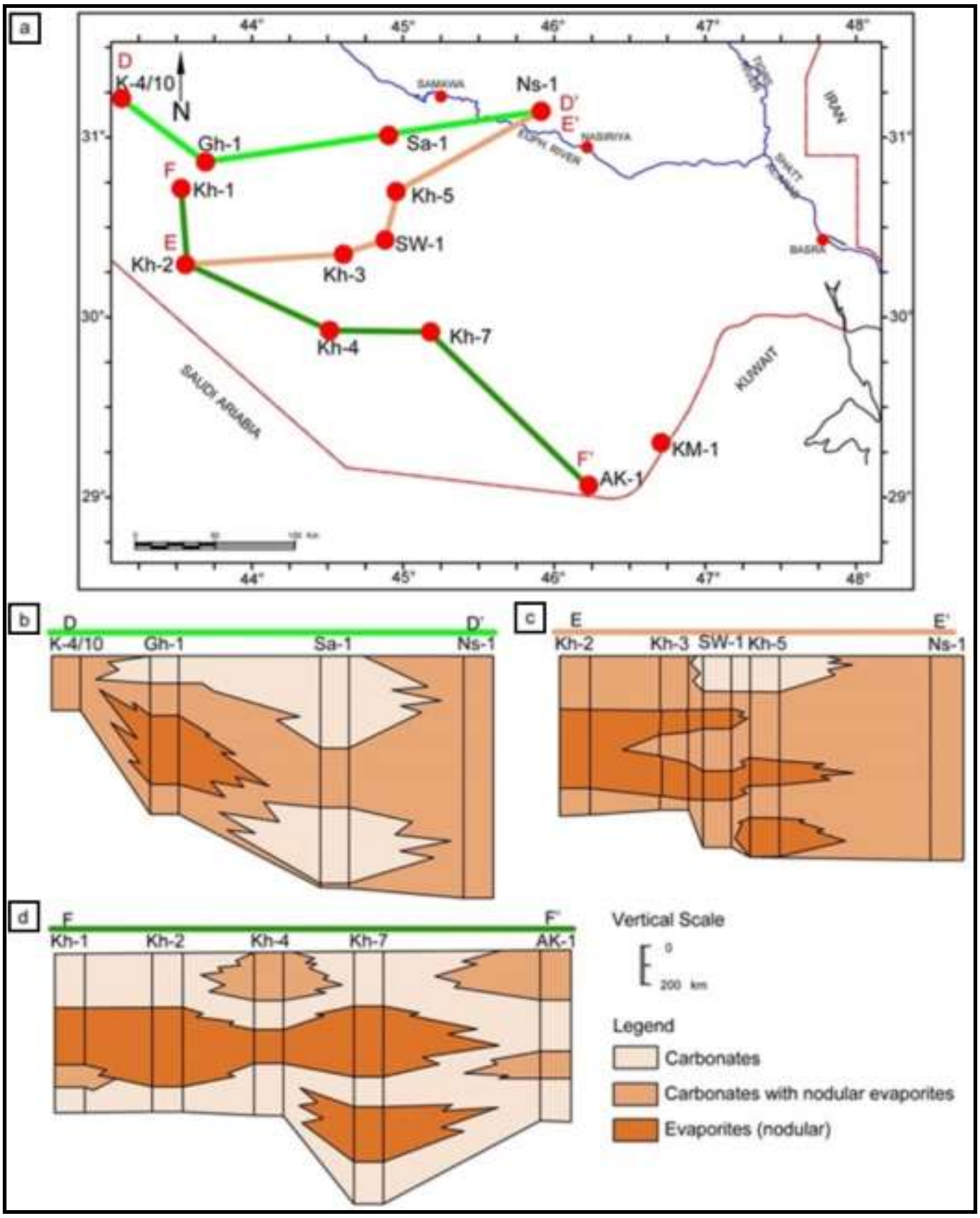

Fig.4: **a)** Map showing the section lines along which the internal stratigraphic entities of the Umm Er Radhuma Formation are correlated, **b)** Correlation along section line D-D′, **c)** Correlation along section line E-E’, **d)** Correlation along section line F-F′ (from Tamar-Agha and Al-Sagri, 2015)

Core and petrographic studies led to identifying six lithofacies extending from shore towards the basin, these lithofacies are: **1)** Evaporites Lithofacies; **2)** Laminated Dolomite Lithofacies; **3)** Non-laminated Dolomite Lithofacies; **4)** Sucrose Dolomite Lithofacies and **5)** Massive Fossiliferous Dolomite Lithofacies and **6)** Phosphatic arenite lithofacies. These lithofacies are described below:

- **Evaporites Lithofacies**

Evaporites Lithofacies is characterized by white to pale grey, primary (depositional) evaporite beds exhibiting chicken-wire (nodular) and less frequently massive (Figs.5a, b, c and d). Sulphate beds and nodules are found embedded in dolomitized lime mudstone matrix, clayey at times. The massive evaporites are structure-free mass of pure evaporite. It is less common in the Jerishan Group sediments, present mainly in Abu Radham Beds, Thaydi Member and Rus Formation. The thickness of the evaporite beds ranges from 1 to 15 meters. They are usually grouped in the evaporite units of the Jerishan Group. This facies is one of the salient facies in the studied Paleocene – early Eocene sequence.

The name of this lithofacies indicates the presence of sulphate minerals, such as gypsum and anhydrite with some minor occurrences of celestite, as the basic components. The sulphate minerals are found clustered or disseminated in the dolomite matrix. They are found in the form of nodules micro-concretions as laminae, beds, veinlets, rosettes, laths and cavity filling (Fig.5). The sedimentary structures found associated with this facies are enterolithic folding, chicken-wire texture, rosettes, wispy, massive and occasionally laminated. The basic unit which forms the bulk of the sulphate rock is the nodule. The size of the nodules ranges from a fraction of a centimeter to a decimeter in diameter. The nodules are spheroid, ovate or irregular. The gypsum in the nodules is formed of very fine acicular fibres, occasionally clustered in irregular patches. They are also found as granular, interlocked, fine and anhedral crystals of gypsum with disseminated inclusion of anhydrite and/or carbonates. The size of the gypsum crystals ranges from 0.15 to 1.5 mm. The anhydrite is granular or bladed interlocked crystals, their size ranges from 0.02 to 1.6 mm. The original texture was most probably destroyed by hydration-dehydration processes. These alteration processes are quite frequent and pertinent character of such rocks. The nodules are found as solitary individuals 'floating' in a dolomitic marl or clayey dolomite. The outlines of these nodules under the microscope are never sharp but gradual. In his studies on KH-7 at Abu Radham, Basi (1983) found some fossils in the groundmass. Subangular to angular intraclasts are not uncommon in association with the carbonate matrix.

The nodules cluster in all degrees of packing until a stage reaches whereby the nodules boundary become vague. At some stages the nodules are partially united leaving only thin carbonate and/ or argillaceous filament surrounding the evaporite nodules. This arrangement gives rise to wispy and chicken-wire texture. Usually such cases are found in the upper part of the thick evaporite beds.

Massive gypsum beds are developed by the total replacement of the host sediments. This description is meant to the imparity in the genesis of the massive evaporite and the other nodular forms. Most of the laminated gypsum is formed of nodules which are united laterally. The presence of satin spar veins in between the nodular layer enhances the appearance of the laminated form. Accordingly the role of the nodular form is stressed here to be the basis of almost all kinds of bed forms and internal evaporite structure.

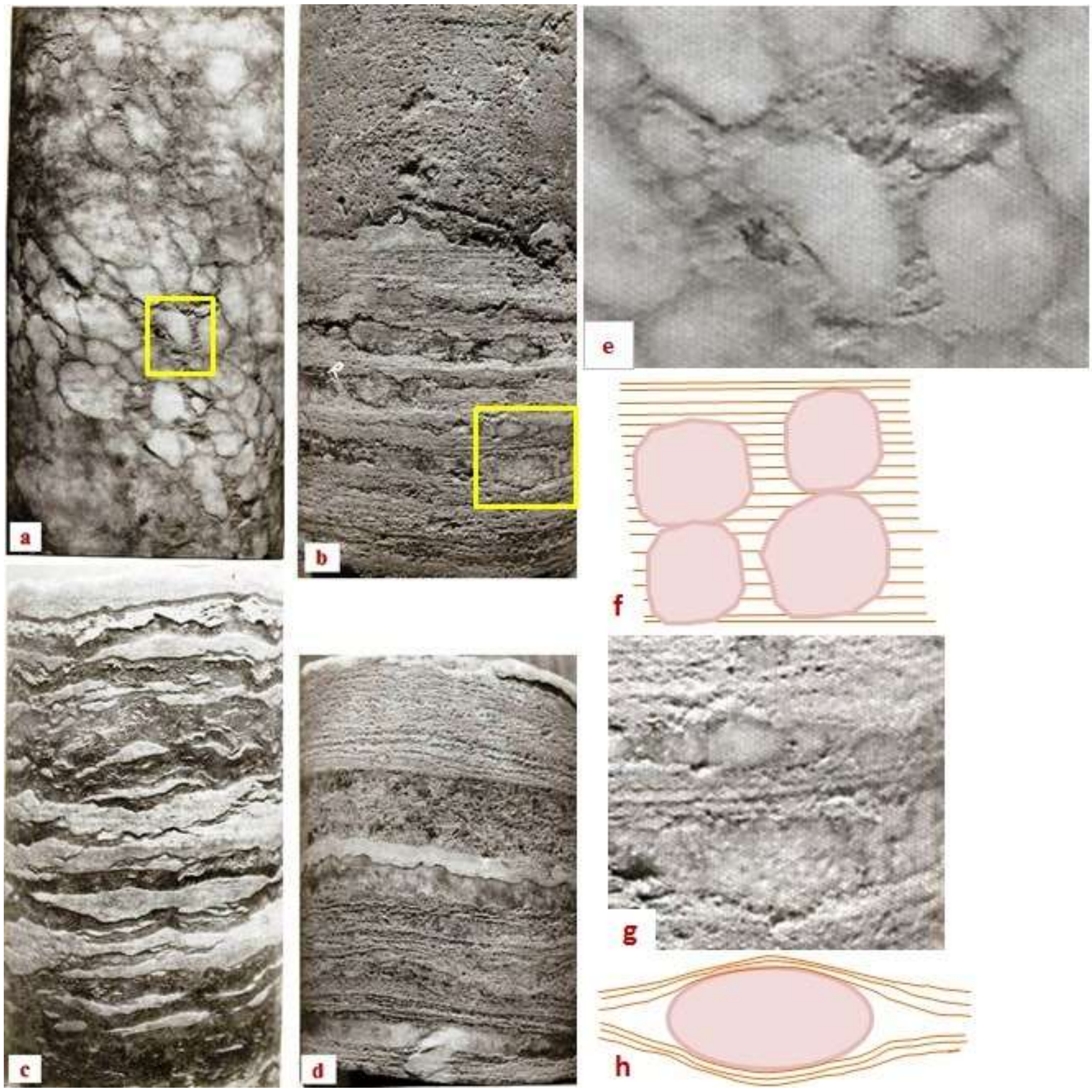

Fig.5: Core samples of Sulphate-rocks Lithofacies, Umm Er Radhuma Formation, KH-6 at Ansab area. Diameter of the cores is 11 cm. **a)** Chicken-wire texture, drilling depth 217.2 m. **b)** Alternating laminated biomoldic carbonate mudstone and nodular sulphate-beds, though some are solitary, drilling depth 270.0 m. **c)** Laminated gypsum and carbonates. The gypsum lamina are made of coalesced nodules, drilling depth 260.4 m. **d)** Laminated anhydrite (dark) and gypsum (light), drilling depth 262.3 m **e)** Enlarged view from a) showing replacive nature of evaporite nodules. **f)** Sketch showing replacive nature of evaporite nodules. The carbonate mudstone laminae truncate against the nodules. **g)** Enlarged view from b) showing displacive nature of evaporite nodules. **h)** Sketch showing displacive nature of evaporite nodules. The carbonate mudstone laminae circumscribe the nodules

Interpretation: The chicken-wire texture indicates marine-marginal and/ or supratidal sabkha deposits. The massive evaporites indicate shallow, subaqueous marine deposits (Schreiber *et al*., 1987; Kendall, 1997; Warren, 2016). The tidal flat-associated evaporites beds may form in hypersaline ponds on the tidal flat surface.

The variation within this lithofacies suggests different depositional subenvironments within a tidal flat system to shallow marine environment. For example, the burrow mottled dolomitized lime mudstone suggests a lower intertidal environment, where burrowing animals obliterated original laminations, leaving a churned sedimentary structure (Fig.6). The fine-scale laminated dolomitized lime mudstone represents microbial mats of an intertidal environment, where the original fabric has been preserved. The presence of the fenestrae also supports a tidal flat environment interpretation (Grover and Read, 1978).

- **Laminated Dolomite Lithofacies**

Laminated Dolomite Lithofacies is frequent in the Paleocene – early Eocene (Jerishan Group). It is basically fine-scale laminated, grey to pale brown, dolomitized lime mudstones, which have suffered intensive early diagenetic alterations, such as dolomitization, growth of evaporites and leaching. The original framework is slightly destroyed by diagenesis, yet still can be recognized (Figs.7a, b and c). Three distinct sedimentary structures are fenestral fabrics, burrow mottling and fine-scale microbial laminations (Figs.6a and b). The porosity ranges from 2 – 15 % and the pores are mostly microvugs, mesovugs, mesomolds and microintercrystals.

Interpretation: Laminated Dolomite Lithofacies show features that are typical of tidal flat system, such as the burrow mottled dolomitized lime mudstone which indicate lower intertidal environment (Al-Qahtani, 2019), where burrowing animals disrupted the original laminations (Fig.5 and 6). The fine-scale laminated dolomitized lime mudstone represents microbial mats of an intertidal environment (Tucker and Wright, 1990; Flügel, 2010). Fenestral fabrics represent a tidal flat environment (Grover and Read, 1978; Tucker and Wright, 1990; Flügel, 2010). Bioturbations in the form of vertical tubes such as skolithos supports the tidal flat system (Al-Qahtani, 2019).

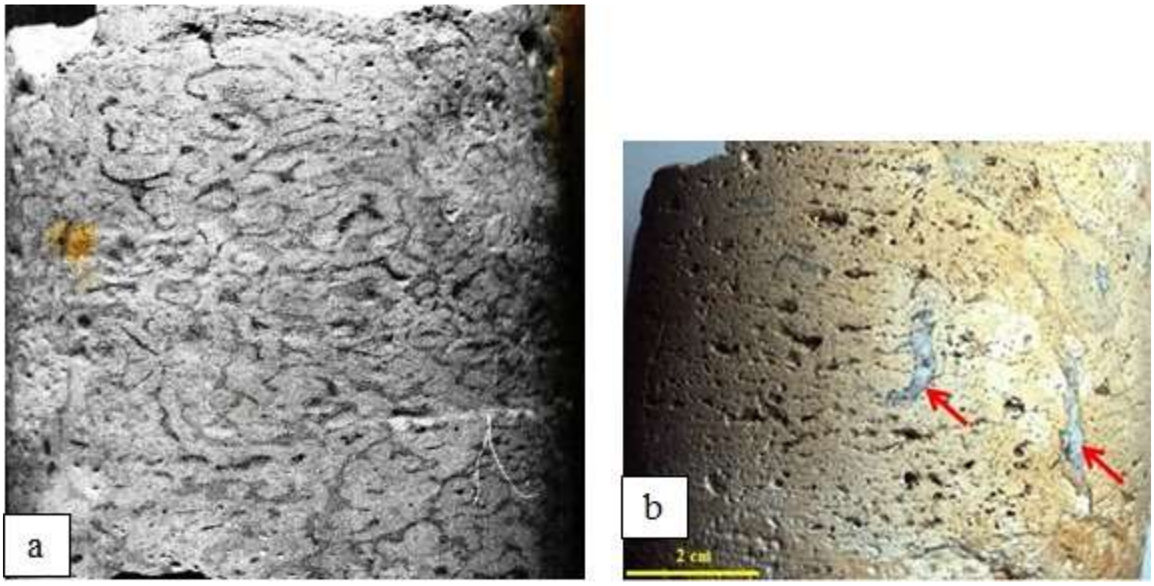

Fig.6: Core samples of **(a)** burrow mottling from KH-6 at Ansab – drilling depth 110 m, and **(b)** Fenestral fabrics with early diagenetic gypsum filling bioturbations (↑) i.e. skolithos tubes and fenestrae, from KH-6 at Ansab – drilling depth 123.5 m. Width of core is 11 cm

- **Non-laminated Dolomite Lithofacies**

Non-laminated Dolomite Lithofacies is grey to pale brown, massive (i.e. almost devoid of sedimentary structures) dolomitized lime mudstone with occasional solitary evaporite nodules and rare laminations. This lithofacies is the most common throughout the sequence and is usually associated with the Laminated Dolomite Lithofacies and the Organodetrital Dolomitic Limestone and Dolomite Lithofacies. In thin sections, this lithofacies corresponds to two microfacies namely, Non-laminated Dolomitized Lime Mudstone. Microfacies. It is mostly fossil barren with the rare occurrence of foraminifers (such as miliolids, textularids), gastropods, bivalves, ostracods, and algae at some levels. The grains look "floating" in the matrix. The abundance of the skeletal grains is variable ranging from about 1 – 30 %. The size of the various taxa present in this dolomite is variable too, depending on the fossils themselves. They range from 30 microns to one centimeter. The matrix is mostly dolomitized lime with mosaic texture. Phosphatic fragments are common but in minor amount distributed throughout the sequence but usually clustered at the top of the Umm Er Radhuma Formation.

Interpretation: The burrowed, largely fossil barren, massive dolomitized lime mudstone is interpreted as a deposit of low energy, restricted lagoon behind a shoal complex (Read, 1985; Al-Qahtani, 2019). The near absence of fossils, and the presence of rare biota such as miliolids, textularids, ostracods, gastropods and algae, in conjunction with the granularity (finely crystalline) and the presence of peloids indicate that the deposition took place in quiet subtropical to warm, low-energy restricted lagoons, with relatively high salinity condition (Braiser, 1980; Haq and Boersma, 1980; Flügel, 2010). The deposition of evaporites within this lagoon lithofacies indicates an arid climate and an episodic hypersaline lagoon setting (Wilson and Jordan, 1983; Al-Qahtani, 2019).

- **Crystalline Dolomite with Evaporite Nodules Lithofacies**

This lithofacies is characterized by massive, brown, fossil barren and crystalline dolomite. It is mostly associated with clustered evaporite nodules. It occurs at more than one level and associated with Evaporite and Non-laminated Dolomite Lithofacies. In thin section, this lithofacies exhibits euhedral and anhedral, fine to coarsely crystalline dolomite (Fig.7). Despite that no fossils are recorded in this lithofacies, limited biomolds and ghosts of fossils are recorded (Fig.7).

Interpretation: Similar facies to the Crystalline Dolomite Lithofacies with evaporite nodules is interpreted to have formed within a shallow subtidal setting associated with arid sabkha sequences (Moore and Wade, 2013; Al-Qahtani, 2019). The dolomite fabric destroyed the precursor lime mudstone whether dolomitized or not.

- **Fossiliferous Dolomitic Limestone and Dolomite Lithofacies**

Moderate numbers of the studied carbonate samples in the Paleocene – early Eocene (Jerishan Group) belong to this class. It is basically massive, pale grey or brown carbonate mudstones which have occasionally suffered intensive diagenetic alterations, such as dolomitization and leaching. In thin sections, the original framework is slightly destroyed by diagenesis and thus can be recognized (Figs.7a, b and c). The allochems are mostly skeletal grains and subordinate peloids of different sizes and types look "floating" in the matrix. The abundance of the skeletal grains is variable ranging from about 1 – 30 %. The size of the various taxa present in these dolomites is variable too, depending on the fossils themselves. They range from 30 microns to one centimeter. The fossils identified in this microfacies are foraminifers (such as operculina, miliolids, textularids, etc.), some gastropods, pelecypods, ostracods, algae, etc. The matrix is mostly dolomitized lime with mosaic texture. Phosphatic fragments are common but in minor amount distributed throughout the sequence but usually clustered at the top of the Umm Er Radhuma Formation. As microfacies this lithofacies can be referred to as Dolomitized Wackestone and Mud-dominated Packstone microfacies. The porosity ranges from 2 – 15 % and the pores are mostly microvugs, mesovugs, mesomolds and microintercrystals.

Interpretation: This Wackestone and Mud-dominated Packstone lithofacies is interpreted as low- to moderate-energy shoal flank deposits downdip from the high-energy shoal crest on both flanking regions: lagoon-ward and seaward (Rankey *et al*., 2006; Flügel 2010).

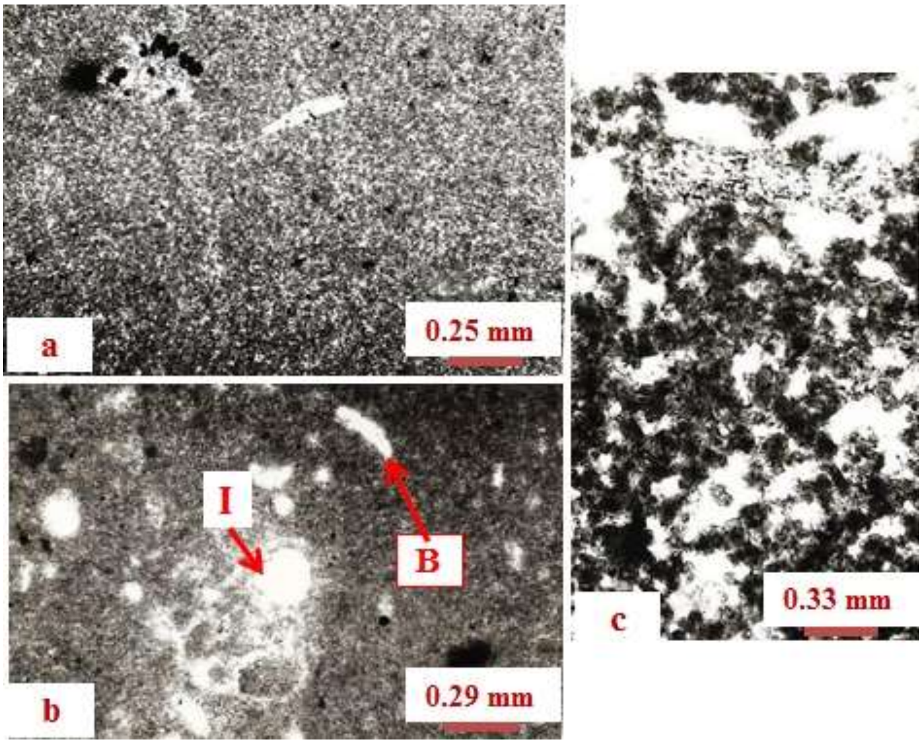

Fig.7: Photomicrographs of Dolomitized lime mudstone-wackestone microfacies: **a)** From Umm Er Radhuma Formation, KH-3 at Al-Salman depression, Plane polarized light. **b)** From the Jil Formation, Ab-3 at Abou Allum. Note both intraparticle porosity (I) and biomolds (B), Plane polarized light. **c)** From the Jil Formation, KH-3 at Al-Salman Depression. The original texture is devastated, porosity is noticeably high. Dark areas are mixture of organic matter and the matrix (Plane polarized light)

- **Phosphatic Arenite Lithofacies**

This lithofacies is restricted in its occurrence to one or two levels near and at the top of the Paleocene Umm Er Radhuma Formation. The uppermost level is taken as the contact with the Jil Formation. This layer is absent in the areas where the Rus Formation overlie the Umm Er Radhuma Formation. The phosphatic grains are polygenetic and are mostly rounded to sub-rounded such as coprolites, bone remains and fish teeth and are mixed with detrital quartz and clays in carbonate groundmass. The grains seem to have suffered little abrasion and make good marker horizons. In Great Britain, such sediments are almost invariably associated with local erosion and non-sequence (Greensmith, 1978, P.209). These beds usual1y formed by washed out material of nodular phosphate bed or by the erosion of bedded phosphorites. It is believed here that they are a kind of reworking and concentration of the intraformational clasts.

Geochemical analysis showed that the P_2O_5 in the Phosphatic Arenite Licrofacies ranges from 1 to 4% and the insoluble residues ranges from 5 to 20% (Tamar-Agha, 1983). By contrast, further north of this basin, in juxtaposition, lays the Akashat basin where the Paleocene sequence embraces the thickest and richest phosphorite deposits in Iraq (Jassim *et al*., 1984).

DEPOSITIONAL ENVIRONMENTS

The faunal assemblage recognized in the studied sequence at some levels such as alveolinids, nmmulites, operculina, mi1iolids, textularids (*Gaudryna* sp. and *Textularia* sp.), shell fragments, algae and ostracods indicate lagoonal environment. Alveolinids, nummulites and operculina indicate deposition in shoal back-shoal environments whereas mi1iolids and textularids indicate hypersaline shallow-water conditions (Haq and Boersma, 1980, Braiser, 1980, Gooday, 2001 and Flügel, 2010). Such conditions resemble the present day situation of the Arabian Gulf. The presence of blue green algae indicates that the depth of the lagoon in the Paleocene Period not exceeding 30 m (Flügel, 2010). The lagoon was temporarily influenced by open marine conditions. This conclusion is achieved by the presence of planktonic fauna in some parts of the Umm Er Radhuma Formation. Such planktonic fauna are *Globorotalia unicata* BOLLI and *Globorotalia pseudobullcides* (PLUMMER). These planktons are indicative of tropical-subtropical open marine conditions (Petrizzo, 2005).

Lithofacies and lithofacies associations of the Umm Er Radhuma Formation (Paleocene) are sabkha/ saline evaporite, tidal flat, lagoon, shallow subtidal, shoal flank and open marine influence is encountered at some levels. The lithofacies associations and succession resemble the older Khuff (Permian-Triassic) Formation which was interpreted by Al-Qahtani (2019) to represent “arid, homoclinal ramp within an extensive tectonically-stable low-relief epeiric sea” (Fig.8b).

By contrast, the early Eocene time (i.e. Rus/Jil Formations) shows shoaling upwards succession which represents rimmed carbonate platforms. It indicates deposition in a semi-barred restricted marine platform lagoon with the dominance of supersaline conditions (during the deposition of Lithofacies 6) (Fig.8a). The presence of *Quinqueloculina* sp., *Spirolina* sp., *Triloculina* sp., pelecypods and gastropods indicate deposition in lagoonal subtropical environment with a depth about 0 – 20 meters. The bar which acted as a barrier between the main sea and the lagoon is most probably a nummulitic shoal. The lower part of the Jil Formation is of nummulitic facies. Towards the top of Umm Er Radhuma Formation and in the Jil Formation shelf mud-sabkha cycles are recognized. Each cycle commences with a shoal which changes upwards to a quiet restricted marine or lagoonal environment (subtidal). This is followed by the development of intertidal and supratidal sabkha. Evidence of intertidal to supratidal setting is indicated by some sedimentary structures such as fenestral fabrics (Fig.6). The evaporitic phase is terminated by a return to intertidal – subtidal phase.

Salinity of the water fluctuated during the Paleocene and varied from normal marine quiet condition to supersaline. The normal marine, quiet condition is indicated by: diversity of fauna, presence of planktonic fauna at some levels and high ratio of carbonate mud. These conditions were changed to hypersaline and supersaline conditions in a semi-barred basin. The latter is indicated by thick evaporite beds encountered in this sequence. A short period of basin desiccation and break in the sedimentation is registered in the late Paleocene represented by the phosphatic gravely bed discussed earlier in the text. The break is believed to be relatively short.

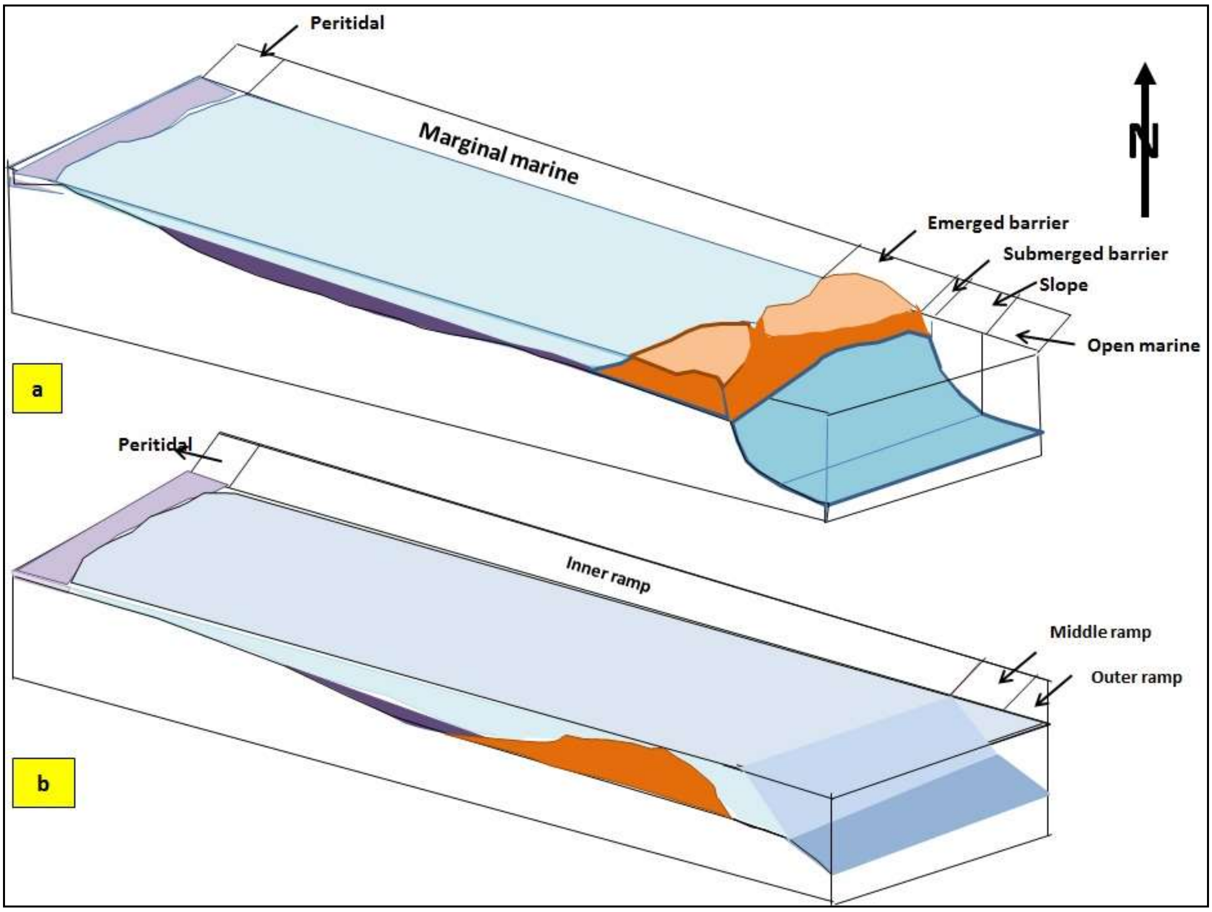

Fig.8: Schematic depositional model for the Jerishan Group deposits. **a)** Ramp depositional model with submerged barrier of the Umm Er Radhuma carbonates – evaporites and **b)** Rimmed carbonate platform model of the Jil-Rus carbonate – evaporite Formations

During the Paleocene – early Eocene the area is characterized by evaporite deposition. Evaporites are early diagenetic, formed at almost syngeneic precipitation from concentrated brines, i.e. almost penecontemporaneous to deposition, by replacement and displacement. The replacement is much more common (Fig.5). The concentration necessary for sulphate precipitation is generally achieved from the evaporation: at the air – water interface, brine freezing, subsurface processes such as ion-filtration of residual connate fluids (Schreiber, 1978; Kendall, 1997; Warren, 2016). They summarized the physical environment of evaporite deposition, the main facies present and divided the evaporites into continental, coastal sabkha and subaqueous marine. In the continental evaporite, deposition is expected to be in subaerial and lacustrine environment. In coastal sabkha, it is expected that deposition took place in the vadose and the shallow phreatic zones of the groundwater. In the subaqueous marine system evaporite can form in shallow or deep marine conditions.

The evaporite in the Paleocene – early Eocene is nodular. Even massive evaporite beds are nodular and the nodules have coalesced during the diagenetic history, recrystallized, dehydrated and hydrated. Nodules of gypsum and anhydrite are known from coastal sabkha such as the Trucial Coast of Abu Dhabi (Shearman, 1978) mud flats of lagoons and shallow marine environment (Kerr and Thompson, 1963) such as Lagoona Madre in the U.S.A. and inland sabkha, i.e. playa (Glennie, 1970).

The possibility that deposition took place in inland (continental) sabkha is excluded here owing to lack of any evidence of continental deposition. We are left with coastal sabkha (or mud flats of coastal lagoons) and subaqueous marine. Shearman (1978) concluded from his study on the Trucial Coast of Abu Dhabi that the presence of five features together with their characteristic fabrics, textures and dimensions in a cored profile of an ancient sediment that indicates its possible origin in a sabkha environment. It is believed here, that the evaporites are formed in coastal flats and semi-barred lagoon. Possibly the evaporite nodules grew under the sediment/ water interface in the lagoon. The sulphate could have grown by mixing of waters of different salinities.

The evaporitic basin seems to have shifted its geographic position with time (Fig.4). During early Paleocene (i.e. during the deposition of the Abu Radham Beds) the evaporite beds are located in a narrow strip running in a northwest-southeast direction. Present studies did not allow the detection of the barrier, neither its location nor its nature. During the deposition of the Thaydi Member (possibly mid to early Paleocene) the evaporite basin became wider and covered a quite large area. The evaporites are concentrated in a similar trend to the older unit but covered further areas of the western side. The nature and the location of the barrier are ambiguous too.

DIAGENESIS

Petrographic studies showed that the dominant minerals in these rocks are dolomite and gypsum with clay admixtures. Calcite, anhydrite and quartz are subsidiary. The calcite is present most probably as a secondary mineral i.e. as a product of dedolomitization and vanished evaporites (Figs. 9 and 10).

The original sediments were deposited, in general as aragonitic mud and skeletal grains, whose tests and shells were mostly aragonitic too with some high- and low-magnesium calcite. Two processes seem dominant during the early stage of diagenesis, namely leaching (dissolution) and dolomitization. Leaching affects aragonite and high-magnesium calcite more than low-magnesium calcite (Tucker and Wright, 1990; Nichols, 2009; Boggs, 2009). The following pattern of physicochemical changes is suggested (Fig.11):

1. During this study most of the samples showed that the entire texture is aphanocrystalline, very fine and fine dolomite with some biomolds. The dolomite crystals are cloudy, anhedral to subhedral and usually are devoid of zoning (xenotopic texture). Such textures are known in primary, penecontemporaneous and early diagenetic dolomite. Primary dolomite i.e. primary precipitation from hypersaline water is excluded because the presence of dolomitized fossils within the formation is sufficient proof that the dolomite is not a primary deposit (Greensmith, 1978; Nichols, 2009; Boggs, 2009). This is deduced because the presence of such diversified fauna in the deposit excludes the hypersaline conditions required for direct dolomite precipitation. The dolomitization is believed to be penecontemporaneous or early diagenetic origin.

The dolomitization in the Paleogene sequence has possibly taken place in the supratidal flats of the arid regions. In such supratidal flats, the sediments are inundated with water intermittently, usually during highest spring and storm tides. During such ephemeral periods the coastal lime mud becomes soaked with normal sea water. Some of the water in the pore spaces is also supplied by percolation of groundwater from the adjacent sea. Continuous evaporation of this water in such warm regions increases the concentration of salts in the surficial pore water and brings them to a critical point whereby calcium sulphate precipitates.

This mechanism can be assigned to some of the dolomite. Other processes are also expected, such as seepage reflux process. The growth of the gypsum nodules in the lagoon also leads to the depletion of Ca^{++} ion from the pore water and thus aids in the dolomitization. The latter process takes place in almost a similar manner like the sabkha model but occurring under the water-sediment interface in the lagoon. The process of dolomitization has rearranged and enlarged the pore spaces allowing further drastic solution and mineralogical changes with an increase in porosity.

2. The skeletal grains such as forams, pelecypods, gastropods, ostracods and algae whose shells are mostly aragonite and calcite were susceptible to leaching. Most of these constituents were leached leaving moulds behind. This process increases the porosity. The leaching was selective because some of the skeletal grains were partially or entirely dolomitized.
3. In the diagenetic history, selective filling of some pore spaces by direct precipitation of gypsum seems to follow the abovementioned processes. The available pores originated during the depositional process, leaching and possibly during the penecontemporaneous dolomitization. This gypsum filling has undoubtedly caused a decrease in the pore spaces.
4. The gypsum and anhydrite are susceptible to dissolution at later times. So selective leaching of gypsum was recorded in some samples. This is clearly demonstrated by moulds of gypsum crystals, In general this process led to increase in porosity.
5. Silicification followed the abovementioned processes. Silica is found in the form of fibrous chalcedony or as facetted quartz crystals occasionally bipyramidal. The fibrous chalcedonic silica seems to replace the original gypsum gradually forming gypsum pseudomorphs. However, the euhedral and subhedral quartz shows syntaxial lines which probably means that silicification occurred in stages. The silicification indicates a change in pH of the intrastratal solution. They are believed to become acidic.

Silica replacement of former evaporites seems to be associated with meteoric water activity (Knauth and Epstein, 1976 and Geeslin and Chafetz, 1982). Nonetheless, in the Paleogene deposits the model of silica replacement differs from Knauth and Epstein (1976) and Geeslin and Chafetz (1982) that the silicification took place before deep-burial. Silica replacement is present and interrelated to the present level of groundwater (i.e. in the vadose zone), it is therefore believed that silica replacement is related to the activity of meteoric water (Fig.12) but it took place at epigenesis (i.e. late diagenetic stage).

6. Some of the studied sediments show another variety of dolomite crystals. They are coarser crystals (0.06 – 0.25 mm), zoned, showing equigranu1ar rhombic texture. Relics of the obliterated skeletal grains can still be observed. This leads to the conclusion that replacement affected the remaining primary calcite which is not affected by first stage dolomitization. Simultaneously the early formed dolomite crystals were enlarged by size to form the late diagenetic mosaic. It was difficult to ascertain whether the second stage dolomitization has followed the first stage immediately or it took place at much later time. This process has left the rocks formed almost entirely of dolomite and some silica or gypsum filling pores.

According to Bathurst (1975) the late diagenetic dolomitization is produced by the migration of deep subsurface water (intrastratal solution) containing dissolved ions. The concentration of Mg/Ca needed in the percolating solution is near to 1:1 leading to the crystallization of dolomite from dilute solutions.

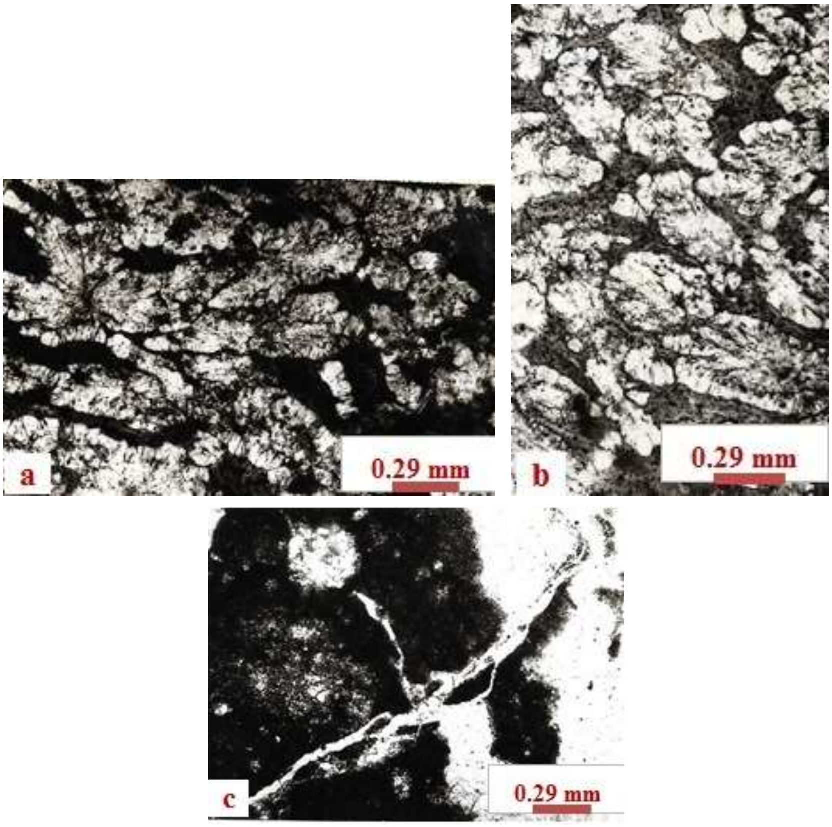

Fig.9: Photomicrographs of crystalline limestone (vanished evaporite). Light areas are calcite whereas dark areas are clayey carbonate mud **a)** Elongated calcite veins, which are probably calcitized satin spar veins, from the Jil Formation, Ab-3, at Abou Allum area. Plane polarized light. **b)** Calcite rosettes that replaced gypsum mineral, from the Umm Er Radhuma Formation, KH-3 at Al-Salman Depression. Plane polarized light. **c and d)** Radiating calcite crystals “Calcite suns” indicative of vanished evaporite, Jil Formation, Ab-3 at Abou Allum area, Plane polarized light

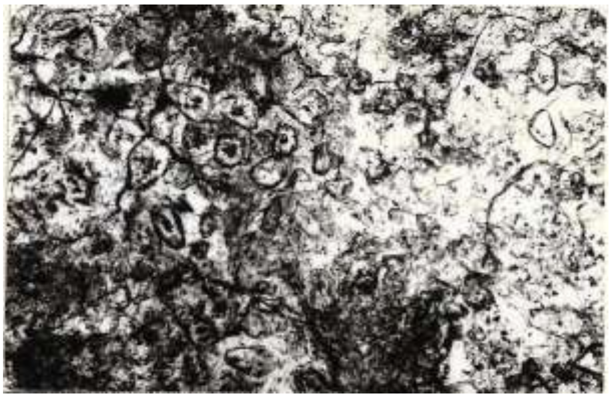

Fig.10: Photomicrograph of the dedolomitized rock from the Jil Formation, Ab-3, at Abou Allum area, Large calcite crystals show poikilotopic texture with dolomite as inclusion or as ghosts of the original dolomite crystals outline. Dolomite rhombs are partially replaced by calcite, especially the outlines. The dark centres of the crystals are usually remained unaltered. Plane polarized light. The dark areas represent clayey lime-mud

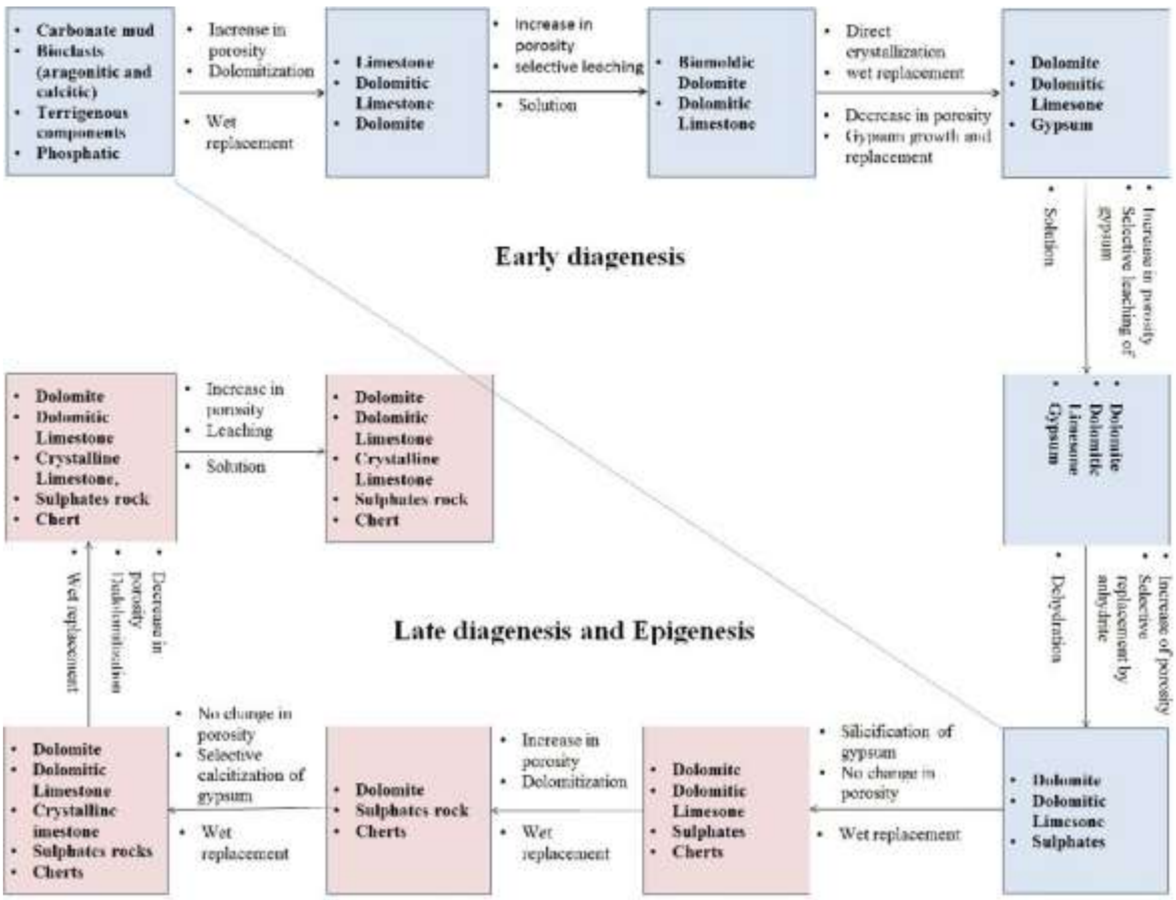

Fig.11: Flow chart showing the paragenesis in the Jerishan Group sediments (Paleocene – early Eocene)

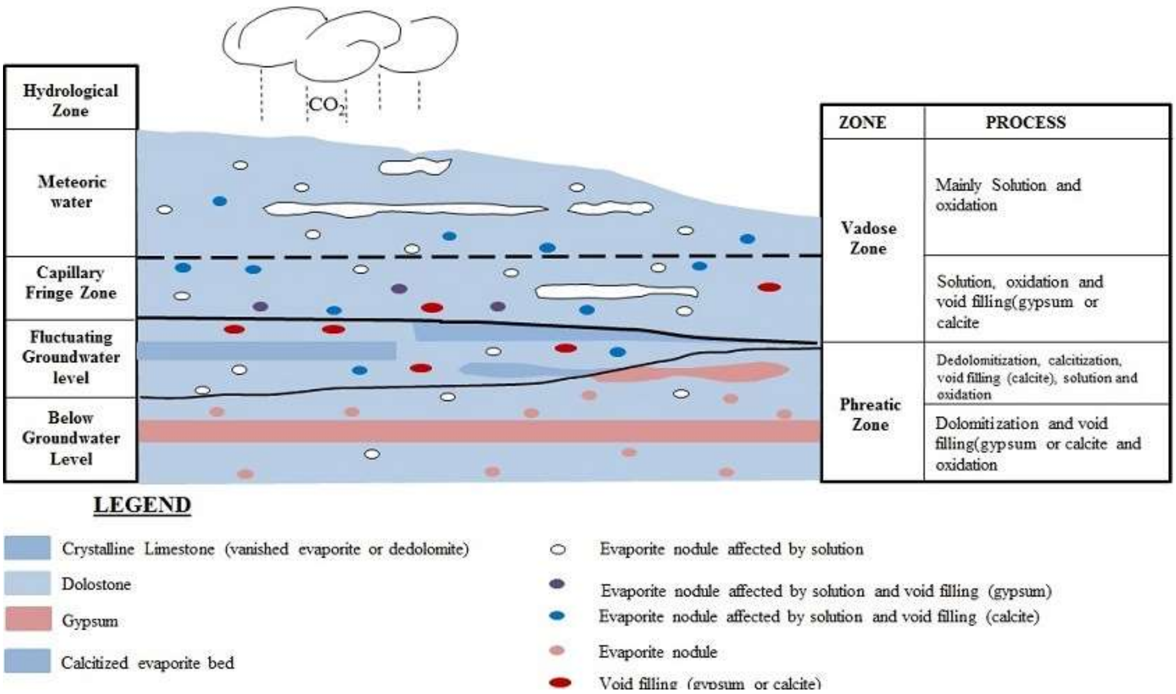

Fig.12: Schematic diagram showing epigenesis and groundwater relationship (not to scale)

7. The final episode in the diagenetic history was the calcitization, whereby minerals like dolomite, gypsum and quartz were replaced by medium to coarse crystalline calcite.

   A. One kind of calcitization is that of gypsum replacement by calcite. The calcitization is not restricted to the replacement of odd and scattered crystals of gypsum throughout the carbonate rocks. It is believed that some gypsum beds in borehole Abou Allum 3 were completely transformed to crystalline limestone. The crystalline calcite has maintained the original texture and structure of the beds including the fibrous habit of the satin spars, lozenge shape euhedral crystals, etc. The clay minerals present in the original evaporite beds and surrounding the gypsum nodules were pushed slightly aside, i.e. by displacement. In one case only it was found that aragonite is in radial form forming what is known as "aragonite suns" (Fig.9d). At present the aragonite is changed by neomorphic process to calcite.

   B. Dedolomitization - this is evident in many samples whereby all sizes of dolomite crystals become susceptible to dedolomitization. Dedolomitization is a diagenetical process occurring at shallow burial environments and is often linked with sulphates in mixed carbonate-evaporite successions. Such setting leads to elevation of Ca^{2+}/Mg^{2+} ratios necessary for dedolomitization (Hauck and co-workers *et al*., 2018). The dolomite crystals look "floating" in a medium to coarse calcite crystals or as minor inclusions in them. The water enriched with $CaSO_4$ released by the process of calcitization of gypsum aided in the dedolomitization process. This is used to indicate that calcitization of gypsum has preceded the dedolomitization.

   C. Another form of calcitization is the replacement of silica by calcite. This is evident especially when siliceous grains were left as little floating 'islands' in calcite crystals with a reaction rim. It is almost impossible to recognize those calcite crystals which have entirely replaced the siliceous grains. Such calcite crystals could have simply been formed by pore filling. The replacement of silica by calcite is attributed to the change of pH conditions from acidic to alkaline. During the various processes of calcitization it is expected that some calcite crystals grew in the pore spaces. This has undoubtedly caused some reduction in the porosity.

CONCLUSIONS

The Jerishan Group (Paleocene – early Eocene) is characterized by evaporite-bearing sequence sandwiched between two primary limestone sequences namely, the underlying Tayarat – Shiranish Formations (Campanian – Maastrichtian) and the overlying Dammam Formation (Middle – Upper Eocene). The Tayarat Formation also contains some evaporite nodules but they are of late diagenetic origin.

The Jerishan Group (early Eocene – Paleocene) incorporates the Umm Er Radhuma, Rus and Jil Formations. The sequence comprises grey clayey dolomite, dolomitic marl and nodular or bedded evaporites, and crystalline limestone representing vanished evaporites and dedolomite and was deposited in a carbonate platform. The lithofacies and lithofacies associations of the Umm Er Radhuma Formation (Paleocene) are interpreted as sabkha/ saline evaporite, tidal flat, lagoon, shallow subtidal, shoal flank and open marine influence is encountered at some levels. The deposition took place in arid, homoclinal ramp within an extensive tectonically-stable low-relief epeiric sea. A proper barrier such as shoal to isolate the wide lagoon from the open sea is not noticed. By contrast, lithofacies and lithofacies associations of the carbonate platform of the overlying Rus and Jil Formations (lower Eocene) show a complete shoaling upwards cycle with the following subenvironments: shoal, subtidal, intertidal and supratidal system. The deposition took place in a rimmed carbonate platform with semi-barred lagoon and coastal sabkhas. The barrier is represented by well-developed nummulitic shoals which led to the restriction of the lagoons from the main sea. Some of the evaporites are sabkha cycles and subaqueous shallow marine evaporite. Possibly the evaporite nodules grew under the sediment/ water interface under the lagoon. The sulphate could have grown by mixing of waters of different salinities. The evaporitic basin seems to have shifted its geographic position with time.

Several diagenetic processes affected the sequence, such as neomorphic replacement, dissolution, dolomitization, sulphate development, vanished evaporites and dedolomitization. Some of these processes obliterated the primary textures. Petrographic studies showed that the dominant minerals in these rocks are dolomite and gypsum with clay admixtures. Calcite, anhydrite and quartz are subsidiary. The calcite is present most probably as a secondary mineral i.e. as a product of dedolomitization and vanished evaporites.

Two processes seem dominant during the early stage of diagenesis, namely leaching (dissolution) and dolomitization. Leaching affects aragonite and high-magnesium calcite more than low-magnesium calcite. The following pattern of changes is suggested:

1. The entire texture is aphanocrystalline, very fine and fine dolomite with some biomolds. The dolomite crystals are cloudy, anhedral to subhedral and usually are devoid of zoning (xenotopic texture). Such textures are known in penecontemporaneous and early diagenetic dolomite. The dolomitization in the studied succession took place in the supratidal flats of the arid regions. In such supratidal flats, the sediments are inundated with water intermittently, usually during highest spring and storm tides. During such ephemeral periods the coastal lime mud becomes soaked with normal sea water. Some of the water in the pore spaces is also supplied by percolation of groundwater from the adjacent sea. Continuous evaporation of this water in such warm regions increases the concentration of salts in the surficial pore water and brings them to a critical point whereby calcium sulphate precipitate and thus rise the Mg/Ca ratio and leads to dolomitization.
2. Selective filling of some pore spaces by direct precipitation of gypsum seems to follow the abovementioned processes. The available pores originated during the depositional process, leaching and possibly during the penecontemporaneous dolomitization.
3. The gypsum and anhydrite are susceptible to dissolution at later times. So selective leaching of gypsum was recorded in some samples. This is clearly demonstrated by moulds of gypsum crystals.
4. Silicification then followed and silica is in the form of fibrous chalcedony or as facetted quartz crystals occasionally bipyramidal. Silica replacement is present and interrelated to the present level of groundwater (i.e. in the vadose zone), it is therefore believed that silica replacement is related to the activity of meteoric water but it took place at epigenesis (i.e. late diagenetical stage).
5. The final episode in the diagenetical history was the calcitization, whereby minerals like dolomite, gypsum and quartz were replaced by medium to coarse crystalline calcite.

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