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Comprehensive Facies Analysis and Depositional Environment Modeling of the Eocene Dammam Formation in Central to Southern Iraq

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ABSTRACT: The Dammam Formation holds immense geological significance, as it spans across a substantial portion of southern Iraq, encompassing a vast area. This formation stands out as the primary aquifer source in the region. To gain a comprehensive understanding of its sedimentology, a comprehensive study was conducted using 310 samples extracted from various boreholes. These boreholes, including Kr-1, Kr-c.q., Nj-20, Ns-13, Ns-24, R-742, and Ru-509. The lithology of the Dammam Formation is limestone, dolomitic limestone, and dolomite rocks, which are also used as raw materials in the manufacture of cement. The microfacies analysis was carried out on Lower- Upper Eocene carbonate rocks along a center-south transect in Iraq. This analysis establishing larger benthic foraminifera enables to reconstruction of the paleoenvironmental model and to show the evolution of a platform along the depth gradient. The analysis revealed the presence of five primary microfacies within the Dammam Formation, each offering unique insights into its composition. These microfacies include Lime-mudstone, Wackestone, Packstone, Floatstone, and Rudstone, all of which contribute to a comprehensive understanding of the formation's sedimentary makeup. Moreover, this in-depth examination uncovered an additional eight submicrofacies. The benthic foraminiferal assemblages within the Dammam Formation provide valuable insights into the progressive shifts along an ecological gradient, indicating a gradual transition from shallower, more protected (inner) shelf environments to deeper, more open (outer) shelf settings. Within the inner shelf, one can observe the prevalence of orbitolitids, alveolinids, and, to some extent, small miliolids, indicative of this relatively shallow and sheltered environment. Moving towards the inner ramp or shoal region, the foraminiferal composition is characterized by robust nummulitids, signifying the distinctive conditions of this particular zone.

From a paleoenvironmental perspective, the Dammam Formation reflects deposition in a diverse range of environments, including peritidal inner ramp areas, lagoons, shoals, restricted-marine platforms, and open marine interior platforms. This variability underscores the complexity of the formation's geological history and the diverse conditions under which its sediments accumulated over time.

Keywords: Dammam Formation, sedimentary model, Nummulite, Microfacies, Eocene, Iraq.

1.Introduction

The Dammam Formation serves as a crucial aquifer resource in southwest and southern Iraq, playing a pivotal role in supporting both agricultural and industrial activities. This geological formation is recognized as one of the primary sources of brackish water, making it invaluable for irrigation and sustaining agricultural practices. Additionally, it holds immense significance for the oil industry, as it provides an ideal reservoir for the injection of fluids into oil wells.

Larger benthic foraminifera are a useful resource for interpreting biostratigraphic and paleoenvironmental data [1], [2], [3]. During the Early Palaeogene, the larger benthic foraminifera occasionally formed enormous accumulations along Neo-Tethys' western, central, and eastern regions. They also contributed significantly to shallow marine sediments in tropical and subtropical areas [4], [5]. They flourished in warm, oxygenated conditions that are often found in shallow waters and lagoons. A significant Tethyan sea mass that spanned between Eurasia in the north and Africa-Arabia in the south generated huge carbonate platforms on its southern boundary in the mid-Eocene [6].

Large benthic foraminifera (LBF) are the main biogenic component of the Eocene shallow-water carbonate succession from the western desert's Dammam Formation. Four Late Paleocene-Eocene strata are included in the research borehole's age. They are the Euphrates/ Ghar, Dammam, Rus, and Umm Er Radhuma formations, listed in order from top to bottom and originally named by Sander in 1952. The Rus Formation was initially identified by [7] using the type section on the SE flank of the Dammam dome in eastern Saudi Arabia. While in Iraq, was found in the Mesopotamian Zone of southern Iraq at the Zubair-3 well, where the formation is primarily formed of anhydrite and contains a tiny amount of unfossiliferous limestone. The Dammam Dome in eastern Saudi Arabia is composed of dolomites, marls, shales, and chalky, organoderital, or dolomitic limestone, according to [7] provided the first description of the Dammam Formation. The new type section of the Mesopotamian Zone's Zubair-3 well in Iraq, according to [8] [9], was constructed of a light gray, porous, dolomitized, and intermittently chalky limestone. Due to their richness and sensitivity to environmental changes, Eocene foraminiferal fossils are particularly helpful for biostratigraphy and paleoenvironmental reconstructions.

The Eocene deposits in Iraq reflect a warm, tropical to subtropical climate with a varied marine ecology, according to [10], [11] *Nummulites* and other marine fossils are signs of lagoons, shallow marine habitats, and marginal marine regions. Significant portions of the Earth's continent were covered by shallow oceans during the Eocene period. There have been numerous discoveries of *Nummulites* fossils around the world, showing their widespread distribution. [12] Large foraminifera in the form of lenses known as *Nummulites* were extremely prevalent throughout the Eocene period. They are significant indicator fossils for the middle and upper Eocene since this is when their variety and abundance peaked. In [4] the majority of *Nummulites* were marine creatures that lived in shallow tropical and subtropical seas. They flourished in warm, oxygenated conditions that are often found in shallow waters and lagoons. [13] claim that *Nummulites* lived in the shallow marine domain, usually in water depths between a few meters to a few hundred meters. In areas that were rather shallow, their variety and abundance were at their peak. Most of the neritic shoal limestone in the Dammam Formation is recrystallized and/or dolomitized, with the bottom half being nummulitic and the upper half having miliolids. The Dammam Formation from several Eocene shallow-water regions of Iraq have been the focus of the most thorough investigations by a number of researchers, including [14, [15], [16], in addition to several researchers in the GEOSURV in [11]. This study aims to identify multiple paleoenvironmental interpretations of carbonate systems and to create a sedimentary model of the Dammam Formation, which is located in the middle of southern Iraq. The studied boreholes are; Kr-1, Kr-c.q, Nj-20, Ns-13, Ns-24, R-742, and Ru-509, they are situated in the middle of south Iraq (Western to Southern Desert), between (43 3' - 47 23' E and (30 25' - 32 33' N), as shown in Figure 1.

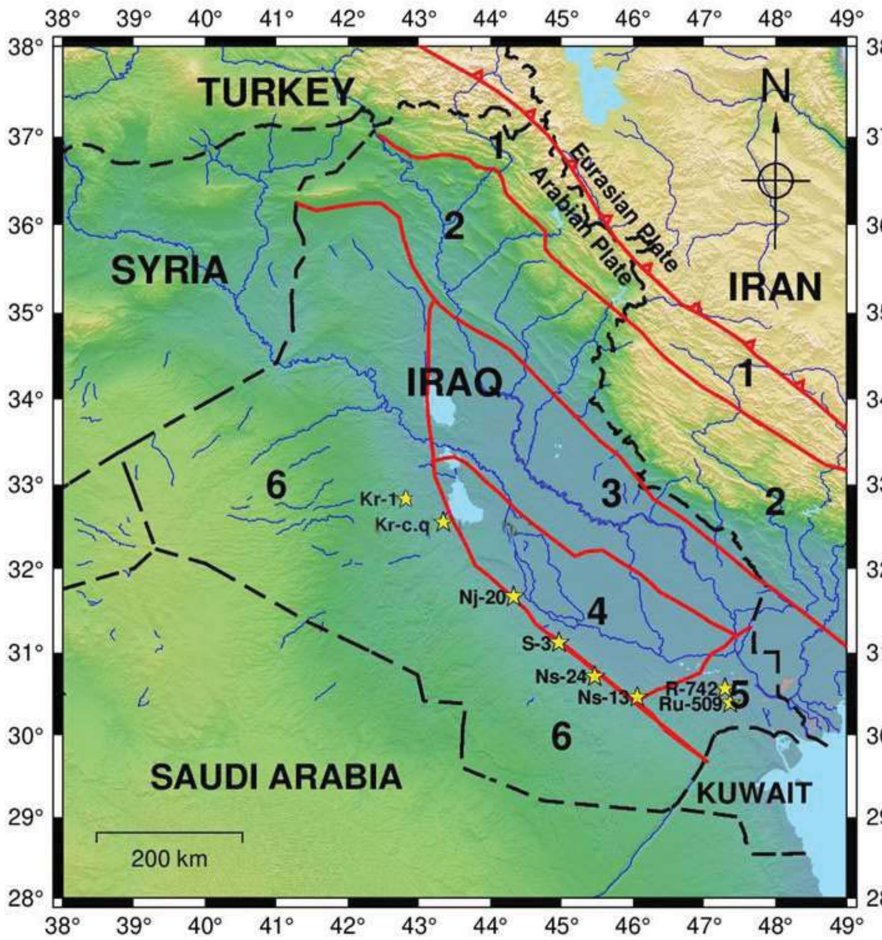

Fig. 1. Location map of the study area (After Fouad 2015) (yellow stars present the studied wells), 1. Sanandaj-Sirjan Zone, 2. Zgros Fold-Thrust Belt, 3+4+5 Mesopotamia Plain, 3. Tigris subzone, 4. Euphrates subzone, 5. Zubair subzone, 6. Inner Platform.

2.Geological setting

The Eocene epoch, spanning approximately 56 to 33.9 million years ago, marked a period of profound global geological transformations. Notably, during this era, the Neo-Tethyan Ocean ceased to exist as a result of the convergence of tectonic plates. The Arabian Plate, subjected to subduction, converged with the Turkish and Iranian plates, initiating significant geological events [17]. A more recent categorization by [18] divides Iraq into the Inner and Outer Platforms. The demarcation between the Outer and Inner Arabian Platforms in Iraq is primarily defined by two notable geological features: the Anah Graben Fault in the far western region and the Abu Jir-Euphrates Active Fault Zone in the southwestern part of the country. This contact zone, where the platforms meet, encompasses the majority of the boreholes examined in this study (Fig.1). Additionally, other boreholes are situated within the Inner Platform (Kr-c.q (Karbala cement quarry)) and Zubair subzone (R-742, and Ru-509), contributing to a comprehensive understanding of the geological dynamics in this area. These distinct fault zones play a pivotal role in delineating the boundaries and geological characteristics of the Arabian Platforms in Iraq [18] [19]. The edge of the Arabian continental plate undergoes uplift and extension, curving around the outer swell, just before becoming subducted within the descending slab, as elucidated by [20], [21]. This phenomenon serves as an early indicator of the impending collision during the Eocene era, profoundly influencing the development and distribution of various stratigraphic successions in the region

3. Methodology

310 samples from the 1270-meter-thick sequence in the Umm Er Radhuma, Rus, Dammam, and Euphrates formations were obtained from boreholes (Kr-1, Kr-c.q., Nj-20-, Ns-13, Ns-24, R-742, and Ru-509). The carbonate rocks of this formation are classified by [22], as well as by [23], depending on the depositional texture of the rocks. Grain varieties like bioclasts and infraclasses may fall under this category. The updated Dunham classification from 1962 is also employed in this paper [24]. The detected carbonate microfacies of the formation are compared to Ramp Standard Microfacies Types (RMF) from well-known environments (such as [25], [26]). Most studies on the petrographic features of the depositional environments of carbonate microfacies come from [27] and [26] The work follows one of two ways:

1- To achieve the goal of the current research, soft samples were gathered from the boreholes (S-3, Ns-24, R-742, and Ru-509). Each sample's microfaunal components were extracted using at least 250 gm. to achieve the aim of the current experiment, soft samples were obtained from the boreholes. or an acetic acid content of 40%. The samples were washed with running water and sieved using a 63 m sieve, according to [28]. The residue was dried and separated into various sections to facilitate the selection of unique microfossils under a binocular microscope. The foraminiferal tests that were chosen were captured on camera and identified down to the species level.

2- Addition to the 545 thin-section samples needed for this investigation. Some of the thin sections (6 cm× 8 cm, 2.5 cm× 7.5 cm, and 7.5 cm ×7.5 cm) were examined using binocular microscopes and digital photography. The identification of the Larger Benthic Foraminifera (LBF) of the Eocene is mostly based on taxonomic descriptions provided by [29] and [30].

4. Microfacies of the Dammam Formation:

More than 80% of the world's neritic carbonate production during the Eocene was accounted for by shallow-water carbonates that accumulated across a sizeable area of the peri-Tethyan region throughout the Paleogene [31]. Due to favorable geographic circumstances and temperate weather, large benthic foraminifers (LBF) and coralline algae were the main contributors to sediment in temperate locales [32]. Paleoenvironmental and paleobathimetric reconstructions have benefited from the knowledge of the relative distribution of different foraminifers across carbonate ramps [33]. Large concentrations of large benthic foraminifers were typically found in ramp settings in the Tethyan region [34]. The distribution patterns of fossil large benthic foraminifers were primarily investigated by extrapolating environmental proxies obtained from extant foraminifers in an effort to determine parameters such as nutrient and oxygen availability, water chemistry and depth, hydrodynamic energy, substrate type, and stability [35].

In addition to being abundantly exposed in Iraq's southwest, the Dammam Formation may also be found underground in wells in the south and center of the nation. Relative sea-level change is the main factor controlling the distribution of facies zones in carbonate environments [36], [37]. Significant identified microfacies include the following:

4.1. Bioclastic mudstone submicrofacies: *(mf1)*

This submicrofacies were found with boreholes (Nj-20, S-3, Ns-24, and Ns-13). In terms of its composition, it is made up of micrite that has fully recrystallized into microsparite. Small Miliolids, *Nummulite striatus*, *Nummulite* sp., *orbitolitids* sp., *Alveolina* sp., *Textularia* sp., and shell fragments are the recognized fossils. Most dolomite crystals have anhedral shapes. Dissolution is preserved as biomolds in biomoldic mudstone fossils, and some of them are bonded by secondary calcite or silica. Vugs, intercrystalline pores and veins are common in this submicrofacies. This submicrofacies is similar to the restricted inner ramp area's standard microfacies RMF16 deposit [26] (Fig.2, A). The presence of small benthic miliolids, large orbitolitids, and alveolinids is interpreted as shallow water or possibly hypersaline [38].

4.2. Wackestone microfacies: This microfacies is divided into three submicrofacies as follows:

4.2.1. Bioclastic- foraminiferal wackestone submicrofacies: *(mf2)*

This submicrofacies is found within boreholes (Kr-1, Kr-c.q., Nj- 20, S-3, Ns-24, and Ns-13). The skeletal components of this microfacies are *N. gizhensis*, *N. bayhariensis*, *N. elevate*, *N. discorbinus*, *Nummulite* sp., miliolids, algae, echinoderm fragments, mollusk fragments and ostracods. Also, *Nummulite* molds are identified (Fig.2, B). The rocks have large holes and many biomolds resulting from the dissolution of these fossils. The main pores impacted by this submicrofacies include biomolds, intraparticles, intercrystalline, vugs, and veins. Similar to the ramp microfacies RMF20 [26], which are deposited within the lagoonal inner ramp, algae and miliolids were also present in the lagoon area environment. Due to relatively low water turbulence and the presence of extensive mud, imperforate foraminifera in these facies suggests lagoonal shallow subtidal settings [39]. [40] determines this submicrofacies in lagoonal deposits, the presence of molluscan, and the bryozoa skeletons show that these deposits were deposited in lagoons with relatively shallow seawater [40].

4.2.2. Miliolid – peloidal wackestone submicrofacies: *(mf3)*

These submicrofacies were found in depths of 21.5, 19.5, 13.5, 10.5,136 and 6 meters at B.H. S-3 and found in B.H. Ns-13 at depth 107m. Petrographically, it is composed of pelloids and bioclastic embedded in micritic groundmass that has been totally replaced by extremely fine dolomite. It is tough and varied in color from yellowish-gray to brown. Due to extreme dolomitization, the bioclastic is completely destroyed, leaving only fossil ghosts like *Nummulite* sp., *Rotalia* sp., *Peneroplis* sp., *Bigenerina* sp., remnants of pelecypod shells, and a large number of miliolids, gastropods, and ostracods (Fig.2, C). The poloidal range in size from extremely medium to fine is composed primarily of dolomite, with form spherical and elliptical. Early dolomitization, dissolution, and porosity developments such biomolds, intraparticles, vugs, and interparticles were the key diagenetic alterations that impacted these submicrofacies [26]. This submicrofacies type is unlaminated and is thought to have developed on a maritime substrate with limited circulation and low energy, it resembles to the RMF16 that is deposited in a restricted environment [26].

4.2.3. Wackestone to floatstone submicrofacies: *(mf4)*

This submicrofacies is present in boreholes (Nj-20 at a depth of 11m and Ns-24 at a depth of 94m). Petrographically, it is composed of aphano to very fine crystalline dolomite (Fig.2,D). Intraclasts are irregular in shape. In some samples fossils present within intraclasts, completely affected by dolomitization remain as ghosts. vugs, veins, fractures, and intraparticle pores are the most common pores within this submicrofacies. This submicrofacies is equivalent to the standard microfacies (RMF24) deposited within the peritidal platform area [26].

4.3. Packstone microfacies: This facies divided into two submicrofacies, these are:
4.3.1 Nummulitic packstone submicrofacies: ***(mf5)***

This submicrofacies is found within boreholes (Kr-1, Kr-c.q., Nj- 20, S-3, and Ns-24). Nummulitic is present, which defines it. Petrographically, the recognized fossils include *Nummulites gizehensis*, *Nummulites bayhariensis*, *Nummulites gizehensis*, *N. elevata*, *N. planulatus*, *N. preforates*, *N. murchisoni*, *N. globulus*, *N. millecaput*, *N. beaumonti*, *Nummulites* sp., and *Lockhartia* sp. It is made up of calcite crystals that have partially replaced the bioclasts. These assemblages are located at depths of 71m, 73 m, 120 m, and 122 m in S-3 and at a depth of 82.5, and 92.5 m in B.H Kr-1. The nummulitic packstone's inclusion of diverse nummulitic and bioclasts is comparable to ramp microfacies RMF 14 (Fig.2, E) [26]. [42] summarized the complex relationships between typical larger foraminifera of Early Cenozoic carbonate platforms and he concluded that *Nummulites* occupied a broad range of open marine environments on both ramps and shelf. According to [38], the Nummulitids represent the relatively deepest organisms among the observed components (alveolinids and orbitolitids).

4.3.2. Miliolid - peloidal Packstone submicrofacies: ***(mf6)***

The submicrofacies that may be discovered in depths of (150m-142m, 134m, 137m, 125m, and 33m) in B.H. S-3 and Ns-24 at depths (38.5m and 19.5m), and Nj-20, may contain a variety of fossils (Fig.2, F). About 75% of the groundmass is made up mostly of bioclasts, which are either completely or partially replaced by very fine dolomite. Calcite makes up the majority of the closely packed bioclasts; some have undergone dolomitization. A typical type of bioclast in these submicrofacies is echinoderm plates. Among the various bioclasts discovered in this submicrofacies are Miliolids sp., *Coskinolina* sp., *Nummulites* sp., algae, bryozoa, ostracods, and shell fragments with radial calcite. Dolomitization, neomorphism of a few fossils (recrystallization and inversion), dissolution development (biomolds, vugs, and intraparticle), cementation by syntaxial overgrowth calcite, and selective silicification of a few fossils, matching of microfacies with ramp microfacies RMF17 [26] that deposited at lagoon environments were all identified as having some influence on the diagenetic processes. Alveolinids, *Nummulites*, *operculina*, miliolids, *Textularia* sp., shell fragments, algae, and ostracods indicate a lagoonal environment also presence of miliolids and textularids (Fig.7,F) indicates hypersaline shallow-water conditions [26] in [16]. The lagoon environment was impacted by the presence of dolomitic beds, but it might also periodically get overrun with an excessive number of algae [26].

4.4. Nummulite floatstone- grainstone submicrofacies: ***(mf7)***

This submicrofacies is present in the borehole B.H. S-3 at depths of 102m, 99.5m, and 72m and other boreholes Ns-24 at a depth of 98m as well as Kr-c.q. at depths of (34m-

35m), Nj-20 at depths of 110m-120m, and Kr-1 at depths of 63.5m and 94.5m (Fig.2,G). They include biomolds, secondary calcite, and macrofossils. Dolomite which ranges in size from fine to medium crystalline and has a euhedral to rhombohedral form makes up the groundmass. The identified fossils include *N. gizehensis*, N. *bayhariensis*, *N. planulatus*, *N. preforates*, *N. murchisoni*, *N. globulus*, *N. beaumonti, Nummulites* sp., *lockhartia* sp., bryozoa, algae, and echinoderm plates, with an average size of more than 2.8 mm (Fig.7,A). Various types of cement, including granular and block cement. The three most common forms of pores in these submicrofacies are biomolds, vugs, and intercrystalline pores. This submicrofacies is equivalent to the ramp microfacies RMF13, which are deposited in shoal-to-open marine settings, according to [26]. The variety of the collection suggests that it is a typical marine deposit in the photic zone. It is viewed as a more energetic counterpart to the open shallow subtidal inner ramp configuration of [43], which is less limited. The abundance of large benthic foraminifera with perforate walls, corallinacea, echinoid, bryozoa, mud–micrite matrix represents deposition in a shallower environment [33], [44], bryozoa, on the other hand, indicate open marine circulation [44], [45].

4.5 Rudstone microfacies: the microfacies are recognized depending on the percentages of the textural components of two types. These are:

4.5.1. Alveolina- bioclastic Rudstone submicrofacies: *(mf8)*

The facies is present in B.H. (S-3 at a depth of 94- 96 meters), They include a lot of *Alveolina*, with maximum sizes of >2 mm in diameter (Fig.2,H). Few samples have secondary calcite filling the porose (veins and vugs) in terms of petrography. It is distinguished petrographically by the abundance of bioclasts embedded in a microsparitic groundmass, which is partially replaced by extremely fine dolomite.

The majority of the bioclasts are made of echinoderm plates, echinoid spines, *Alveolinea olongat*, *Alveolinea elipite*, *Alveolinea subtilis*, *Alveolinea* sp., *N. gizehensis*, *N. planulatus*, *Assilina* sp., *Linderina baruges*, *Lockhartia* sp., *Orbitolites minimus*, *Sphaerogypsina globulus* (Reuss), *Rotalia* sp., and *Coskinolina* sp. The primary diagenetic modifications that have affected in this facies include partial dolomitization, neomorphism (recrystallization and inversion), development of porosity (intraparticle biomolds, vags, intercrystalline, and veinlets), cementation by secondary calcite (granular iso spacious rim cement, and drusy). The ramp microfacies is RMF26 [26]. Numerous and prominent *Nummulites* in the middle shelf zone next to the inner shelf, provide evidence of its occurrence in a relatively shoal inner ramp.

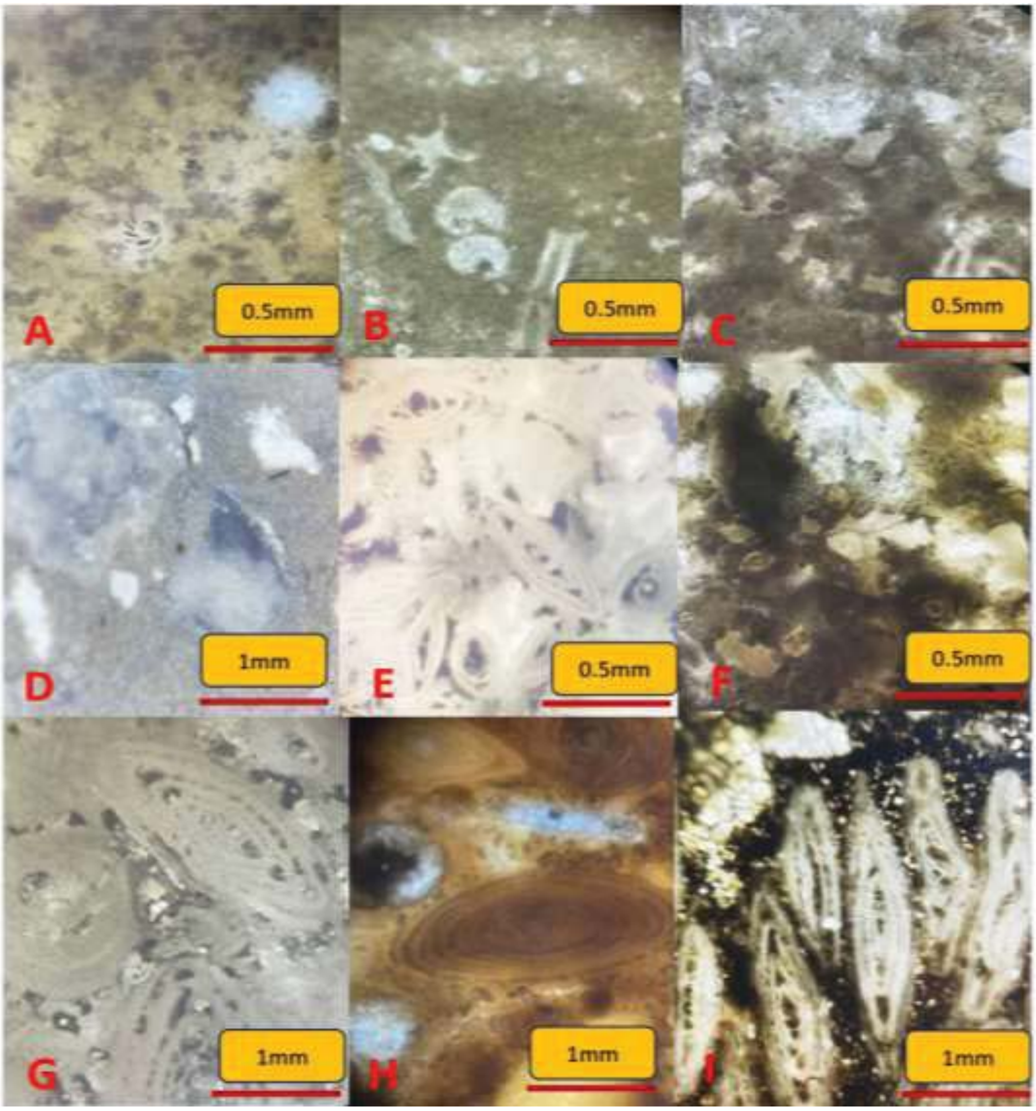

Fig.2 A)Bioclastic mudstone submicrofacies; B.H. S-3; depth 50.5m; B) Bioclastic- foraminiferal wackestone submicrofacies: B.H. S-3; depth 36m; C) Miliolid – peloidal wackestone submicrofacies: B.H.Ns-13; depth 36m; D) Wackestone to floatstone submicrofacies): B.H. Ns-24 depth 94m; E) Nummulitic packstone submicrofacies: B.H. Kr-c.q.; depth 12m, F) Miliolid- Bioclastic-peloidal Packstone submicrofacies: B.H.S-3; depth135m, J)Nummulitic floatstone- grainstone submicrofacies: B.H. Kr-1; depth 72m, H) Alveolina- bioclastic Rudstone submicrofacies: B.H.S-3, Depth 94.5m including bioclast of *Nummulites* sp., *Alveolinid* sp., and *Lockhartia* sp., I) Bioclastic- Nummulites Rudstone submicrofacies: B.H. Ns-24; Depth 113m including types of *Nummulites* sp.

Index fossils for the biozonation of early Tertiary shallow inner platform and shelf edge carbonate include *Nummulites* sp., and *Alveolina* sp. [26] [27]. An association of *Nummulites* and Alveolinids has been seen in Middle Eocene rocks and is thought to have formed in mid-ramp settings [47], occurs in shallow waters both in inner and outer platform environments [26], also possibly with lower energy and reduced light conditions [12], [48], [49].

Alveolinids, *Nummulites*, and *operculina* indicate deposition in shoal back-shoal environments [26 in [16]], [50], Alveolinids are significant faunal contributors to the inner ramp open water sediment. In comparison to *orbitolitids*, they have a significantly wider depth range [51].

4.5.2. Bioclastic- Nummulites Rudstone submicrofacies: (*mf9*)

This microfacies were found within borehole NS-24 at depths 117.5 m and 113.5m. Petrographically, it consists of micrite recrystallized to microsparite, selectively affected by late dolomitization, and partially or selectively by dedolomitization (Fig.2,I). This is indicated by the presence of rhombic crystals of dolomite that are partially replaced by calcite. Fossils are abundant, and affected by recrystallization, inversion, and dissolution remain as biomold filled with secondary calcite. The recorded fossils are *Nummulites gizehensis*, *N. globulus, Lockhartia* sp, echinoderm plate, and shell fragments. The pores of this microfacies are intraparticle, interparticle, and vugs. The ramp microfacies is RMF27 that were deposited in the shoal inner ramp [26].

5. Facies associations of Dammam Formation (Depositional environment)

The information from textural and faunal features contributed to the determination of microfacies zones leading to environmental subdivisions. In the southwest and south of Iraq, the Dammam Formation is extensively dispersed. Several facies are seen during the formation's succession. Depending on how microfacies are described. The characteristics of these depositional areas and their sediments are listed in figures 3 and 4 according to [26].

5.1. Umm Er Radhuma and Rus Formation Formation

Only one environment is recognized in the studied borehole for Umm Er Radhuma and Rus Formation. It is restricted inner ramp (interior environment), indicated by the presence of microfacies associations of Miliolid-peloidal Packstone microfacies.

5.2. Dammam Formation

Five environments are distinguished in the studied borehole. These are: -

1. Peritidal inner ramp (interior environment) the total absence of fauna and the presence of microcrystalline dolomite indicate a peritidal environment for these microfacies, characterized by associations of wackestone to floatstone microfacies.

2. Lagoon inner ramp, indicated by the presence of microfacies associations of Bioclastic-foraminiferal wackestone and Miliolid-peloidal Packstone, which is now transformed to dolomicrite, it was deposited under quiet water conditions that located at the Upper member of the Formation.

3. Shoal environments are characterized by the existence of abundant large types of foraminifera (*Nummulites gizehensis*) and other associated grains including shell

fragments. Medium to coarse rhombic dolomite crystals are scattered randomly throughout microfacies associations Nummulite floatstone- grainstone microfacies, Alveolina- bioclastic rudstone microfacies, and Bioclastic- Nummulites rudstone microfacies.

This facies association was deposited above normal wave base, in a moderate to high-energy shoal environment [25], [26]. This interpretation is supported by the good sorting of grains and the rare absence of a fine matrix.

4. Restricted platform interior environment is indicated by the presence of microfacies associations of Bioclastic mudstone, and Miliolids – peloidal wackestone microfacies.

5. Open marine platform interior environment, indicated by the occurrence of microfacies associations of Nummulitic packstone and Nummulitic floatstone- grainstone microfacies. It is considered to show open marine conditions, especially with the presence of bioclasts (*Nummulites* sp., *Lindrina* sp., *Asslina* sp., *Rotalia* sp., bryozoa, and other small foraminifera). Their coexistence alongside echinoderms, bryozoans, and coralline algae suggests settings with shallow open water or forebanks. The open marine facies association of the Dammam Formation coincides with the shallow subtidal ramp environment of [52], the open marine (inner ramp) to mid-ramp facies zones of [26], and the photic zone are similar to those described by [13] (Figure 3).

6. Discussion

It has been observed that coral populations have decreased significantly and there has been a corresponding increase in the number of larger benthic foraminifera at the end of the early Paleogene period. This shift in marine life can be attributed to the steady increase in ocean temperatures and atmospheric CO2 levels over time [53]. During this period, a large number of sectors around the Tethyan region witnessed the development of mixed carbonate-siliciclastic successions and shallow marine carbonate platforms.

The beginning of sea incursion on the shallow drying-out basin where underlying Rus evaporites were accumulating during the late Paleocene marked the beginning of the Dammam Formation's formation. The earliest deposits of this transgression are a medium-gray fossiliferous muddy limestone with interfingering grey and brown limestone stringers in the top section of the Dammam Formation. These beds include internal structures that are bent upward and correspond to the external surface of the beds. During the first pulse of the sea incursion, these early sediments filled the pre-existing paleo-lows in the peripheral zones. With the exception of top layers with barrow-type lamination, which developed under greater energy circumstances, they therefore show low energy deposits [54].

The sea was probably momentarily receded by a related regressive pulse. These early deposits are distinguished from the underlying strata by a prominent erosional surface that was produced during the second main transgression pulse. Another brown limestone was deposited during this transgression clue. The major transgressive surface of erosion (TSE) is thought to be the sharp, wavy surface that divides the two surfaces (Fig. 5). The degraded rip-up clasts from the underlying previously deposited muddy sediments make up the bed just above this level (Fig. 5). The overlaying brown limestone features lens structures and wavy internal lamination in its top section. It is somewhat dolomitized. These sediments were laid down in intertidal shallow marine habitats. Fast transgression and low circulation within this basin resulted in stratified conditions and anerobic to anoxic conditions, which caused organic-rich shales to be deposited according to stratigraphic position (Fig.6, B+C). This shale facies is correlated with the Midra Shale, described from Saudi Arabia and Qatar [55] from the basal part of the Dammam Formation (Pg20).

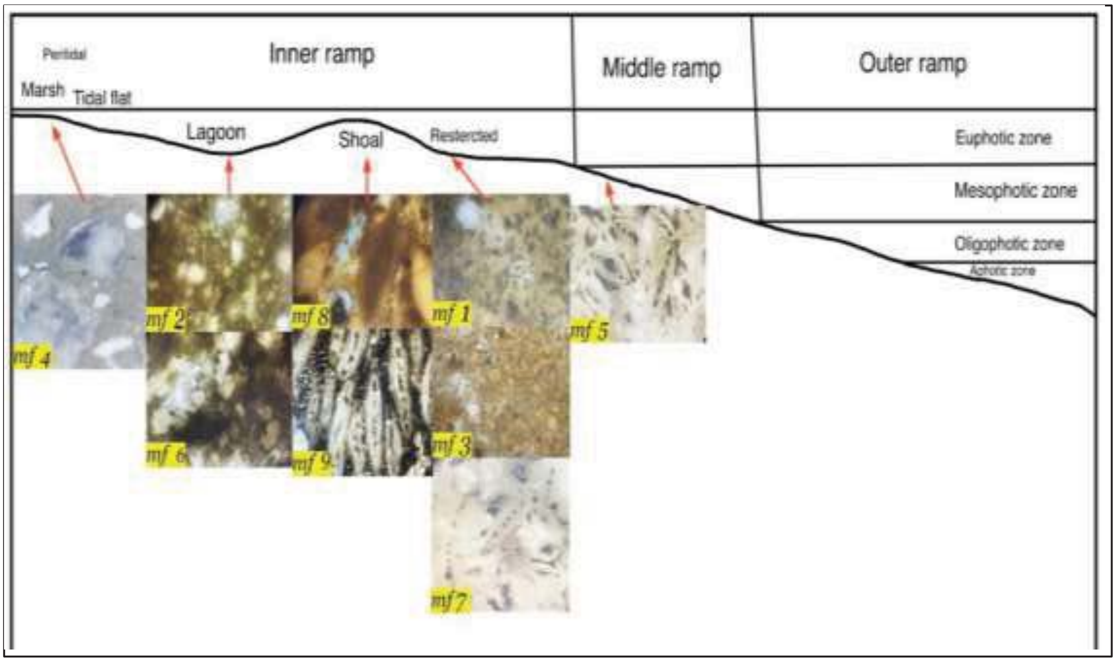

Fig.3 Environmental microfacies distribution for the Lower- Upper Eocene (area study) marine Depositional Sequence. Ramp subdivision is based on [52], photic zones are analogous to those described by [13]

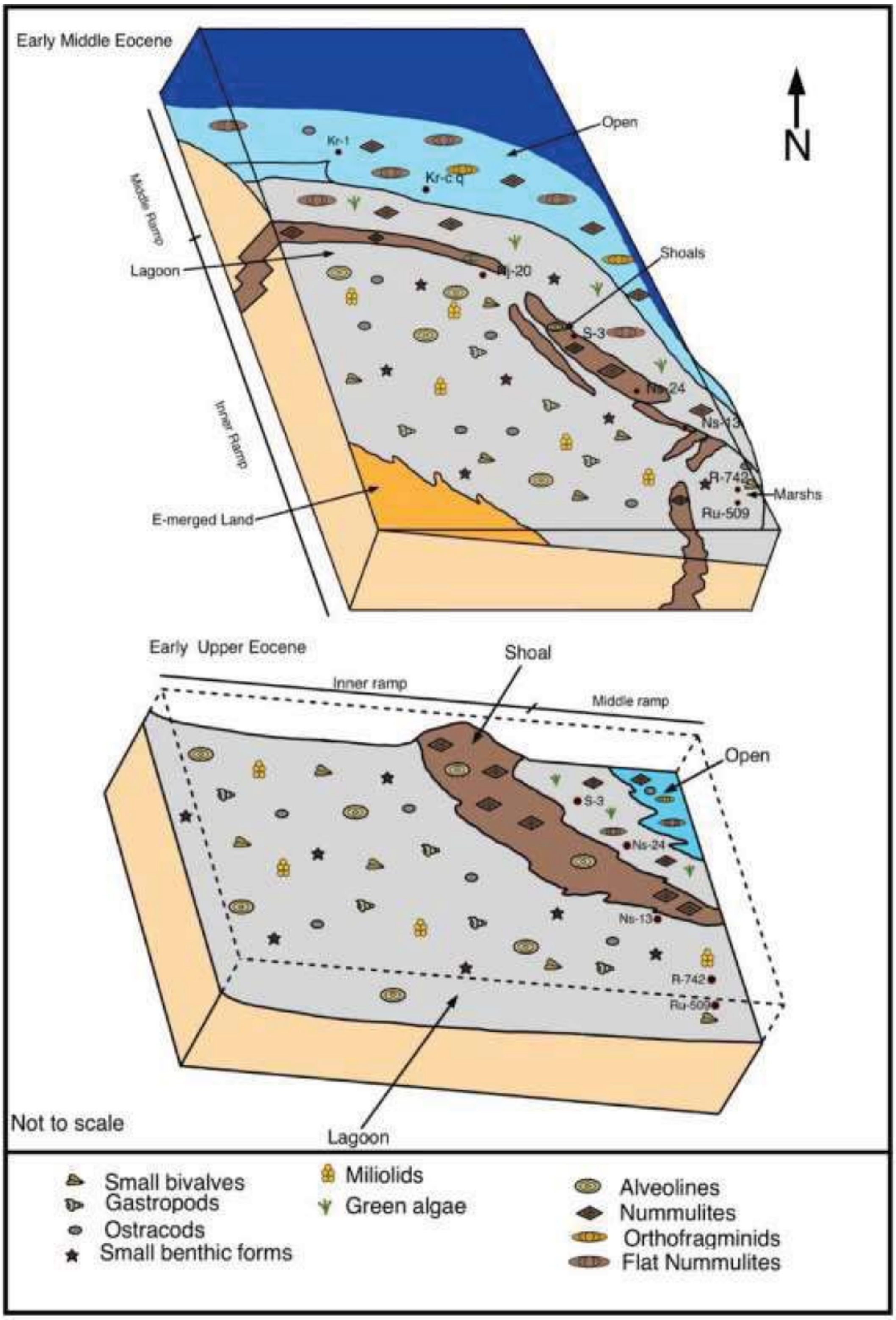

Fig.4 Paleogeographic and Paleoenvironmental sketch of the Dammam Basin area

Inside the shale, two distinct zones of limestone with a grey tint have been identified, which are believed to represent the initiation of deepening up and fining parasequences. These zones also indicate the persistence of relative sea level change pulses through the formation of this facies. Once the intra-ramp basin was filled, a broad shallow ramp was created, which provided an ideal environment for the flourishing of Nummulites. The preservation of these Nummulites led to the formation of the Nummulitic limestone facies, which were eventually collected into banks or shoals [56]. Small colonies with in-place development of organisms were produced on the rear bank side, which was sheltered (Fig.6,D). In inferred shallow inner ramp to intertidal habitats with significantly greater energy levels, parallel laminated facies above them were deposited landward. There was consequently a transgression phase in the lower half of the Dammam Formation, which was followed by shallowing, a regressive sea phase, and a putative sequence boundary in the middle of the Dammam Formation (Fig. 5).

The Middle Member of the Dammam Formation in south Kuwait, as observed through cores obtained from water wells, was found to have lignite layers that interfingered with shale layers towards the top, according to [57]. However, these lignite layers were replaced by tiny organic streaks. The Basra region in Fig. 6(E) depicts this data. Additionally, [57] reported partial dolomitization and partial to entire silicification zones below the lignitic zone, which is believed to have occurred due to acidic fluids seeping down. The researchers inferred that a diastem, or break in sediments, occurred in the midsection of the Dammam Formation based on their analysis. The study agree with the interpretation that a regressive phase was ongoing during the deposition of the Dammam Formation and was likely to have ceased in its middle. A third incursion occurred during this period, resulting in the creation of a lagoonal and shoal-type environment. Chalky mudstone was deposited in these lagoonal habitats, which have now been transformed into dolomicrite, under calm water conditions. Towards the top of this facies, shallow subtidal to peritidal habitats can be observed due to the presence of tractional and algal structures. These climatic conditions facilitate the development of algal structures and microbially laminated muds, while currents are also common in such environments [58]. Common fenestrae structures, vugs, and dissolution chambers in the overlaying facies indicate relatively shallow intertidal to supratidal settings of deposition, particularly in the Basra region (Fig. 6, G+H). An extremely porous, coarse, granular dolomite with algal lamination and breccia makes up the facies. The dolomitization took place during early diagenetic processes in coastal marine habitats with mixed meteoric groundwater and saltwater conditions [59]. Chert stringers and strata are widespread in the formation's highest region. These are more frequently seen along bedding planes, in cavities that have collapsed, and along fractures, because these areas provide simple passageways for circulating fluids. Due to the percolation of acidic groundwater along these weak planes during the post-depositional era, this facies underwent silicification [57]. [60] speculate that the sandier intervals interspersed with the carbonates represent dissolution cavity fills associated with exposed surfaces. Shallow, littoral, and lagoonal environments predominated over the entire study region by the time the Middle Eocene ended and the Early Upper Eocene began (Fig. 5). Strong evidence suggests that the early Upper Eocene shallow water gradually became deeper as it got older. The presence of Mullusca and bryozoan skeletons along with the lithological information points to relatively shallow, seawater, and lagoonal conditions for these layers [41]. The Dammam Formation's top is dramatically karstified, has varying degrees of weathering and erosion, and may have even been folded. The massive, tens of feet deep, and broad paleokarsts at the summit of the formation are filled with Neogene or more recent sediments [60, 61]. The Dammam Formation knobs and fragmented boulders are floating in the younger sandy fill matrix as a result of the dissolution voids and karsts collapsing (Fig.6, I). Two transgressive-regressive mane depositional sequences are seen in the Dammam Formation (Fig.5). In terms of overall high porosity, which exceeds in some facies, such as yellowish-brown dolomite, the deposit offers outstanding reservoir properties. The Basra region exhibits hydrocarbon signs in the form of bitumen remnants and oil stains at various intervals (Fig. 6, F).

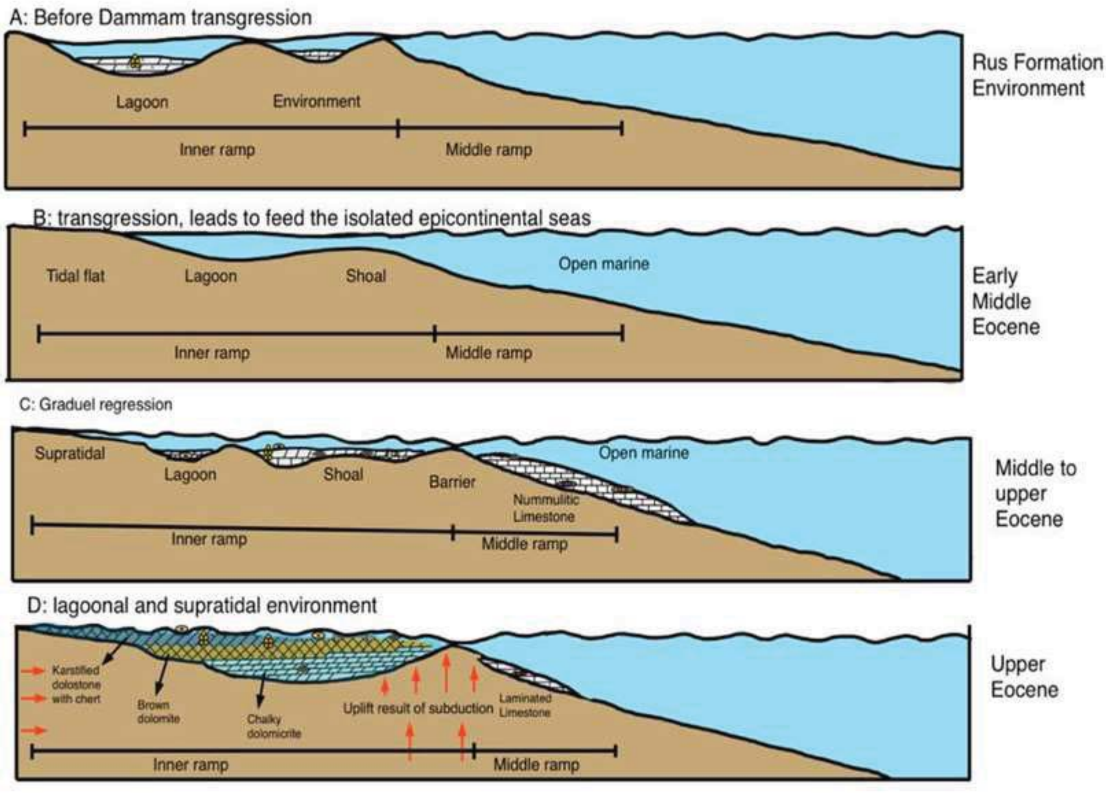

Fig.5. Depositional environment sequence for the Dammam Formation, illustrate the progradation stages for the sea level and type of sediments.

Fig.6 A. Large Foraminifera; B+C. Shale facies samples represent Pg20; D. Small colonies of algae; E. lignite layers; F. Hydrocarbon spots; G. fenestrae structures; vugs, and dissolution chambers; H. colonies of algae; I. dramatically karstified (top of Kr-c.q.).

7. Conclusion

A general stratigraphic sequence of the Dammam Formation was established by the study of cores, catting, and logs of wells. The upwards sequence of the Dammam Formation is as follows.

1- The Dammam limestones and dolomites accumulated during a quiet, stable period of the Eocene with small pulses in the source's land and minor fluctuations in the sea level causing alternating transgressive and regressive cycles. Deposition ended with a major regression in the Late Eocene.

2- The Dammam Formation was deposited in a shallow epeiric sea which was developed due to sea flooding over the Rus evaporitic basin, the culmination of which corresponds to the Arabian Plate MFS Pg20.

3- The diversity of microfacies has been recognized and grouped into nine facies associations reflecting different depositional environments.

4- Five environments are recognized within the Dammam succession, these are: A) peritidal environment represented by the dolomite, B) lagoon environment characterized by the presence of algae and miliolids, C) shoal environment characterized by either larger size of *Nummulites* sp. or texture is grainstone or rudstone like associations Nummulite floatstone- grainstone microfacies, and Bioclastic- Nummulites Rudstone microfacies. D) restricted environment characterized by the presence of miliolid with or without the presence of *Nummulites* sp. and represented by recrystallized limestone. E) open marine environments represented by *Nummulites* sp. were small in size with the presence of bioclastics, *Nummulites* fragments, echinodermata fragments as packstone or floatstone microfacies.

5- The Dammam Formation was deposited in a shallow marine ramp, with minor fluctuations from lagoon to tidal flat and swamp environments and intercalations of lignitic layers within the carbonate sequence of the shallow marine especially in the Basra area.

6- Several diagenetic processes affected the Eocene succession, they include: neomorphism, dissolution (mold porosity, vugs), dolomitization, cementation, silicification, and dedolomitization, these processes are related to three main diagenetic environments; marine phreatic, mixing, meteoric phreatic.

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