

Microfacies, Diagenesis and Depositional Environment Identification of the Albian-Early Cenomanian Mauddud Formation in Selected Wells of Ratawi Oil Field, Southern Part of Iraq

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Received:
24 January 2026
Accepted:
17 May 2026
Published:
31 July 2026

Abstract

One of the most important reservoirs in the southern part of Iraq is the Mauddud Formation. The microfacies, diagenesis, and depositional environment of the Mauddud Formation were identified in four wells in the Ratawi Field (RT-2, RT-4, RT-17, and RT-19). Petrographic analysis of 114 thin sections revealed four main microfacies and five sub-microfacies within the formation. Skeletal grains are more abundant than non-skeletal grains, providing strong evidence that the formation was deposited in a shallow marine environment, including four depositional settings: platform interior open marine, platform interior restricted, platform-margin sand shoal, and reef environment. Diagenetic processes were also classified, revealing that the formation was affected by several alterations. Some processes enhanced porosity, such as dissolution, which produced various porosity types, including intraparticle, interparticle, vuggy, channel, cavern, moldic, and fracture porosity. Other processes negatively affected the porosity and reservoir quality, particularly cementation, with three identified cement types: blocky, granular, and drusy. Dolomitization locally enhanced reservoir quality by creating intercrystalline porosity and improving permeability. In contrast, the chemical compaction, as represented by stylolite formation, had a negative effect, reducing the porosity through pressure solution and acting as a barrier to fluid flow.

Keywords: Mauddud Formation; Microfacies analysis; Diagenesis; Depositional Environment, Ratawi Field, Dissolution, Cementation

1. Introduction

Several important hydrocarbon reservoirs occur within the Cretaceous carbonate succession across the Arabian Plate, particularly in the central and southern parts of Iraq. Among these, the Mauddud Formation represents a key reservoir that extends throughout numerous oil fields (Sadooni and Alsharhan, 2003).

The first description of the Mauddud Formation was by for the subsurface section of the Qatar Petroleum Companies. The formation thickness ranges from 110 to 148 m in the southern part of Iraq, whereas in the northern parts of Iraq it exceeds 250 m (Jassim and Goff, 2006). The Cretaceous carbonate succession of the Arabian Plate contains significant hydrocarbon accumulations across several regions (Alsultan et al., 2022; Al-Khafaji et al., 2022; Hussain and Ibrahim, 2023). In the southern part of Iraq, the Mauddud Formation represents the reservoirs in many oil fields. This formation is composed predominantly of organic limestone, with stratified interbedded of “green or bluish” shale (Owen and Nasser, 1958). Lithologically, Mauddud succession consists mainly of

commonly dolomitized organo-detrital limestone occurring in the southern part of Iraq (Bellen et al., 1959). During the Albian–Cenomanian, *Orbitolina*-bearing limestones and dolomites were deposited within the formation (Hameed and Saleh, 2021). Nasser and Nasser (2017) identified several microfacies deposited in shallow open marine and restricted environments, and highlighted the significant impact of diagenetic processes on the porosity and reservoir performance.

The study area is located in the southern part of Iraq within Basra Governorate. It includes the Ratawi Oil Field, located 70 km northwest of Basrah city, and is parallel to the North Rumaila Field, approximately 20 km to its west, between latitude 3048333°N and longitude 471500°E. The Ratawi Oil Field lies within the Stable Shelf, Zubair Subzone, as a part of the Mesopotamian Zone (Fig.1). This subzone has a uniform structural style controlled by the underlying basement and Infracambrian salt. (Jassim and Goff, 2006). The Zubair Subzone is bounded from the north by the Takhadid-Qurnah Transversal Fault, and the southern boundary is either located at Al-Batin Fault or along a transversal fault in Kuwait. This subzone forms the most southern units of the Mesopotamian Zone. The structures of this subzone are long and relatively narrow anticlines, separated by broad synclines, especially in the east and are controlled by the basement structures and Infracambrian salt (Jassim and Goff, 2006).

The wells Rt-2, Rt-4, Rt-17, and Rt-19 of the Ratawi Oil Field have been selected for this study, which penetrate the Mauddud Formation. Table 1 shows the coordinates, depth, and thicknesses of the Mauddud Formation in these oil wells.

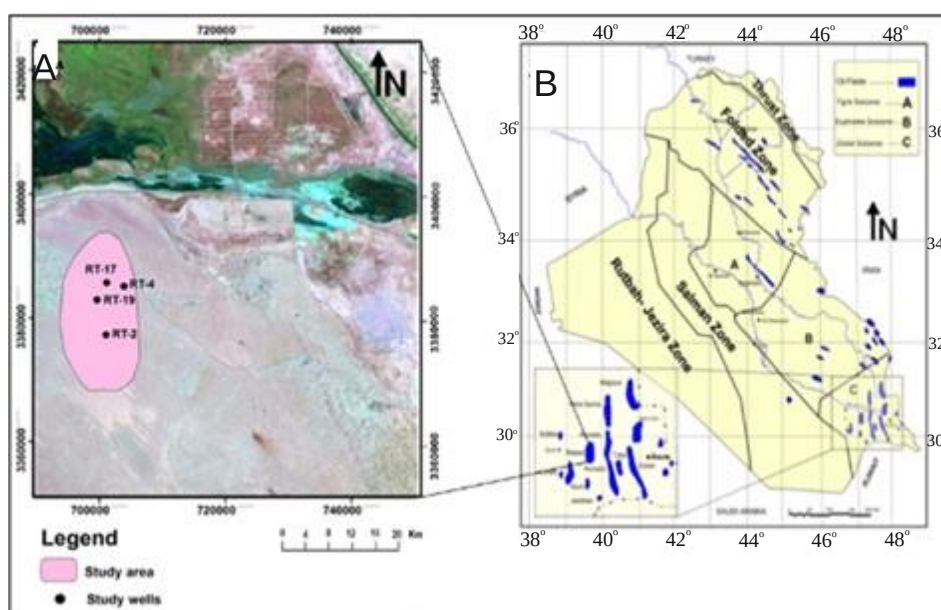


Fig. 1. A) Location map of Ratawi oil field showing the studied wells, B) Location map of Iraq showing the Ratawi Oil Field

This study aims to interpret the microfacies of the Mauddud Formation and to compare them with the standard microfacies of Flügel's (2010) in order to determine the depositional environment of the formation in the Ratawi Oil Field. It also aims to identify and interpret the diagenetic processes that affected the formation, evaluate whether they were constructive or destructive, and assess their impact on the formation.

2. Materials and Methods

In this study, thin-section images of the Mauddud Formation from the Ratawi Oil Field were used to investigate microfacies, diagenetic processes, and depositional environments of the Mauddud

Formation in the southern part of Iraq. One hundred and fourteen thin sections were obtained from core samples of the Mauddud Formation collected from four wells (RT-2, RT-4, RT-17, and RT-19). Table 1 presents the number of samples collected from each well. These images are obtained from the laboratories of the Oil Exploration Company.

In the current study, Dunham's (1962) classification was applied to categorize the microfacies of the Mauddud Formation. The composition of skeletal and non-skeletal grains, along with the matrix (groundmass), is analyzed to identify microfacies features that provide insights into the depositional environment.

Standard microfacies classification, which was later developed by Flügel (2004), and related facies zones are used as reference tools to identify the depositional environment of the Mauddud Formation.

The diagenetic processes were identified, including dissolution, cementation, and compaction. The types of porosity in the formation are also identified using the Choquette and Pray (1970) classification.

Table 1. The coordinates (UTM system) of the studied wells, depths, thickness, and thin section number for the petrographic study of Mauddud Formation

Well Name	Easting	Northing	Depth (m) Top & bottom	Thickness (m)	Thin section number
RT-2	701044	3377287	2493-2612.5	119.5	25
RT-4	582304	3392364	2568.5-2688.5	120	31
RT-17	701151	3385704	2456-2582	126	30
RT-19	699605	3382905	2459-2580.5	121.5	28

3. Results and Discussion

3.1. Microfacies and Depositional Environment

Four microfacies and five submicrofacies have been identified in the Mauddud Formation in the Ratawi Oil Field. The types of microfacies and the content of skeletal and non-skeletal grains allow us to identify the depositional environment; it is one of the widely used methods. Fig.2 shows the relative distribution of carbonate microfacies of the Mauddud Formation. The packstone facies is overwhelmingly dominant, which indicates widespread deposition under moderate-energy conditions. It is followed by grainstone, whereas wackestone and boundstone occur in minor proportions, suggesting limited development of low-energy and reefal or bioconstructed environments within the formation.

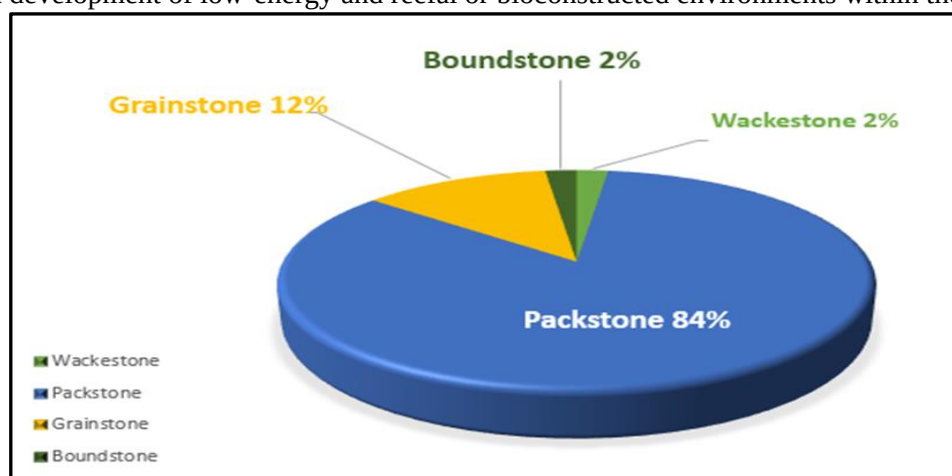


Fig. 2. Distribution of carbonate Microfacies of the Mauddud Formation in all studied wells

3.1.1. Wackestone microfacies

These facies are characterized by a high clay content exceeding the grain proportion, and is also distinguished by the presence of biogenic components, such as echinoids and foraminifera, at more than 10% (Fig. 3A). It corresponds to SMF 9 of Flügel's Standard Microfacies classification, and is related to FZ-7. The microfacies reflects a shallow open marine environment.

3.1.2. Packstone microfacies

This microfacies includes the following submicrofacies

- Foraminefera packstone submicrofacies: It is composed mainly of benthic foraminifera, including *Orbitolina*, miliolid, and *Nezzazata*. (Fig. 3B) It corresponds to standard microfacies 18 of Flügel's Standard Microfacies classification and reflects shallow marine environments FZ-7. The presence of *Orbitolina* indicates an open-marine environment, whereas miliolid and *Nezzazata* are strong indicators of a restricted-marine environment (Figs. 4, 5, 6, and 7).
- Bioclastic packstone submicrofacies: It is a grain-supported facies, and is characterized by abundant bioclasts of varying sizes and by peloids, rudist, and echinoderms (Fig. 3C). It corresponds to SMF-18 of Flügel's Standard Microfacies classification and is related to FZ-7, which is a shallow open marine environment.
- Intraclastic packstone submicrofacies: This sub-microfacies consists of rounded, transported grains redeposited away from their original formation's site, with minor clay content (Fig. 3D). It is found only in wells RT-2 and RT-4 and shows close similarity to SMF 11 of Flügel's standard microfacies, which is related to FZ-6 and reflects a platform-margin sand shoal environment. This zone, located above the fair-weather wave base and within the euphotic zone, is strongly affected by tidal currents. The submicrofacies belt is very narrow (Flügel, 2010) (Figs. 4 and 5).

3.1.3. Grainstone Microfacies

This microfacies includes the following submicrofacies

- Peloidal grainstone submicrofacies: This submicrofacies is composed of non-skeletal grains, which are peloid grains, with a very low percentage of clay (Fig. 3E). It was compared with SMF 10, of Flügel's Standard Microfacies classification and indicates a shallow marine environment FZ-7. These particles reflect marine, warm and arid conditions (Flügel, 2010; Hussain et al., 2020).
- Foraminifera Grainstone submicrofacies: This submicrofacies is entirely composed of benthic foraminifera, including miliolids, *Nazzazata*, and *Orbitolina*, with the absence of clay. This submicrofacies was compared with SMF 18 of Flügel's Standard Microfacies classification and related to FZ-7 (Fig. 3F).

3.1.4. Boundstone Microfacies

The original components were cemented together during deposition (Dunham, 1962). In the Maaddud Formation, this facies is distinguished by the presence of a large and well-preserved rudist framework (Fig. 3G). It is found only in well RT-17 at a depth of 2562.82 m and corresponds to SMF 7 of Flügel's Standard Microfacies classification and is related to FZ-5. (Fig. 6).

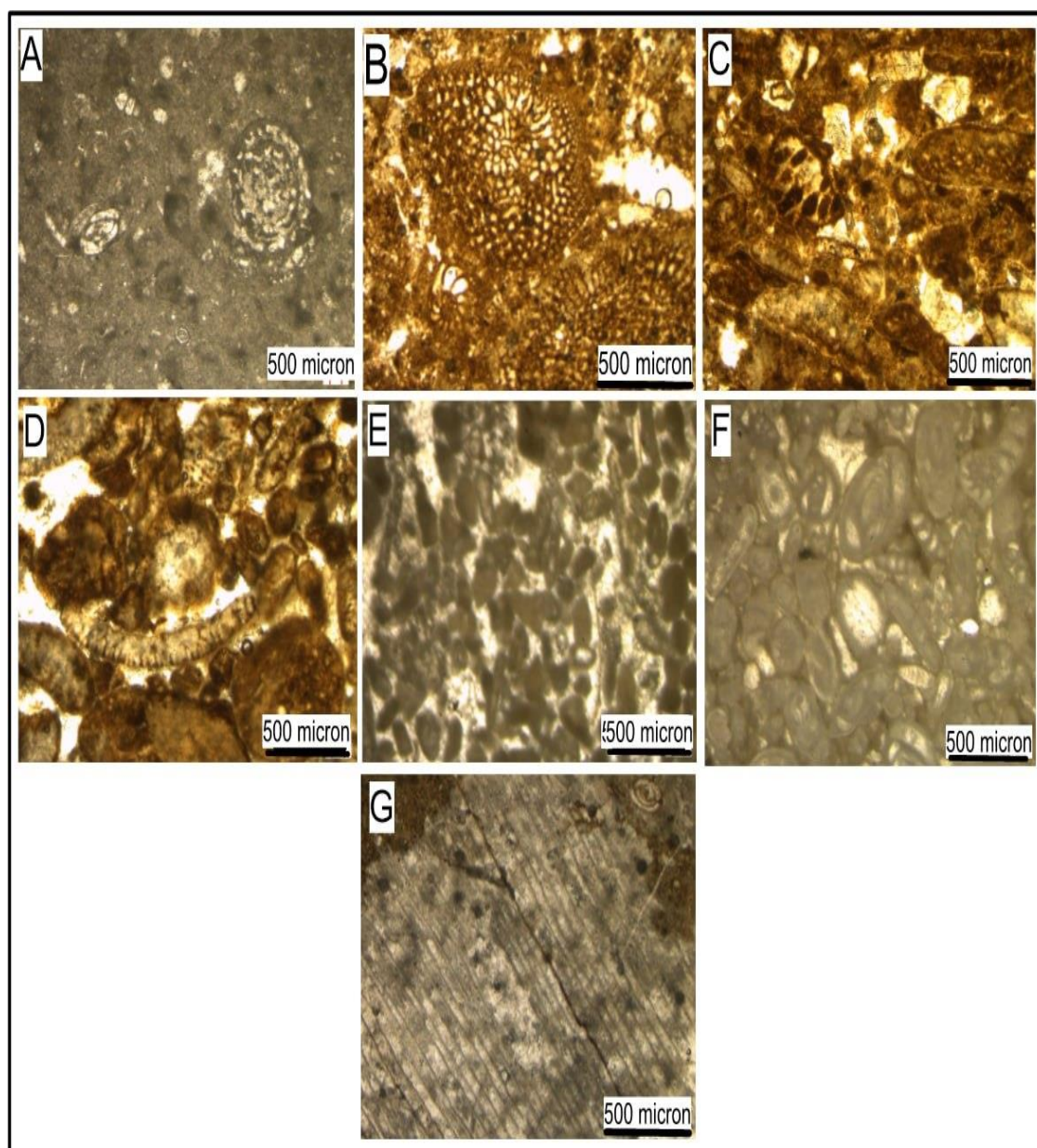


Fig. 3. A) Wackestone Microfacies (well RT-17, depth 2558.10 m), B) Foraminifera packstone submicrofacies (well RT-4, depth 2564.7 m), C) Bioclastic packstone submicrofacies (well RT-17, depth 2495.53 m), D) Intraclastic packstone submicrofacies (well RT-4, depth 2591.5 m), E) Peloidal grainstone submicrofacies (well RT-4, depth 2592.5 m), F) Foraminifera grainstone submicrofacies (well RT-4, depth 2593.5 m), and G) Boundstone submicrofacies (well RT-17, depth 2562.82 m)

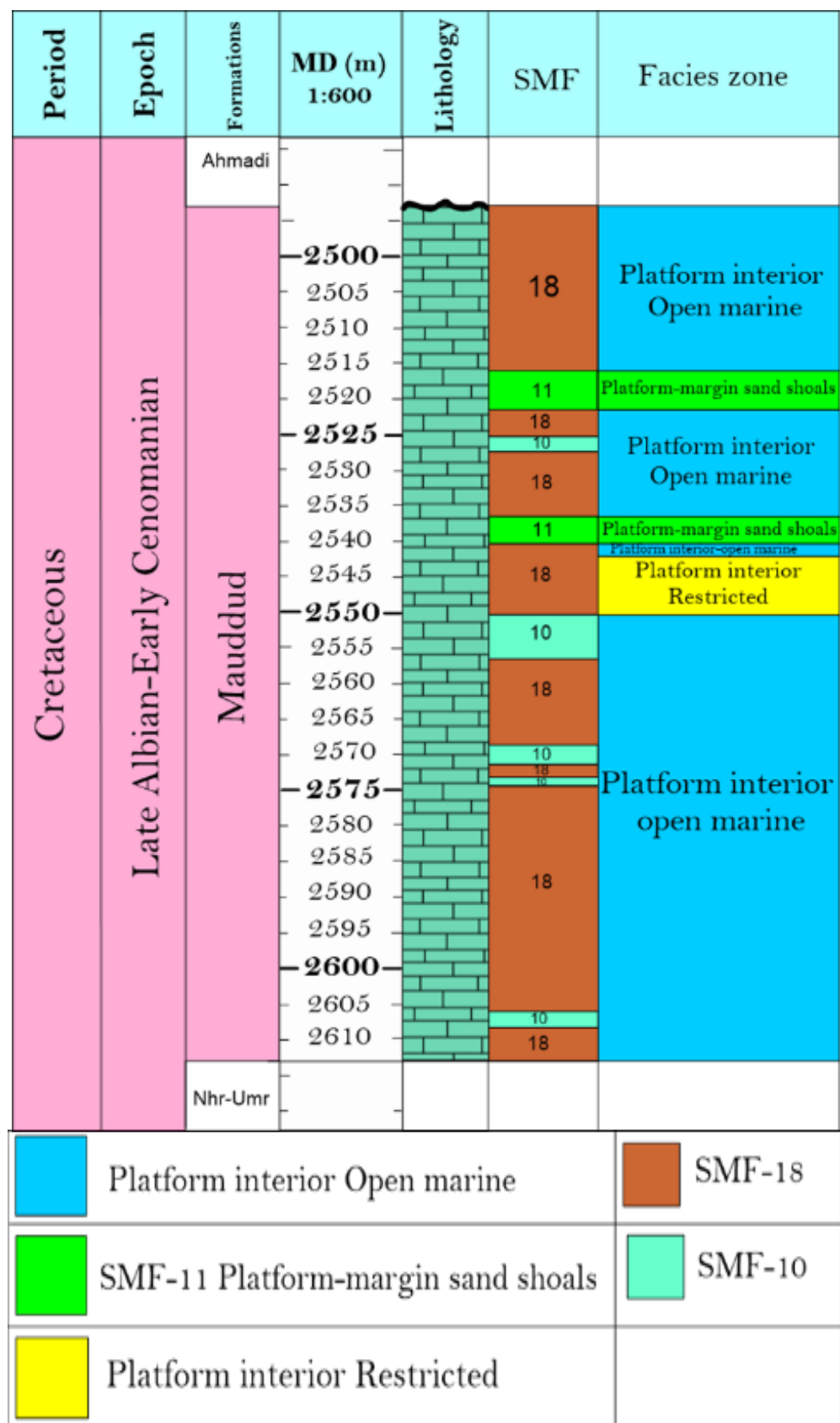


Fig. 4. The environments of the Mauddud Formation depending on SMF and FZ for Ratawi well RT-2

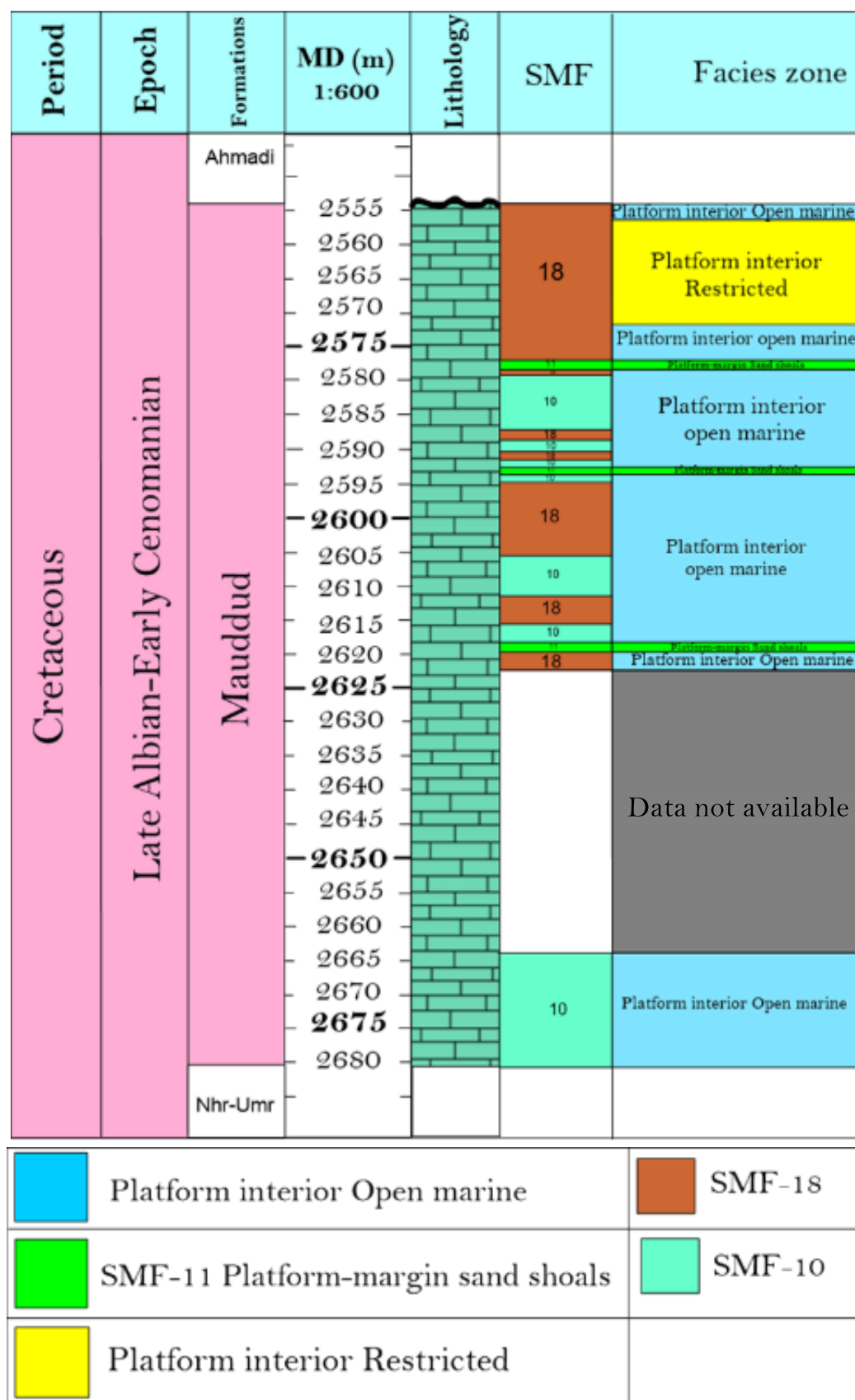


Fig. 5. The environments of the Maudud Formation depending on SMF and FZ for Ratawi well RT-4

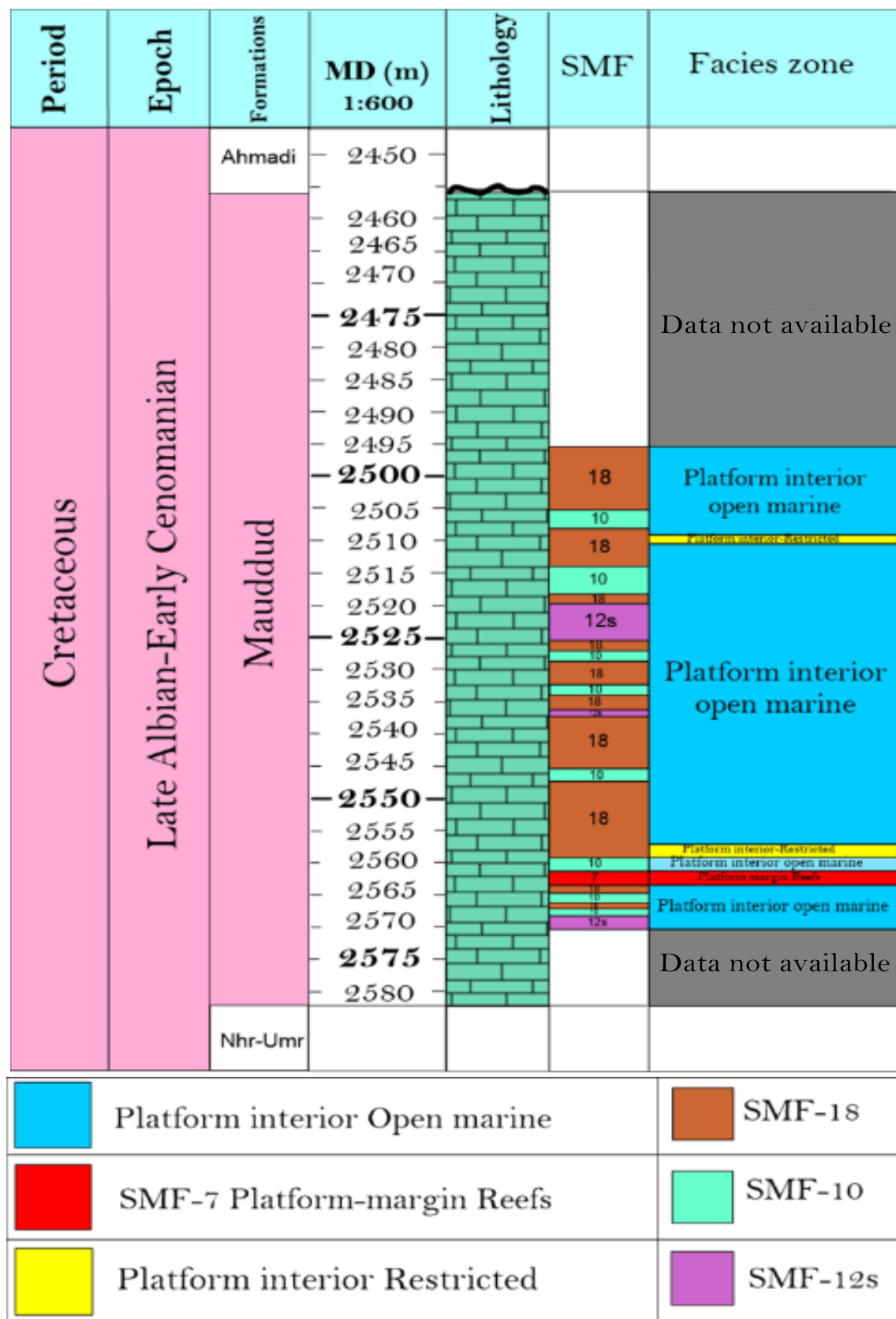


Fig. 6. The environments of the Mauddud Formation depending on SMF and FZ for Ratawi well RT-17

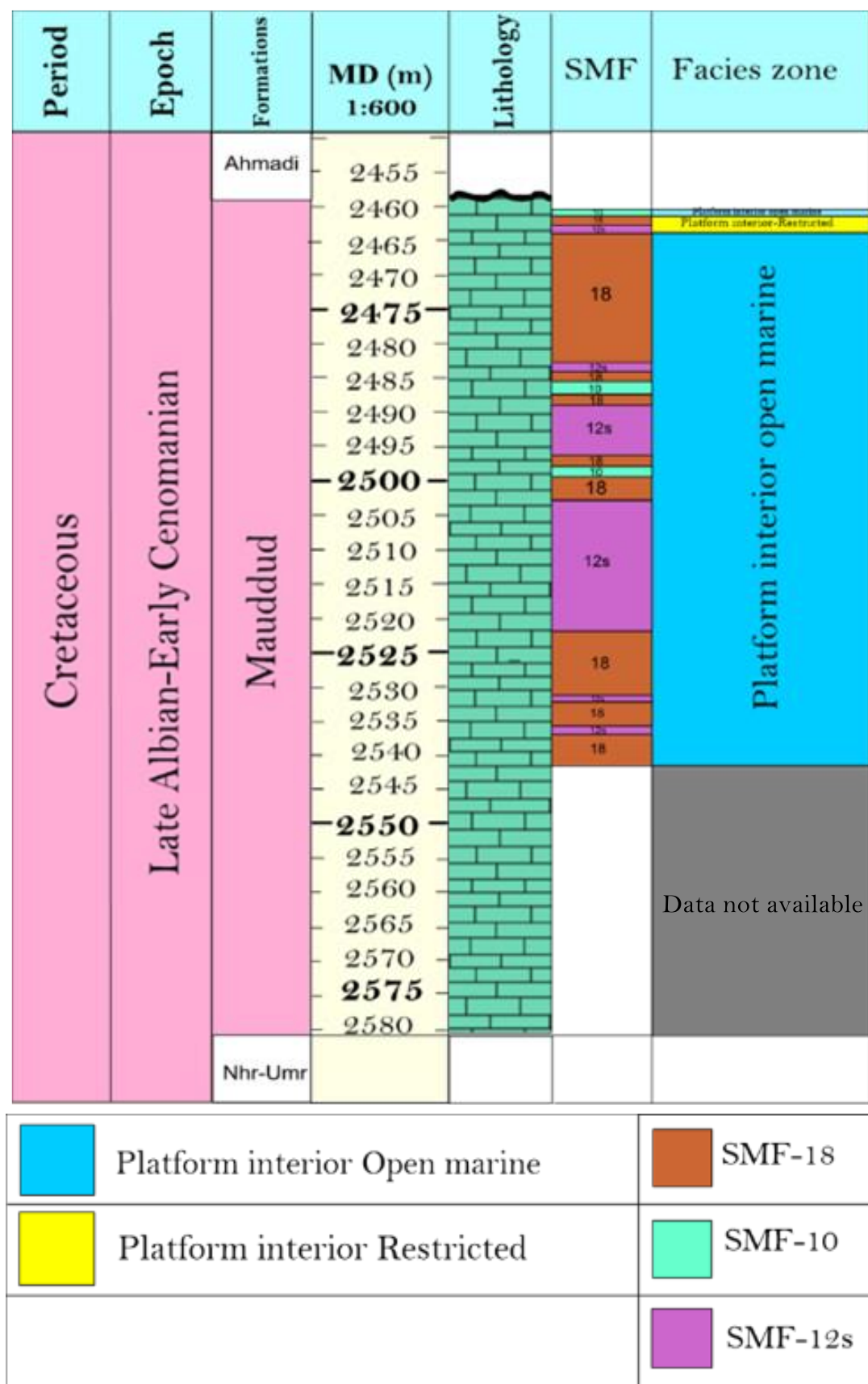


Fig. 7. The environments of the Maudud Formation depending on SMF and FZ for Ratawi well RT-19

3.2. Diagenesis Processes

The diagenesis as all alterations affecting the chemical constituents, shape, size, or crystalline structure of sediments. Carbonate rocks commonly exhibit complex diagenetic histories due to their variable mineral composition and high primary permeability, which make them particularly susceptible to interaction with circulating fluids (Selley, 2000). Several diagenesis processes have been recognized in the Mauddud Formation, including cementation, dolomitization, dissolution, and compaction.

3.2.1. Cementation

The following types were identified.

- **Blocky cement:** This cement type is described as consisting of large calcite crystals formed through slow crystallization following diagenesis (Longman, 1980). It is indicative of a deep burial environment (Flügel, 2010). It occurs in all studied wells at various depths (Fig. 8A).
- **Drusy cement:** Pore-filling and lining cement occurs within interparticle and intrafossil pores, as well as in molds and fractures. It is characterized by equant-to-elongated, anhedral-to-subhedral, non-ferroan calcite crystals, typically larger than 10 μm , which grow inward toward the center of the void. This cement forms in both near-surface meteoric conditions and burial environments (Flügel, 2010). In the present study, drusy cement was observed only in wells Rt-4, Rt-17, and Rt-19 (Fig. 8B).
- **Granular cement:** This type is characterized by equigranular, anhedral and/or subhedral crystals (Bathurst, 1975). It is present in all studied wells (Fig. 8C).

3.2.2. Dolomitization

Most of the dolomite in sedimentary rocks forms during diagenesis and commonly replaces calcite (Nichols, 2009). Dolomitization refers to the process by which CaCO_3 is transformed into $\text{CaMg}(\text{CO}_3)_2$, or limestone is converted into dolomitic limestone (Flügel, 2010). Early dolomitization commonly enhances reservoir quality by creating intercrystalline porosity. Dolomite occurs in a limited amount in the studied wells and is absent in well Rt-4 (Fig. 8D).

3.2.3. Chemical compaction

Pressure-solution features in the Mauddud Formation were classified according to Wanless (1979), who proposed a stylolite classification that was later modified by Choquette and James (1987). All stylolite types were recognized except in well Rt-4, in which only low-peak stylolites were recorded (Figures 8-E and F). Stylolite generally has a negative effect on reservoir quality by reducing the porosity and permeability through pressure solution and compaction.

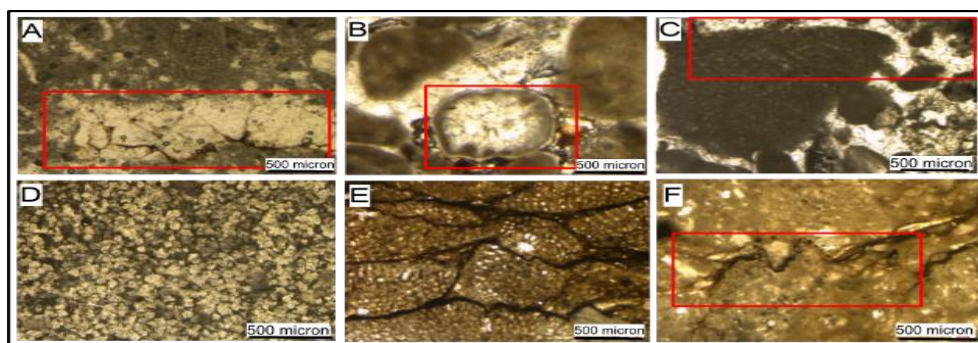


Fig. 8 A) Blocky cement well RT-2 (depth 2542.80 m), B) Drusy cement well RT-17 (depth 2537.16 m), C) Granular cement well RT-19 (depth 2487.35 m), D) Dolomitization process well RT-2 (depth 2606.57 m), E) Chemical compaction (Irregular anastomosing sets) well RT-19 (depth 2522.85 m), and F) Chemical compaction (low peak stylolite) well RT-4 (depth 2572.20 m)

3.2.4. Dissolution process

The primary diagenetic process that enhances the porosity and permeability of the Mauddud Formation is dissolution. This process is influenced by mineral solubility; for instance, calcium carbonate becomes more soluble when it transforms from aragonite or high-magnesium calcite to low-magnesium calcite. Dissolution generates different pore types in the Mauddud Formation, which has been identified according to Choquette and Pray (1970).

- **Intraparticle Porosity:** Intraparticle porosity refers to pore spaces that occur within the skeletal grains, where these voids remain unfilled by diagenetic cement (Allaby, 2008). It is the most effective porosity in the Mauddud Formation; it has been identified in nearly all depths of the studied wells (Fig. 9A).
- **Interparticle Porosity:** Lucia (2012) described this type of porosity as voids between grains or crystals, with sizes not significantly larger than the grains themselves. This porosity type is recognized near the upper and lower intervals of well Rt-2, and it is recorded at three depth intervals (2571.9 m, 2592.5 m, and 2615.5 m) in well Rt-4. In well Rt-17, interparticle pores are widely distributed and commonly observed at depths of 2480.40 m, 2500.29 m, and 2541.05 m (Fig. 9B).
- **Vuggy Porosity:** These are pores with diameters exceeding 1/16 mm, making them visible to the naked eye. Morphologically, these pores are generally equant in shape (Choquette and Pray, 1970). In the Mauddud Formation, the vuggy porosity is identified in the middle interval of well RT-2, in the upper part of well RT-4, and only at a depth of 2489.5 m in well RT-19, while in well RT-17 it is distributed in all depths (Fig. 9C).
- **Moldic Porosity:** The moldic porosity is a type of secondary porosity that forms as a result of the selective dissolution of unstable skeletal or non-skeletal grains, leaving behind voids that preserve the original shape of the dissolved components (Choquette and Pray, 1970). It was identified only in well RT-4, at a depth of 2594.5 m (Fig. 9D).
- **Channel Porosity:** The channel porosity is developed through selective leaching of unstable components, such as skeletal grains or matrix material, resulting in interconnected flow channels (Flügel, 2010). It is typically associated with high-energy fluid flow, where circulating meteoric or subsurface fluids enlarge pre-existing pores, fractures, or stylolites into continuous channels (Lucia, 2012). It was identified only in well RT-17 at a depth of 2567.35 m (Fig. 9E).
- **Cavern Porosity:** The cavern porosity is a type of secondary porosity characterized by very large dissolution cavities that are significantly larger than vugs and may reach several centimeters to meters in size (Choquette and Pray, 1970). This type of porosity forms mainly through intense dissolution processes, commonly under meteoric diagenetic conditions, where aggressive fluids enlarge pre-existing pores, fractures, or vugs (Flügel, 2010). It is found only in well RT-17 at a depth of 2538 m (Fig. 9F).
- **Fracture Porosity:** The tectonic activity can generate fracture porosity through two main mechanisms: compressional anticline structures and tensile stresses developed above the crests of compactional drapes. Moreover, fracture porosity is strongly associated with faulting, and many oil fields show a close structural relationship with particular fault systems (Selley, 2000). In the Mauddud Formation, fracture porosity is the least abundant porosity type; it is identified in wells RT-2, 4, 17 and is absent in well RT-19 (Fig. 10G).

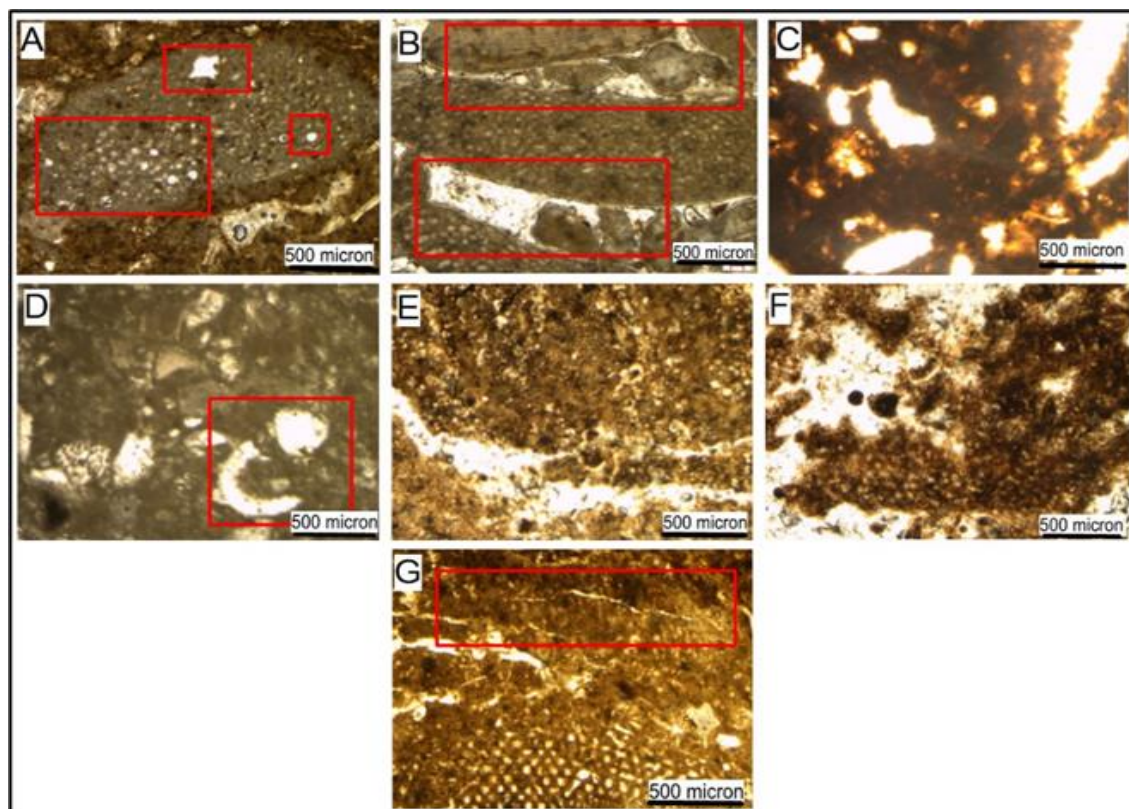


Fig. 9. A) Intraparticle porosity well RT-19 (depth 2499.60 m), B) Interparticle porosity well RT-17 (depth 2537.16 m), C) Vuggy porosity well RT-17 (depth 2564.95 m), D) Moldic porosity well RT-4 (depth 2594.5 m), E) Channel porosity well RT-17 (depth 2567.35 m), F) Cavern porosity well RT-17 (depth 2538.98 m), and G) Fracture porosity well RT-4 (depth 2612.5 m).

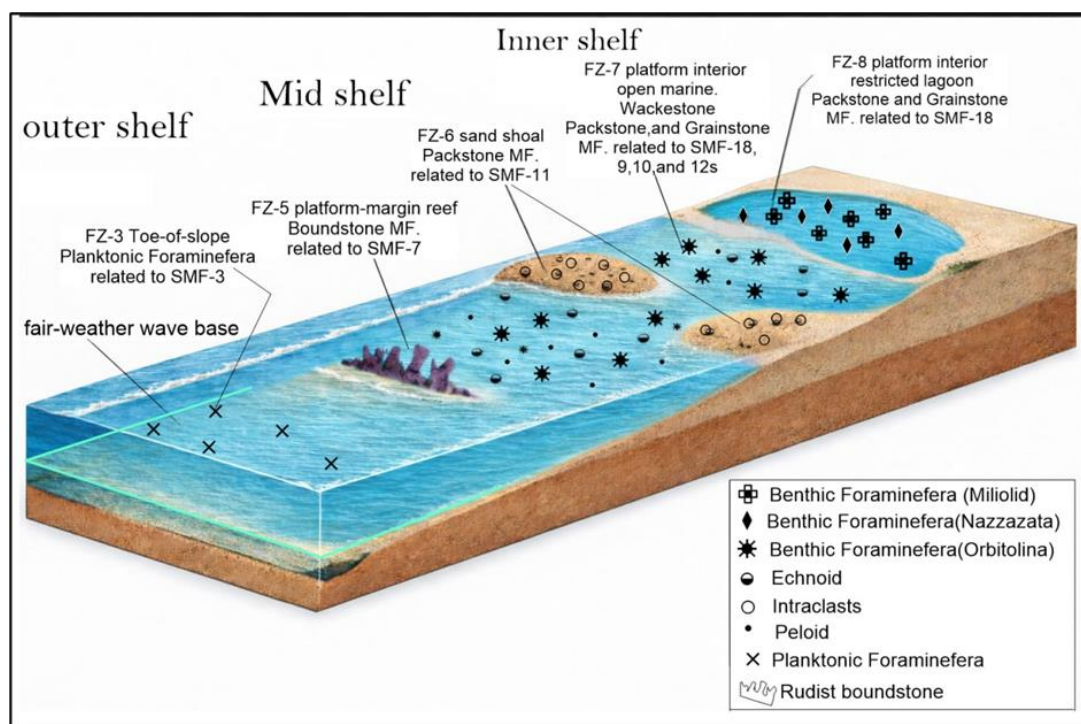


Fig. 10. Depositional model of the Maaddud Formation in all studied wells

4. Conclusions

It is concluded that the Mauddud Formation was deposited in a shallow marine environment, as indicated by the dominance of packstone microfacies. The interpretation of microfacies also confirms that skeletal components play a major role in the composition of the formation compared to non-skeletal components. The diagenetic processes, particularly dissolution, had a significant impact on reservoir quality, as they led to an increase in the porosity through the development of several pore types, including intraparticle, interparticle, moldic, vuggy, channel, and fracture porosity. In contrast, other processes such as cementation and chemical compaction negatively affected the formation and led to a localized reduction in porosity. Therefore, the reservoir quality of the formation is mainly controlled by diagenetic processes, depending on whether they are constructive or destructive.

Author contributions: Credit

- Conceptualization: Asmaa M. Abdullateef & Salah A. Hussain.
- Data curation: Salah A. Hussain & Asmaa M. Abdullateef.
- Formal analysis: Salah A. Hussain & Asmaa M. Abdullateef.
- Funding acquisition: Asmaa M. Abdullateef.
- Investigation: Asmaa M. Abdullateef, Salah A. Hussain.
- Methodology: Asmaa M. Abdullateef & Salah A. Hussain.
- Project administration: Salah A. Hussain & Asmaa M. Abdullateef.
- Resources: Salah A. Hussain & Asmaa M. Abdullateef.
- Software: Asmaa M. Abdullateef.
- Supervision: Salah A. Hussain.
- Validation: Salah A. Hussain.
- Visualization: Asmaa M. Abdullateef.
- Writing – original draft: Asmaa M. Abdullateef.
- Writing – review and editing: Salah A. Hussain.

Declaration of Competing Interest

The authors declare that they have no competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Funding Sources

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sector. The authors personally covered the research expenses.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Acknowledgments

The authors sincerely thanks Prof. Dr. Salah for his continuous supervision, valuable guidance, and generous support throughout this research. His time, effort, and scientific advice were essential to the completion of this work.

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