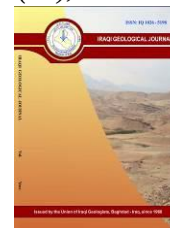




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Microfacies Analysis and Depositional Environments of the Khurmala Formation in Selected Sections, Kurdistan Region, North of Iraq

Sabreen F. Oraibi^{1*}  and Hamid A. Alsultan¹ 

¹ Department of Applied Geology, College of Science, University of Babylon, Hilla, Babylon, Iraq

* Correspondence: sci731.sabreen.fadel@student.uobabylon.edu.iq

Abstract

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This study examines the strata of the Paleocene-Early Eocene Khurmala Formation, focusing on the Gali Zanta and Sheikh Abdulaziz (Ancient Aqra) sections from the Aqra area, Kurdistan Region, North of Iraq. Petrographic analysis of 120 samples indicate a carbonate-dominant succession comprising limestone, marly limestone, and marl intercalations. Petrographic analysis shows that the matrix is mostly made up of micrite, and sparite through crystallization. The skeletal remains show a lot of different types of skeletal forms. The fossil assemblage, composed mainly of benthic foraminifera (which consist of Miliolids, *Discocyclina*, and Rotaliids), along with pieces of corals, bryozoans, and calcareous algae, indicates a shallow-marine depositional environment characterized by moderate-to-low energy conditions. Six different submicrofacies were discovered, including bioclastic mudstone, benthic foraminiferal wackestone, and miliolid packstone. These microfacies associations constitute a complex deposited system that includes lagoonal and peritidal settings, as well as localized patch reefs.

Keywords: Microfacies analysis; Depositional environment; Khurmala Formation; Aqra area; North of Iraq

1. Introduction

Microfacies analysis is an essential tool in petrographic and micropalaeontological studies, providing for stratigraphic correlation and providing critical insights into depositional environments (Flügel, 2010). The present research focuses on the microfacies of the Khurmala Formation, first identified by Bellen (1959) from the Kirkuk-114 well. The lithology can be described by dolomite (partially pseudoolitic) and recrystallized limestone. The formation has a thickness of 185 m at its type locality and is stratigraphically classified as Paleocene–Early Eocene (Bellen et al., 1959). The Khurmala Formation is an essential component of the Megasequence AP10 from a regional tectonic view (Sharland et al., 2001). This megasequence contains a specific Middle Paleocene–Eocene lithostratigraphic succession in the North of Iraq, including the Kolosh, Sinjar, Khurmala, Avana, Gercus, and Pila Spi formations. Jassim and Goff (2006) posited that the Khurmala Formation was likely deposited in a relict basin linked with the southeastern region of the Kolosh trough. This basin was separated from the offshore Aaliji basin by a partially disconnected submarine ridge upon which sediments of the Sinjar Formation were deposited. Al-Qayim and Nisan (1989), while investigating the carbonate-clastic sequence of the Haibat-Sultan area, suggested that the carbonate sequence is lagoon-like in nature. They argue that it should be designated as the Khurmala Formation rather than a Sinjar Formation tongue, as previously believed by Bellen et al. (1959); Kassab (1976); Shathaya

(1980). A great deal of study has been performed on the stratigraphic architecture and lithological differentiation of the Khurmala and Sinjar formations in the North of Iraq. The lateral transitions and depositional boundaries of these Paleogene units have consistently been the focus of intense academic debate. Following Bellen et al. (1959) pioneering regional stratigraphic framework, several key studies have refined our understanding of these successions (Al-Eisa, 1983; Al-Sakry, 1999, 2006; Asaad and Balaky, 2018). In addition, newer sedimentological and biostratigraphic studies (Lawa, 2004; Karim, 2009; Al-Dabagh, 2010; Mohammed Salih, 2013; Al-Dabbas et al., 2014; Omer et al., 2014; Tamar-Agha et al., 2015) have addressed the complexity of facies development within the basin. These cumulative studies, such as the latest critical analyses by Al-Qayim and Barzani (2021), have provided critical criteria for identifying the restricted lagoonal carbonate sequences of the Khurmala Formation from the reefal to fore-reefal assemblages that characterize the Sinjar Formation. In terms of subsurface characterization, Abdula et al. (2025) used neutron-density cross-plots to find lithological variations in the formation in the North of Iraq. These petrophysical data indicate the existence of heterogeneous carbonate successions, which are mainly made up of alternating dolomitic and calcitic layers. The Paleogene succession in Iraq marks the peak development of the Inner Foredeep Basin on the Arabian Shelf (Buday, 1980). This period, associated with the AP10 Megasequence, coincides with the terminal closure of the Neo-Tethys and renewed subduction activities (Sharland et al., 2001).

These geodynamic events induced NW–SE trending structural ridges and basins, causing pronounced lateral facies variations and the absence of Danian deposits due to Early Paleocene regional uplift (Jassim and Goff, 2006). Geologically, this succession represents the Foreland Basin development within the folded zone, characterized by intense Mesozoic and Tertiary folding (Numan and Al-Azzawi, 1993). Structurally, the study area is situated on the southern limb of the Aqra Anticline within the High Folded Zone (Fig.1).

The primary objective of this study is to evaluate the Khurmala Formation in the Aqra area by conducting a detailed microfacies analysis of the Gali Zanta and Gali Sheikh Abdulaziz sections. By describing the rock components and textures. The study aims to accurately determine the depositional environment of the formation.

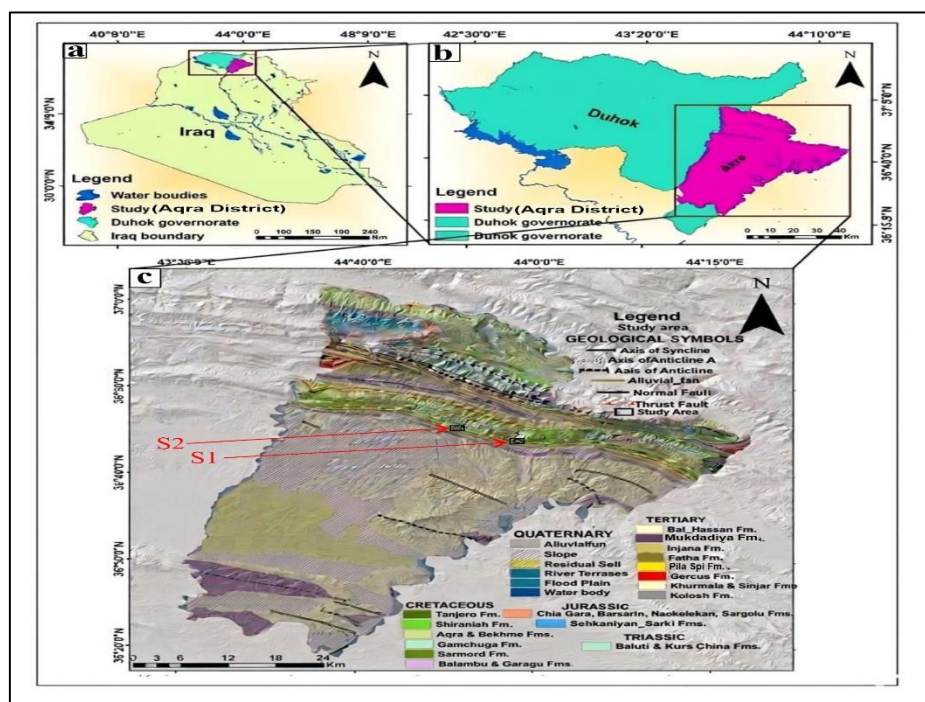


Fig.1. Location maps: a) Iraq map; b) Duhok province map; and c) Geological map of study area originally based on Sissakian and Fouad (2015)

2. Methodology

Fieldwork was performed in the Aqra District, Duhok Governorate, the North of Iraq. Two stratigraphic sections, Gali Zanta and Gali Sheikh Abdulaziz, were chosen to order to identify the Khurmala Formation and establish its lower and upper contacts. Comprehensive lithostratigraphic logging was conducted, and sampling was executed according to lithological variations, color alterations, and fossil occurrences. A total of 54 samples were collected from the Gali Zanta section, and 60 samples were acquired from the Gali Sheikh Abdulaziz section.

Laboratory work was carried out at the Department of Geology, College of Science, University of Babylon. A total of 75 thin sections were prepared for high-resolution petrographic analysis. Microfacies analysis was performed using a polarized light microscope, and the carbonate rocks were classified according to the standard schemes of Dunham (1962). For paleoenvironmental interpretation, the identified facies were correlated with the Standard Microfacies (SMF) and Facies Zone (FZ) models proposed by Wilson (1975) and Flügel (2010).

3. Results

3.1. Petrography and Lithostratigraphy

The Khurmala Formation (Paleocene–Early Eocene) constitutes a noteworthy carbonate period in the Paleogene sequence within the North of Iraq (Bellen et al., 1959; Jassim and Goff, 2006). The stratigraphic structure was examined in the Gali Zanta and Gali Sheikh Abdulaziz sections through lithological transitions. To determine the sedimentological characteristics of the collected 114 samples from both sites, a systematic petrographic study was carried out. The formation reaches a thickness is 95 m at the Gali Zanta section (36° 44' 02.47" N, 43° 58' 20.40" E), with a conformable lower contact with the Sinjar Formation characterized by a change from massive coral-rich limestones to thick-bedded mollusc-bearing units, and a conformable and sudden influx of siliciclastic red beds defining its upper boundary with the Gercus Formation. Lithologically, this section shows a transitions from thick-bedded limestones with significant bitumen impregnation to medium-to-thin-bedded limestones with marl intercalations (Fig.2). In contrast, at the Gali Sheikh Abdulaziz section (36° 45' 48.64" N, 43° 53' 18.56" E), the thickness is 112 m, with the lower contact defined by an unconformity with the underlying Aqra Formation and separated by massive bituminous units, but the upper contact remains obscured due to lack of exposure. This section consists primarily of thick-bedded indurated limestones, dolomite, and bituminous intervals interspersed with thin marly limestone layers.

Microfacies analysis was conducted on the sequence of the Khurmala Formation to clarify sedimentary environments and diagenetic processes. Sedimentary facies vary from other facies due to unique lithological characteristics, such as grain size, mineral chemistry, and sedimentary systems. The matrix predominantly includes micrite, a brown microcrystalline calcite that commonly transforms into microsparite upon recrystallization. In regions with increased cementation, micrite transforms into sparite, which is composed of calcite crystals exceeding 4 microns in size (Flügel, 1982). This matrix comprises both skeletal and non-skeletal grains, suggesting variations in deposition energy and biogenic input. Numerous varieties of skeletal grains exist. Benthic foraminifera, including Miliolids (Fig. 3a), *Discocyclus* (Fig. 3b), *Textularia*, *Lockhartia* (Fig. 3c), *Rotalia* (Fig. 3d), *Lepidocyclus*, calcareous algae (Fig. 3e), echinoderm fragments, coral, Mollusca (Fig. 3f), small foraminifera, (Fig. 3g), *Elliphedium* (Fig. 3h), and ostracoda, indicate shallow, low- to moderate-energy marine environments with fluctuating salinities (Wilson, 1975).



Fig. 2. The lower and upper contacts of the Khurmala Formation at the Gali Zanta section (formations are overturned)

3.2. Microfacies of the Khurmala Formation

3.2.1. Mudstone microfacies

This microfacies is distinguished by its micrite groundmass, which contains fewer than 10% grains (Dunham, 1962). It includes two submicrofacies in the studied rocks of the Khurmala Formation, with fine bioclastic grains and extra clastic quartz. The microfacies includes the following submicrofacies.

- Bioclastic lime mudstone submicrofaices: This submicrofacies (Kf1) comprises a micritic to microsparitic matrix with less than 10% skeletal bioclastic debris. The fossil collection consists mainly of benthonic foraminifera, such as Miliolids and *Textularia*, with sporadic occurrences of

gastropod shells. Moreover, a terrigenous influx is indicated by the presence of detrital grains comprising chert, quartz, and iron oxides, interspersed with dispersed intraclasts. Petrographic studies showed that the micritic groundmass has been locally dolomitized and recrystallized (Fig. 4a). This microfacies occurs mostly in the upper and lower intervals of the stratigraphic section. It is consistent with Standard Microfacies (SMF 23) from Facies Zones 8 and 9, indicating tidal to intertidal depositional environments. These microfacies are observed throughout the lower, middle, and upper parts of the Khurmala Formation in the Gali Zanta and Gali Sheikh Abdulaziz sections (Figs. 5 and 6).

- Non-fossiliferous lime mudstone submicrofacies: The submicrofacies (Kf2) mainly occurs in the upper intervals and occasionally in the lower intervals of the examined stratigraphic section. It features a uniform micritic matrix, largely lacking skeletal grains, that has experienced extensive dolomitization. A distinctive attribute of this microfacies is the incidence of detrital sand grains (quartz or chert), signifying a terrigenous influx (Fig. 4b). The dolomite crystals display a microcrystalline structure, indicating an incipient syngenetic dolomitization process. These microfacies are observed throughout the lower, middle, and upper parts of the Khurmala Formation in the Gali Zanta Section and the upper part in the Gali Sheikh Abdulaziz section (Figs. 5 and 6). This facies aligns with Standard Microfacies (SMF 23), located within Facies Zone 8 or 9, indicative of a lagoonal to tidal flat depositional environment, as per the standard microfacies models of Flügel (2010) and Wilson (1975).

3.2.2. Wackestone microfacies

The microfacies includes the following submicrofacies

- Bioclastic Wackestone Submicrofacies: This submicrofacies (Kf3) primarily comprises bioclasts. The bioclasts comprise shell fragments such as pelecypods, echinoderms, ostracods, and bryozoans. A tiny percentage of benthic foraminifers, such as rotaliids and miliolids, as well as uncommon planktonic foraminifers, can be found locally in the lower half of the formation. This microfacies exhibits various diagenetic processes, including dolomitization, neomorphism, selective dissolution, and cementation (Fig. 4c). These submicrofacies are observed throughout the lower parts of the formation in the studied sections (Figs. 5 and 6). This submicrofacies has characteristics similar to Flügel's (1982) SMF10 and Wilson's (1975) FZ 7, and it indicates a low-energy shallow lagoon with open marine water circulation.
- Benthic Foraminifera Wackestone: In the current investigation, this submicrofacies (Kf4) is mostly formed of limestone and partially dolomitic limestone with bioclastic and micrite groundmasses. The particles are primarily composed of small benthic foraminifera such as Miliolid and Rotaliid with echinoderm plates (Fig. 4d). Other diagenetic processes' materials that worked on this submicrofacies include cementation and stylolization, with the stylolite being filled with organic mechanical compaction, which has influenced micritization, a process that results in skeletal grain disintegration and the development of moldic porosity. Some chamber skeletal grains may be partially or completely filled with sparry calcite cement or organic substances. These submicrofacies are observed throughout the lower and upper parts of the formation in the Gali Zanta section and the lower part of the formation in the Gali Sheikh Abdulaziz section (Figs. 5 and 6). According to Flügel (1982) and Wilson (1975), this microfacies correlates with Standard Microfacies (SMF-19), deposited within an open circulation lagoon, corresponding to FZ-8.

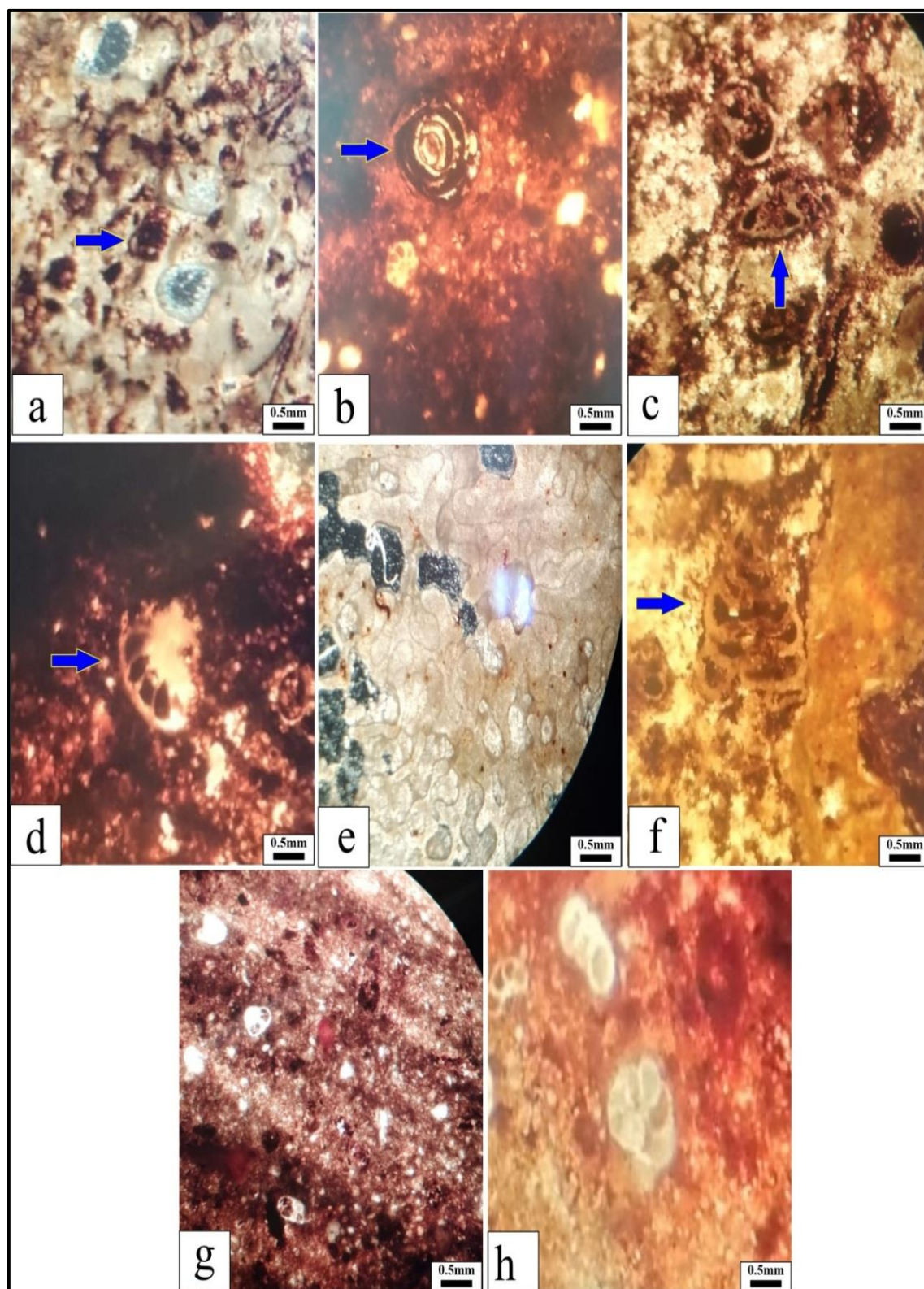


Fig.3. a) Miliolids (benthic foraminifera), sample No.48 in Gali Zanta section, b) *Discocyclina* (benthic foraminifera), sample No.27 in Gali Sheikh Abdulaziz section, c) *Lockhratia* (benthic foraminifera), sample No.10 in Gali Sheikh Abdulaziz section, d) *Rotalia*, (benthic foraminifera), sample No.6 in Gali Zanta section, e) calcareous algae sample No.5 in Gali Sheikh Abdulaziz section, f) gastropoda sample No.41 in Gali Sheikh Abdulaziz section, g) small foraminifera, No.13 in Gali Sheikh Abdulaziz section, h) *Elliphedium* sample No.43 in Gali Zanta section

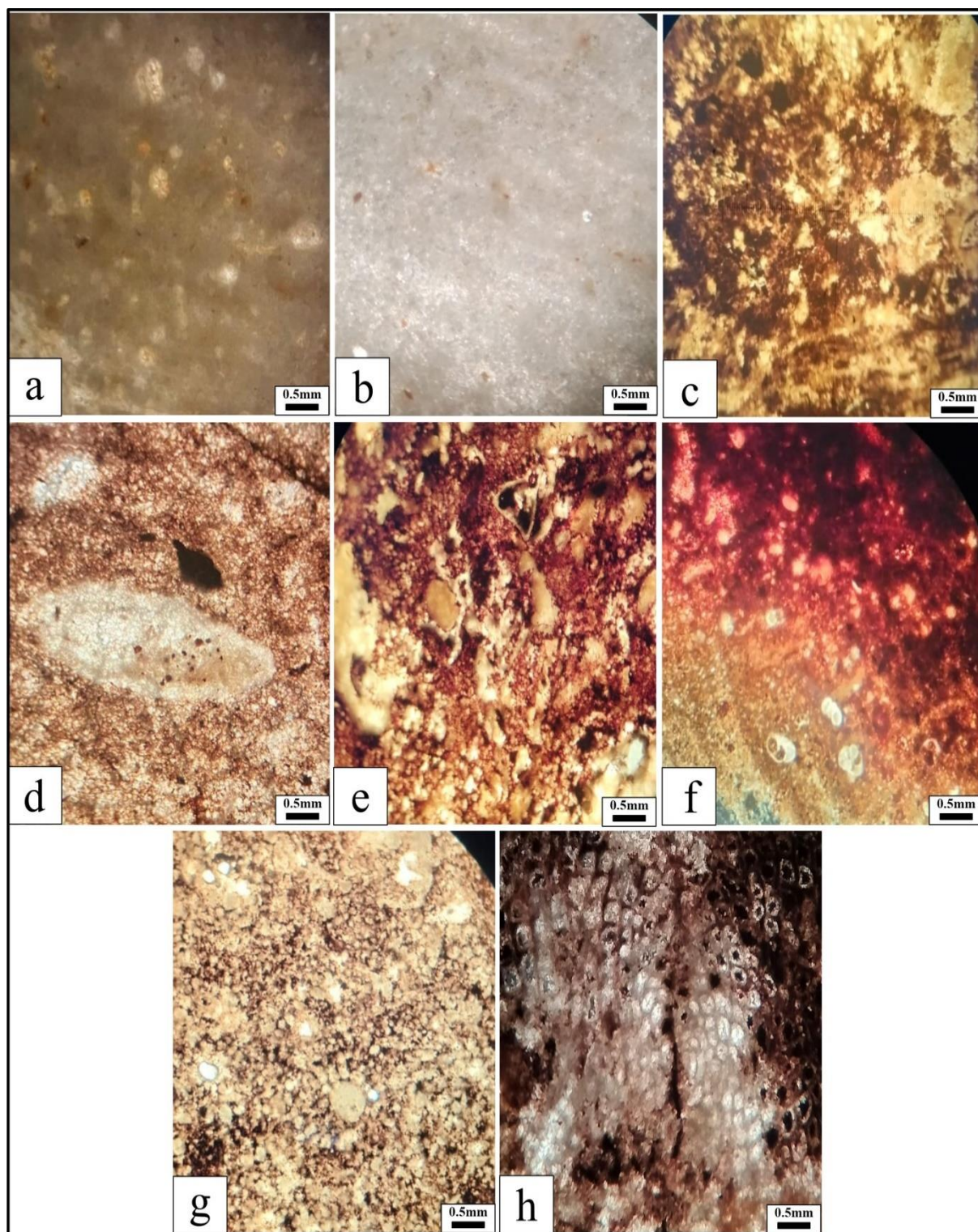


Fig.4. a) Bioclastic mudstone submicrofaices, sample No. 36 in Gali Sheikh Abdulaziz section, b) Homogenous mudstone submicrofacies, sample No. 52 in Gali Sheikh Abdulaziz section, c) Bioclastic Wackestone submicrofacies, sample No. 6 in Gali Zanta section, d) Benthic Foraminifera wackestone submicrofacies, sample No. 13 in Gali Zanta section, () Bioclastic packstone submicrofacies, sample No. 27 in Gali Sheikh Abdulaziz section, f) Miliolidal packstone submicrofacies, sample No. 55 in Gali Sheikh Abdulaziz section, g) Grainstone microfacies, sample No. 43 in Gali Zanta section, h) Boundstone microfacies, sample No. 46 in Gali Zanta section

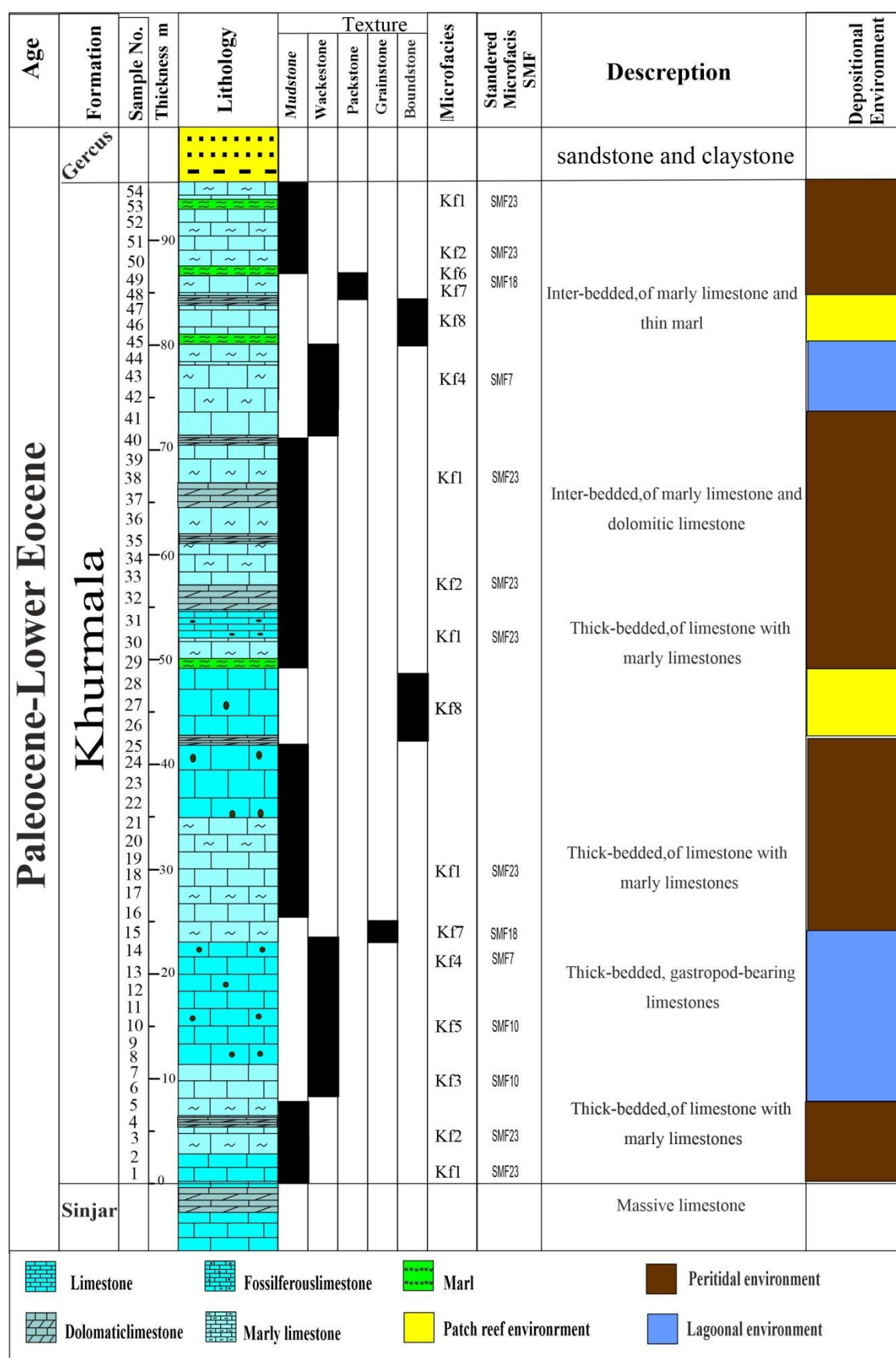


Fig. 5. Lithostratigraphic column showing the main lithology, samples and microfacies of the Khumala Formation in the Gali Zanta section

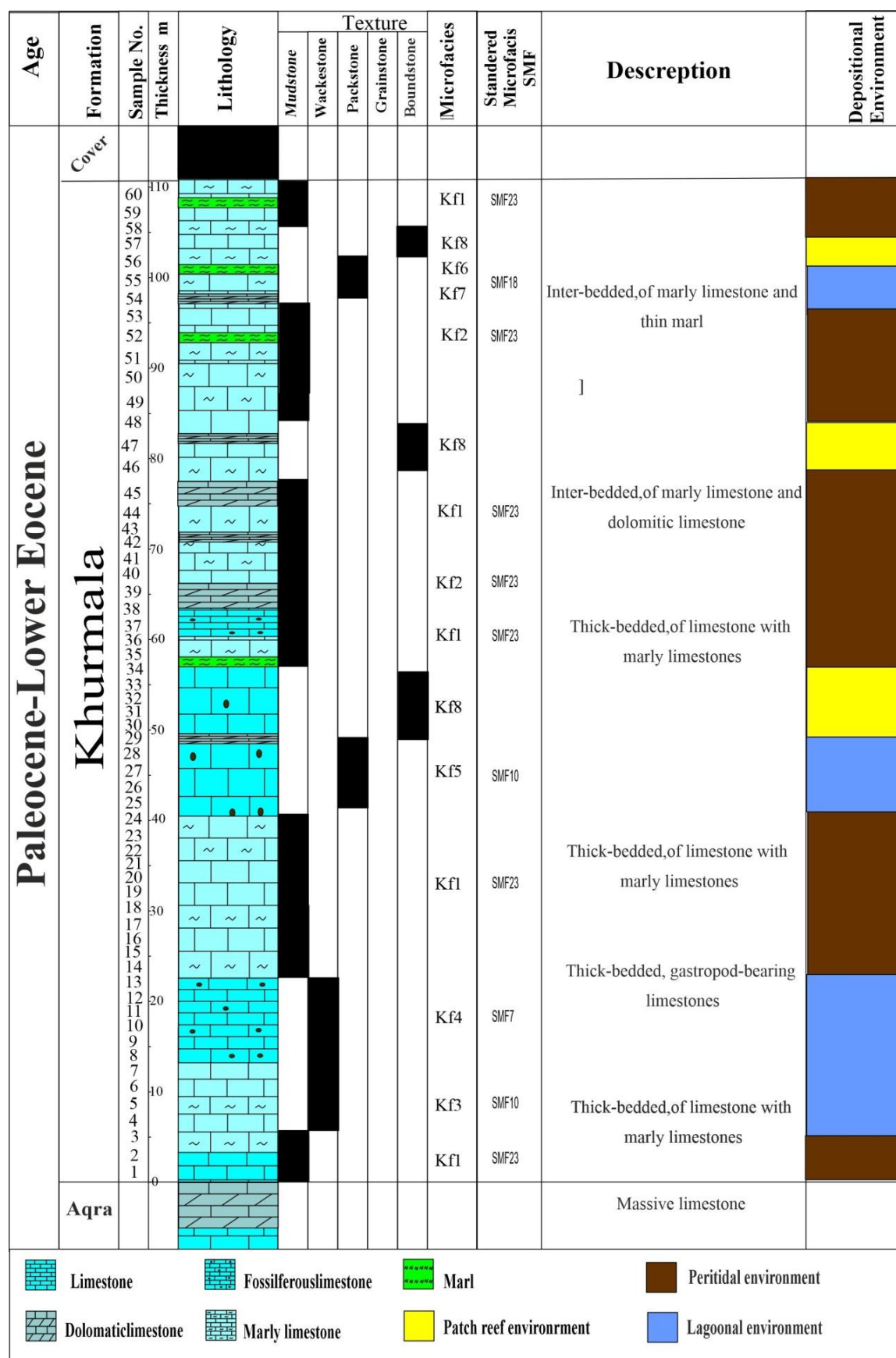


Fig. 6. Lithostratigraphic column showing the main lithology, samples and microfacies of the Khumala Formation in the Gali Sheikh Abdulaziz section

3.2.3. Packstone microfacies

- Bioclastic Packstone Submicrofacies: This submicrofacies (Kf5) consists of shell fragments of miliolids, calcareous algae, benthic foraminifera, echinoderm fragments and ostracods. This microfacies are likewise affected by recrystallization, and the biomolds are filled with calcite cement (Fig. 4e). The fragmentation of skeletal grains is mostly determined by energy from waves, as is the case with SMF type10 with Fz7. These microfacies are observed throughout the lower parts of the Khurmala Formation in the Gali Zanta section and the middle part in the Gali Sheikh Abdulaziz section (Figs.5 and 6).
- Miliolidal Packstone Submicrofacies: This submicrofacies (Kf6) is mainly composed of miliolids (*Quinqueloculina*, *Pyrgo*, and *Triloculina*), with the last one accounting for more than 60% of the total components (Fig. 4f). Bioclasts from pelecypods, gastropods, and echinoderms are also observed. This submicrofacies is observed in the upper part of the formation in both studied sections (Figs. 5 and 6). This microfacies corresponds to SMF 18 within FZ 7 (Wilson 1975; Flügel 1982) and reflects a lagoon.

3.2.4. Grainstone microfacies

This microfacies occurs in the lower part of the Gali Zanta section. The bioclastic grainstone particles (Kf7) account for 55% of the total composition (Fig. 4h). The bioclasts are made up of various shell fragments such as gastropods, pelecypods, echinoderms, and a moderate amount of benthic foraminifers (miliolids), like *Quinqueloculina* and *Triloculina* (Fig. 4g). Peloids are also abundant locally, and they are supported by microspars and sparites, indicating a depositional environment with high water energy (Flügel, 2010). Furthermore, the round shape of the allochems indicates depositions with high energy environment conditions. It is equivalent to standard microfacies 18 of Flügel (1982) and Wilson's facies zone 7 (1975), which represent the restricted lagoonal platform environment. These microfacies are observed throughout the upper and middle parts of the Gali Zanta section and the upper part of the Gali Sheikh Abdulaziz section.

3.2.5. Boundstone microfacies

The skeletal components form the most important structure of this microfacies (Kf8). These elements are predominantly represented by sessile benthic organisms, including calcareous green algae, corals, and bryozoans. A small percentage of associated biota, including echinoderms, benthic foraminifera, and Mollusca shells, exist as interstitial inhabitants within these colonies. This microfacies is observed in the upper and middle parts of the formation of the Gali Zanta section and in the whole formation of Gali Sheikh Abdulaziz section. The microfacies is primarily sustained by bryozoans and green algae, with sporadic occurrences of Rotaliids and Miliolids (Fig. 4h). Some fine crystal calcite cements surround early (marine) corals, such as acicular, and are mainly neomorphized in later stages of diagenesis.

3.3. Microfacies Association and Depositional Environment

The Khurmala Formation in the Aqra is a complex carbonate platform system formed by changes in depositional energy, water depth, salinity, and biological productivity. These factors resulted in the formation of various sediment facies that reflect different depositional environments across the platform. The interpretation of these environments is based on integrative core description, thin-section petrography, and facies analysis (Flügel, 2010). The Khurmala Formation has facies associations that include open marine, restricted lagoon, and Patch reef settings (Figs. 3 and 4). Each of these

environments provided a distinctive contribution to sediment composition, texture, fossil collections, and porosity evolution.

3.3.1. Lagoonal environment

The lagoonal environment can be described as a low-energy and shallow-water region sheltered within the inner carbonate shelf. This study characterizes the environment through wackestone to Packstone microfacies, primarily consisting of miliolids, calcareous green algae, and molluscs (including pelecypods and gastropods), along with peloids, all set within a micritic matrix. The most notable miliolid genera discovered are *Quinqueloculina* and *Triloculina*, as well as other benthic foraminifera including Rotaliids and Textulariids. This environment is defined by bioclastic wackestone, benthic foraminifera, wackestone, bioclastic packstone, miliolidal packstone, and grainstone.

Much sedimentological researches suggest that these biotic assemblages are indicative of a shallow lagoonal environment. Pomar et al. (2014) and Bucur and Sasaran (2005) indicate that the presence of Miliolids, Rotaliids, and calcareous green algae (notably the family Dasycladaceae), alongside Gastropods and Pelecypods (Bivalves), denotes a sheltered, shallow-marine lagoon. These organisms grow in confined environments and demonstrate a significant tolerance for changing salinity levels. A moderate-energy zone, located between the platform interior and the deeper basins, consists of facies such as bioclastic wackestone, bioclastic packstone, and bioclastic grainstone, including fossils such as benthic foraminifera wackestone, and echinoderms. This zone indicates good circulation (Flügel, 2010) (Figs. 5 and 6). Grainstones typically occur in higher-energy and shallow-water environments, like back reefs or lagoons (Ghosh and Sarkar, 2013). While the distributed branching coral fragments within bioclastic grainstone explain diminutive water energy in the deep part of the lagoonal setting (Sahraeyan et al., 2014).

A moderate-energy zone, located between the platform interior and the deeper basins, is consists of facies such as bioclastic wackestone, bioclastic packstone, and bioclastic grainstone, including fossils such as benthic foraminifera, wackestone, and echinoderms. This zone indicates good circulation (Flügel, 2010) (Figs. 5 and 6). Grainstones typically occur in high-energy, shallow-water environments such as back-reef and lagoonal settings (Ghosh and Sarkar, 2013). However, the presence of branching coral fragments within bioclastic grainstone may indicate episodic high-energy conditions, even within deeper parts of the lagoon (Sahraeyan et al., 2014). Bioclastic packstone, consisting of bivalves, gastropods, bryozoan fragments, miliolids, red algae, and coral fragments, usually appears on back reefs or in lagoonal setting; the mentioned bioclast components belong to the back reef (Shakeri et al., 2007). Such facies with these faunal assemblages were considered as patchy distribution in the Paleocene-Eocene by Waśkowska et al. (2014) in Outer Carpathian basins.

3.3.2. Peritidal environment

The peritidal environment is mainly identifiable in the upper layer of the examined stratigraphic sections. The occurrence is shown by the existence of homogeneous, microcrystalline dolomitized non-fossiliferous lime mudstone and bioclastic lime mudstone, both showing an influx of detrital quartz grains. Based on Ivanova et al. (2008), the high incidence of early-stage (syngenetic) dolomitization, the scarcity of evaporites, and the homogeneous, fossil-poor nature of the dolomitized mudstone facies all point to early diagenetic processes, which are typical of tidal flat settings. Furthermore, Colombie and Strasser (2005) suggested that the association of homogeneous dolomatic mudstone with bioclastic mudstone facies indicates a transition from lagoonal to intertidal environments. The existence of detrital quartz grains in these facies indicates their proximity to the shoreline and terrigenous source. A low-energy, poorly circulated setting located behind shoals is constructed of bioclastic mudstone,

homogeneous mudstone, and miliodal packstone. A fine micritic matrix with occasional clay indicates warm, saline, and stagnant conditions (Flügel, 1982; Tucker and Wright, 1990). The accumulation of abundant micritic matrix, low benthic faunal variety, and the existence of microcrystalline dolostone all point to inactive water circulation in these lagoonal sediments. It is well-developed near the lower part of both sections.

3.3.3. Patch reef

The Boundstone microfacies, observed at the base of the Khurmala Formation in the Gali Zanta section and the central part of the formation in the Gali Abdul-Aziz section, signifies a comparatively high-energy depositional environment. The facies are situated within the lagoonal environment as organic buildups (bioherms), predominantly derived from a framework of bryozoans and calcareous green algae, along with associated benthic foraminifera (Miliolids, Rotaliids, and Textulariids) and molluscan fragments. Bryozoans, while capable of enduring cool-water conditions, predominantly thrive in warm, shallow marine environments marked by moderate to high hydrodynamic energy (Nakrem, 1992; Cuffey, 2006). In these ideal conditions, bryozoans establish colonial structures within the lagoon, producing rigid organic formations. The prevalence of peloids within a sparry calcitic cement (sparite) offers additional petrographic evidence of high-energy conditions. Thus, this microfacies coincides with SMF 12, signifying winnowed organic accumulations that occur in the inner shelf environment (Flügel, 2010). Bryozoans, while capable of enduring cool-water conditions, predominantly thrive in warm, shallow marine environments marked by moderate to high hydrodynamic energy (Nakrem, 1992; Cuffey, 2006). In these ideal conditions, bryozoans establish colonial structures within the lagoon, producing rigid organic formations.

The presence of algae indicates shallow deposition conditions, suggesting the presence of patch reef (Shirazi et al., 2012), perhaps in the first stage of evolution. Scheibner et al. (2007) discovered boundstone and bindstone with algal mats in the Upper Paleocene (Pyrenees, Spain), while Zamagni et al. (2008) discovered Thanetian in an enclosed and restricted environment in the northern Tethys (SW Slovenia).

4. Conclusions

- The Khurmala Formation (Paleocene–Early Eocene) in the North Iraq was investigated by petrographic analysis of 114 samples collected from the Gali Zanta (95m thick) and Gali Sheikh Abdulaziz (112 m thick) sections. Lithologically, the sequence includes thick-to-thin bedded limestones, dolomites, and bituminous intervals with marl intercalations. Stratigraphic contacts vary from a conformable contact with the Aqra Formation to an unconformity with the Gercus Formation, reflecting significant Paleogene environmental transitions.
- Five main microfacies are recognized in the Khurmala Formation: Mudstone, Wackestone, Packstone, Grainstone, and Boundstone. These are further subdivided into several submicrofacies, including Bioclastic Mudstone, Homogenous Mudstone, Bioclastic Wackestone, Benthic Foraminiferal Wackestone, Bioclastic Packstone, and Miliolid Packstone.
- Microfacies analysis indicators of the Khurmala Formation depositional environment are represented by a peritidal environment, lagoonal environment, and patch reef

Author Contributions: (CRediT)

Sabreen: Field sampling, preparation of thin sections, and interpretation of results.
Hamed A. Al-Sultan: Supervision and scientific guidance during field and laboratory work.

Declaration of Competing Interest

The author declares that there are no conflicts of interest regarding the publication of this research.

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Data Availability

All data generated or analyzed during this study are included in this published article and its supplementary materials. The data were obtained from field samples and laboratory analyses, and interpreted using relevant previous studies.

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