Porosity Evolution and Microfacies Analysis of the Khurmala Formation (Paleocene-Early Eocene) from Selected Sections in Kurdistan Region, Northern Iraq Revealed by Cathodoluminescence Spectroscopy

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Abstract

The microfacies analysis and porosity evolution of the Khurmala Formation (Paleocene-Early Eocene) were studied in the Gomaspan and Sheraswar sections in the High Folded Zone, northeastern Erbil City, Kurdistan Region (N-Iraq). Lithologically, the Khurmala Formation in the Gomaspan section is about 23.5 m comprised of thick to massive bedded brecciated grey dolomitic limestone in lower and middle parts and interbedding of medium to thick beds of grey dolomitic limestone and yellow calcareous shale in the upper part. The Sheraswar section comprises 18.5 m yellow marl, thick yellowish-grey dolomitic marly limestone in the lower part, and bedded grey limestone interbedded with thin blue marl, shale, and mudstone in the upper part. The petrographic and cathodoluminescence (CL) studies of 20 thin sections of the Khurmala carbonates show that most skeletal grains are shallow marine derivative faunas and non-skeletal grains represent intraclasts, peloids, ooids, and extraclasts (monocrystalline quartz). Five main microfacies were identified in the studied rocks, and they integrated into two facies associations relating to their environmental interpretation: back reef/lagoon and patch reef. A new eight pore types were distinguished in the carbonate rocks of Khurmala Formation: interparticle, intraparticle, growth framework, intercrystalline, moldic, vuggy, fracture, and stylolite porosities. Most of the primary porosity was reduced by compaction and cementation due to effect of intensive diagenesis. Secondary porosity is predominant in both studied sections, the most common being the moldic porosity associated with different microfacies fabrics. CL investigations revealed that dolomitized lime wackestone microfacies has two types of different cementations in the late stages of blocky calcite cement which are discontinuous light to dull orange luminescence without zoning, and pure calcite cement of coarse to very coarse blocky calcite cement with characteristic bright orange luminescence and tight zoning.

Keywords: Paleocene-Early Eocene; Khurmala Formation; Microfacies; Porosity; cathodoluminescence; Kurdistan Region-Iraq

1. Introduction

The porosity in carbonate rocks is of considerable interest because it comprises approximately half of the world’s hydrocarbon reservoirs. Most reservoir rocks are formed in shallow marine environments. Carbonates contain both primary and secondary porosities, which decrease with progressive burial

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leading to an increase in the toughness of the rock (Dasgupta and Mukherjee, 2020). The determination of carbonate rocks characteristics including microfacies and diageneis are critical in controlling their pore system (Boutaleb et al., 2022).

The Middle Paleocene- Eocene succession, which include the Khurmala Formation, are important oil reservoirs in the Kurdistan region (North Iraq) (Lawa, 2004). The carbonate rocks of the Khurmala Formation have undergone many diagenetic modifications after deposition and have a debatable role as a potential reservoir after renewed hydrocarbon exploration in the Kurdistan region (Barzani and Al-Qayim, 2019). The formation was deposited during the Late Paleocene-Early Eocene age and first identified by Bellen in 1953 in the Kirkuk-114 well, comprising 185 m of dolomite (pseudoolitic in parts) and finely recrystallized limestone (Bellen et al., 1959). It lies in the limited zone between Bashiqa-Jabal Maqlub in the northwest and the Chemchemal-Qizil Dagh area in the southeast (Bellen et al., 1959).

Previous studies on the sedimentological, stratigraphic, and palaeontological aspects of the Khurmala Formation in Iraq, have not focused on the detailed microfacies study and porosity types revealed by cathodoluminescence (CL) spectroscopy. The most interested are the studies by Lawa (2004); Salih (2010); Omer et al. (2014); Tamar Agha et al. (2015); Asaad and Balaky (2018); Karim et al. (2018); Barzani and Al-Qayim (2019); Al-Qayim and Barzani (2021); Ahmed (2022) and Asaad et al. (2022). The main objective of this study is detailed microfacies analysis, porosity evolution, and determination of the depositional environment of the Khurmala Formation in the Gomaspan and Sheraswar sections using petrographic investigation and CL spectroscopy.

2. Geologic Setting

The studied outcrops of the Khurmala Formation are located in the northeast Erbil city, Kurdistan region, North of Iraq. The Gomaspan section is situated near Gomaspan village, 30 km northeast of Erbil city on the paved road of the Erbil-Dolly Smaquli, at 36° 16’ 48” N and 44° 20’ 07” E. The Sheraswar section is located near Kore village on the Erbil-Shaqlawa main road, 49km northeast of Erbil city, approximately at 36° 24’ 40” N. and Long. 044° 15’ 53” E. Structurally, the Gomaspan section lies in the southern limb of the Bina Bawi anticline which is characterized by NW-SE trending, vergence to the SW and is linked to the NW with Pirmam anticline together may form one large anticline exceeds 75 km long (Awdal et al., 2013). The Sheraswar section is situated in the southern limb of the Safin anticline in the area where the anticline is dissected by the Hujran stream (Figs. 1a and b). The stratigraphic successions of the Gomaspan section involve the Bekhme, Shiranish and Tanjero formations from the Upper Cretaceous overlain by Tertiary formations, including Kolosh, Khurmala, Gercus, Avanah, Pila Spi, Fatha (Lower Fars), Injana (Upper Fars), Mukdadiya (Lower Bakhtiari) and Bai Hasan (Upper Bakhtiari) (Asaad, 2022). The Stratigraphic successions of the Safin anticline toward its southern limb are represented by the Upper Cretaceous Qamchuqa, Bekhme, Shiranish, Tanjero, tuned on to Tertiary formations including Kolosh, Khurmala, Gercus, Pila Spi, Fatha and Injana (Fig. 1a) (Abid et al., 2022).

Lithologically, the Khurmala Formation in Gomaspan outcrop consists of 23.5m of thick to massive bedded grey dolomitic limestone mostly brecciated in lower and middle part and medium to thick beds of grey dolomitic limestone intercalated with yellow calcareous shale in the upper part (Fig. 2a). In contrast, the formation in the Sheraswar section is about 18.5m thick. The lower part comprises 1.5 m thick yellow marl and 6.5 m very thick to massive yellow to grey dolomitic marly limestone which partly bears bitumen and its upper part includes 5 m of thick grey-bedded bituminous limestone interbedded with very thin blue marl and shale, overlies by 5.5 m of thin to medium grey bedded limestone interbedded with red mudstone of Gercus in last bed (Fig. 2b). Its boundaries are abrupt and conformable with the Kolosh Formation and conformable and gradational with the overlying Gercus
Formation in the Sheraswar section. In contrast, it is tongued within gray shale of the Kolosh Formation in the Gomaspan section.

Fig. 1. (a) Location of studied sections and tectonic subdivision of Iraq (after Jassim and Goff, 2006); (b) Geological map of studied area (after Sissakian and Fouad, 2014).

3. Materials and Methods

The preliminary fieldworks started with the conception of general geology and structural relevance’s of the Cretaceous-Paleogene units in the area of the High Folded Zone in northeastern Erbil city to select appropriate sites for current study. The Gomaspan and Sheraswar sections in the southern limb of the Bina Bawi and Safin anticlines, respectively, were chosen. The field works in both studied sections, including detailed description and measuring of the Khurmala Formation e.g. logging of the lithology and mineralogy. Twenty samples were collected from the carbonate rocks. The upper and lower parts of each sample were marked. Laboratory work was enhanced by preparing 20 thin sections (10 from each section) in the workshop of the department of Earth Sciences and Petroleum, Salahaddin University-Erbil. The thin sections were stained by Alizarin Red S (ARS) solution according to the Friedman (1959) procedure to distinguish between dolomite and calcite. A thoughtful petrographic description and microfacies analysis of the thin sections were performed using polarizing microscope, depending on Dunham (1962) classification. The identification of the porosity types in the studied thin sections were based on the classification of Choquette and Pray (1970). Both porosity evolution and microfacies analyses were dependent on CL investigations.
Fig. 2. Field photographs showing: (a) Khurmala Formation interfingers with grey shale of Kolosh Formation in Gomaspan section; (b) the Khurmala Formation overlying grey shale of the Kolosh Formation and underlying red mudstone of the Gercus Formation in Sheraswar section.

Cathodoluminescence study were performed by using twenty samples in the hot cathode (CL) instrument at Bochum University-Germany (HC1-LM, Neuser, 1995) in integration with high resolution spectral analysis device (Neuser et al., 1996), to determine porosity types and microfacies analysis. The CL equipment was connected to a Kappa DX30C video camera system to recording digital images and with an EG & G-triple grating spectrograph joint to a liquid-N2 cooled CCD detector allowing the documentation of very short-lived and dull luminescence phenomena. An acceleration potential of 14KV and beam current densities between 5 and 10mA = mm2 are generally used for CL measurements. The Integration times for CL spectra were typically between 10 and 60s.

4. Results

4.1. Petrography

Petrographic studies of 20 thin sections (10 from each section) of Khurmala carbonates revealed that the its grain size ranged between, 0.05 and 1.2 mm in both sections. Carbonate grains are dominant
in all the studied thin sections of the Khurmala Formation in the Gomaspan section, except for the intervals in lower and middle parts. In the Sheraswar section, the carbonate grains are common in lower and upper parts and less common in the middle part. The compositional maturity of the Khurmala Formation in the lower and middle parts is mature and in the upper part is immature due to an increase in the number of carbonate constituents (e.g., intraclasts, fossils, micrite, matrix, and terrigenous minerals), because maturity increase with reducing number of these constituents (Smosna, 1987). In contrast, in the Sheraswar section, the compositional maturity was mature in the lower part and immature in the middle and upper parts, as indicated by an increase in the numbers of peloids, ooids and monocrystalline quartz grains among the fossils of the Khurmala Formation. Regarding the sorting of the grains, the Gomaspan section was poorly sorted in the lower and middle parts and well sorted in the upper part. Meanwhile, the Sheraswar section is characterized by poorly sorted in the lower part and moderately to well sorted in the middle and upper parts.

Various types of fossils were identified in the carbonate rocks of the Khurmala Formation including: benthonic foraminifera (miliolids (Figs. 3a and b) and rotaliids (Fig. 3c), rare planktonic foraminifera (Fig. 3d), coralline red algae (Figs. 3b and e), dacycladacean green algae (Fig. 3f), coral (Fig. 4a), ostracods (Fig. 4a), pelecypods (Fig. 3f), bryozoan (Fig. 3b and f), echinoderm spines (Figure 4b), micro gastropods (Fig. 4b), mollusks (Fig. 4a) and bioclasts. Non-skeletal grains include intraclasts (Fig. 3e), peloids (Figs. 3a and c), ooids (Fig. 3a) and extralasts which are mainly monocrystalline quartz grains (Fig. 3e). The groundmass of the Khurmala carbonates in both studied sections was mainly micrite which changed to sparry calcite in the upper part due to neomorphism.

4.2. Microfacies Analysis and Facies Associations

The Khurmala carbonates in both Gomaspan and Sheraswar sections were divided into five major microfacies based on Dunham’s (1962) classification. Subsequently, they were subdivided into 12 microfacies according to fossils and grain types (Table 1). The identified microfacies in the studied section were grouped into two facies associations depending on their environmental interpretations. The facies associations are as follows:

4.2.1 Back reef/lagoon facies association

Occupied 4.5 m in the lower part, 2 m interval in the middle part, and 5m in the upper most part of the Gomaspan section (Fig. 5). It consisted mainly of thick-bedded dolomitic limestone, brecciated dolomitic limestone rich- poorly sorted lime wackestone, moderately to well sorted packstone and grainstone, which have joints and are interbedded with yellow calcareous shale in the upper part. In the Sheraswar section, it occupied the lower 1.5 m comprising yellow marl and the upper 12.7 m comprising thick grey bedded bituminous limestone -rich poorly sorted lime mudstone and wackestone and moderately sorted packstone interbedded with a very thin layer of blue marl and shale. It also consists of thin to medium grey bedded dolomitic limestone-rich well sorted lime packstone and grainstone, characterized by fractures and joints, showing bitumen on their bed and bearing molds of bivalves and gastropods in the upper part. A petrographic study of this association showed that the skeletal grains contain benthonic foraminifera (miliolids and rotaliids) , red algae, dacycladacean green algae, ostracods, pelecypods, gastropods, echinoderms, bryozoan and rare planktonic foraminifera. Non-skeletal grains include intraclasts and extralasts (monocrystalline quartz). The groundmass is mainly micrite which changed to sparry calcite in the grainstone submicrofacies.
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<tr>
<td><strong>Lime Mudstone</strong></td>
<td>Dolomitized lime mudstone (Fig. 4c)</td>
<td>Found in the lower part of Sheraswar section characterized by severe dolomitization and dissolution.</td>
<td>19</td>
<td>Subtidal (lagoon)</td>
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<td>Bryozoan-algal-plecypod lime wackestone (Fig. 3f)</td>
<td>Bryozoa, red algae, dacycladacean and plecypods in micrite matrix observed in upper part of Gomaspan section and middle part of the Sheraswar section.</td>
<td>9</td>
<td>Shallow lagoon with open circulation</td>
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<td><strong>Lime Wackestone</strong></td>
<td>Rotaliid- dacycladacean-peloidal lime wackestone (Fig. 3c)</td>
<td>Benthonic foram (rotaliid), dacycladacean and peloids in micrite matrix which subjected to severe dolomitization discriminated in the middle part of Sheraswar section.</td>
<td>8</td>
<td>Shelf lagoon with circulation</td>
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<td>Fossiliferous lime wackestone (Fig. 4b)</td>
<td>Foraminifera-bioclasts lime packstone (Fig. 3d)</td>
<td>9</td>
<td>Shallow lagoon with open circulation</td>
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<td><strong>Lime Packstone</strong></td>
<td>Red algae-plecypod-rotaliid lime packstone (Fig. 4d)</td>
<td>Red algae, plecypods and rotaliid affecting by mechanical compaction and occurred in the middle part of Gomaspan and upper part of Sheraswar sections.</td>
<td>8</td>
<td>Shelf lagoon with circulation</td>
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<td>Sandy -red algae-intraclasts lime packstone (Fig. 3e)</td>
<td>Monocrystalline quartz, red algae and intraclasts subjecting to dolomitization and dissolution occurred in the upper part of Gomaspan section.</td>
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<td>Shelf lagoon with circulation</td>
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<td>Ooid-miliolid-peloidal lime packstone (Fig. 3a)</td>
<td>Includes ooid, miliolid, peloidal grains in spary calcite matrix and common in the upper part of the formation.</td>
<td>18</td>
<td>Restricted platform lagoon</td>
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<td><strong>Grainstone</strong></td>
<td>Algal-miliolid-peloidal grainstone (Fig. 3b)</td>
<td>It noticed in the upper part of the formation, contain more than 90% of grains common by miliolid, peloids and red algae in spary calcite matrix.</td>
<td>18</td>
<td>Restricted platform lagoon</td>
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<td>Coral boundstone (Fig. 4e)</td>
<td>It found in the lower part of the both studied sections composed &quot;in situ massive fossils of calcareous red algae and corals.</td>
<td>7</td>
<td>Reef setting</td>
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<td><strong>Boundstone</strong></td>
<td>Mollusks-ostracod- coral boundstone (Fig. 4a)</td>
<td>Coral bounded together and include other fossils like mollusks and ostracods interstices between corals and occurred in the lower parts both studied section.</td>
<td>7</td>
<td>Reef setting</td>
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<td></td>
<td>Algal, intraclasts-coral lime packstone-boundstone (Fig. 4e)</td>
<td>Composed of tabular or lamellar fossils which encrusted and bound extra clasts and intraclasts grains during deposition, formed in the middle part of the Gomaspan section.</td>
<td>7</td>
<td>Reef setting</td>
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Fig. 3. Photomicrographs of Khurmala Formations showing: (a) Ooid (Oo)-miliolid (M)-peloidal (P) lime packstone submicrofacies affected by neomorphism and dissolution. KS.7, X.N. (b) Milolid - algal -peloidal grainstone submicrofacies include miliolids (M), red algae (Re), peloids (P), bryozoan debris (Br) and characterized by interparticle (yellow arrows) and intraparticle (red arrow) pore types. Micrite envelopes formed around miliolids. KG.10, X.N. (c) Rotaliid (Ro)- dacycladacean (Da)- peloidal (P) lime wackestone submicrofacies affected by dolomitization. KS.9, P.P. (d) Foraminifera (Planktonic foram (Parasubbotina (Ps))-bioclasts lime packstone submicrofacies affected by neomorphism. KG9., P.P. (e) Sandy (monocrystalline quartz (Q)) -red algae (Ra)- Intraclasts (In) lime packstone submicrofacies having vuggy porosity (yellow arrows) and micrite envelopes formed around red algae (white arrow). KG8., X.N. (f) Bryozoan (Br)-algal (red algae (Ra) and dacycladacean (Da)) –pelecypod (Pe) lime wackestone submicrofacies (Bryozoa supposed to be genus Tabuclliaria filled by dolomitization and preserved inside layered wall undetermined fossil). K9., P.P. **Key:** KG= Khurmala Gomaspan, KS= Khurmala Sheraswar P.P.= Plane polarized light, X.N = Crossed Nichols
Fig. 4. Photomicrographs of the Khurmala Formation showing: (a) Mollusks (Mo)-ostracod (o)-coral (c) boundstone submicrofacies KS.2, P.P. (b) Fossiliferous lime wackestone submicrofacies includes pelecypods (Pe), micro gastropods (Mg), echinoids (Ech). KG.1, P.P. (c) Dolomitized lime mudstone submicrofacies affecting by dissolution and including stylolite porosity (red arrow). KS.3, P.P. (d) Red algae (Ra)-pelecypod (Pe)-rotaliid (Ro) lime packstone submicrofacies. KG.7, P.P. (e) Coral boundstone submicrofacies include growth framework porosity (red arrows). KG.3, X.N. (f) Algal (red algae (Ra), intraclasts (In)-coral (C) lime packstone- boundstone submicrofacies. KS.2, P.P.
4.2.2. Patch reef facies association

This association occupies the intervals in the lower and middle parts of the Gomaspan section, and the interval in the lower part of the Sheraswar section (Fig. 5). The total thickness was approximately 12 m and 4.3 m in the both Gomaspan and Sheraswar sections, respectively. It comprised of thick to massive beds of gray brecciated dolomitic limestone-rich lime boundstone dominated by coralline algae and characterized by chemical compaction stylolites in Gomaspan section.

**Fig. 5.** Columnar sections of the Khurmala Formation with microfacies distribution, facies associations and proposed environments (a) Gomaspan section; (b) Sheraswar section.

Contrastingly, Sheraswar section comprises very thick to massive yellow to gray dolomitic marl limestone-rich boundstone, which partly bears bitumen and is subjected to bioturbation. Petrographically, skeletal grains of this association consist of scleractinian coral, red algae, ostracods, bivalves and benthonic foraminifera, whereas non-skeletal grains are intraclasts and rare monocrystalline quartz.

4.3. Carbonate Diagenesis Overview

The carbonate rocks of the Khurmala Formation in both studied sections were influenced by several diagenetic processes. The diagenetic features and paragenetic history of the formation in the Sheraswar section were studied by Omer et al. (2014) using petrography and cathodoluminescence spectroscopy and they concluded that the Khurmala carbonates were subjected to different diagenetic processes including micritization, compaction, dissolution, neomorphism, pyritization and cementation that occurred during marine to shallow burial stages and culminated during intermediate to deep burial.
stages. The microscopic study of the Khurmala carbonates in the studied sections revealed that micritization was observed as rims and envelop around foraminiferal tests and red algae fossils (Figs. 3b and c) in the upper part of the Gomaspan section and the lower and upper parts of the Sheraswar section. It is regarded as the earliest diagenetic process and is possibly formed by endolithic algae in shallow marine environments (Tucker, 1981). Both the early and late phases of dolomitization occurred in the Khurmala carbonates. Early dolomitization was common in the upper part of Gomaspan, and the lower part of the Sheraswar section was indicated by very fine to fine crystals (Fig. 4c). It was supposed to be formed earlier than solidification of sediments in high-Mg marine waters (Tucker, 1981). Late dolomitization is characterized by coarser crystals (Fig. 6a) and is common in the middle part of the Gomaspan section and upper part of the Sheraswar section. Different types of cementation noticed in the Khurmala carbonate rocks includes granular calcite cement (Fig. 6b), blocky calcite cement, which are common cement in dolomitized lime wackestone submicrofacies (Figs. 6c, 9e and f) and syntaxial overgrowth cement (Fig. 6d). Mechanical compaction was observed in both studied sections and was characterized by fractures filled with deferent type of cement (Fig. 6e), in addition to packing, breaking and deformation of grains. Chemical compaction occurred in the form of stylolites. Based on the classification of Wanless (1979) only one type of microstylolite was recognized in both studied sections, which was sutured seam stylolite, irregular type with peaks of low amplitude (Fig. 6f). Pyritization was also observed in the thin sections of the formation in both cubic and framboidal shapes (Fig. 6e). Silicification was also observed in both studied sections, particularly in the lower part of the Gomaspan section, which selectively affected either the skeletal grains or ground mass (Fig. 6f). In addition, diagenetic cherts were noticed in the carbonate rocks of the Sheraswar section, which are supposed to be an input from land by high silica content water in shallow marine setting (Asaad and Balaky, 2018) (Figs. 9c and d). The studied thin sections were subjected to neomorphism, which obliterated most depositional features and influenced different skeletal grains in addition to the groundmass of the formation (Fig. 3d).

4.4. Porosity Characterization of the Khurmala Formation

Porosity is one of the main properties of carbonate reservoirs and is more complex than the that siliciclastic (Moore and Wade, 2013). There were different pore types in the carbonate rocks of the Khurmala Formation in the studied sections. Porosity types in the Khurmala Formation were studied based on the classification of Choquette and Pray (1970) and Lucia (2007). The following pore types were identified (Fig. 7):

4.4.1. Primary porosity

Primary porosity forms within the pre-depositional phase and during the depositional period (Flugel, 2010). The following pore types are identified in the studied rocks the formation:

4.4.1.1. Interparticle porosity

Fabric selective pores are formed during deposition, creating spaces or voids between grains (Choquette and Pray 1970). Based on the classification of Lucia (2007) two classes of interparticle porosity were recognized in the Khurmala Formation depending on the size and sorting of their grains and crystals,

• Class 1: This is formed between miliolids, peloids and algal grains in grainstone fabrics (Fig.3b) and is common in the upper part of both the Gomaspan and Sheraswar section. This class of interparticle porosity is characterized by grain-controlled pore size and pore size, which is less than 50 μm in Khurmala Formation. According to Lucia (2007) It has a higher permeability than other classes.
Class 2: It is characterized by pores between grains in the packstone fabrics in micrite or sparite groundmass (Fig. 3a) and is common in the upper part of the Sheraswar section.

Fig.6. Photomicrographs of Khurmala Formation showing: (a) Medium to coarse crystalline planner’s (subhedral) mosaic dolomite KS.4, P.P; (b) Granular cement filling the ostracods shell. KG.6, P.P; (c) Blocky calcite cement (red arrow) formed in the vein between the intraclasts and mollusk bioclasts. KG.1, X.N; (d) Syntaxial overgrowth cement formed in the echinoids grain (Ech), vuggy porosity formed in the groundmass (yellow arrow). KS.5, P.P; (e) Fracture porosity (white arrow) filled partially by iron oxide (black arrow) with cubic pyrite (red arrow) and frambooidal pyrite (yellow arrow). KS.10, X. N; (f) Sutured seam stylolite, irregular type with peaks of low amplitude (yellow arrow) above pelecypod valve (Pe) affected by silification. KG.4, X.N
4.4.1.2. Intraparticle porosity

This type of porosity formed within the foraminifera, pelecypods and red algal grains of the Khurmala Formation (Fig. 3b). They are supposed to have been created in the place of the soft organic parts from the carbonate grains (Reeckmann and Friedman, 1982) during the pre-depositional time (Choquette and Pray 1970). They are common in the lower and upper parts of the Gomaspan section and upper part of the Sheraswar section.

Fig. 7. Porosity distribution in the Khurmala Formation in: (a) Gomaspan section; (b) Sheraswar section.

4.4.1.3. Growth framework porosity

These are fabric-selective primary pores related to the growth of reef-building organisms (Flügel, 2010) (Fig. 4e). Terms are precisely used for the pore space of rock frameworks that have grown in place as rigid or semi-rigid fabrics owing to organic and/or inorganic processes (i.e., boundstones or biolithites) (Flügel, 2010). They are common in the lower part of the formation of the Gomaspan outcrop.

4.4.2. Secondary porosity

Secondary porosity includes all pore types formed during diagenesis at any time after deposition (Flügel, 2010). They are more common than primary porosity in the studied sections of the Khurmala Formation. The identified pore types of the secondary porosity include the following:
Moldic porosity

This type of porosity forms formed when skeletal and non-skeletal grains leach (Janjuhah et al. 2021) (Figs. 8a and b). They result from the selective dissolution of various types of carbonate depositional particles (Flügel, 2010). It is common in different parts of the Khurmala carbonates in both the studied sections. Dolomite molds (dolomolds) that occur in the lower part of the Gomaspan section are also regarded as being within this type of porosity and are supposed to be formed by the effect of freshwater on their initial susceptible minerals (Fig. 8a).

Intercrystalline porosity

It is fabric selective porosity when pore spaces occurred between the dolomite crystals (Abdulhussein et al., 2021) (Fig. 8b). It occurs within the medium and coarse dolomite textures of the Khurmala Formation in the middle part of Gomaspan outcrop and upper part of the Sheraswar locality.

Vuggy porosity

This occurs as a result of dissolution and has no criteria for the initial textures of rocks (Fig. 8c) (Reeckmann and Friedman, 1982). Many vugs are formed by the enlargement of fabric-selective pore, such as moldic (Fig. 8d) and intraskeletal pores (Janjuhah et al., 2021). This type of porosity is common in the lower and upper parts of the Khurmala Formation in the Gomaspan and Sheraswar sections.

Fracture porosity

These pore types are common in the lower part of the Sheraswar section and the upper part of the Gomaspan section. They are mainly filled with different types of cement in the studied rocks of the Khurmala Formation (Fig. 6e), and the main factors for their creation are either tectonic activity or compaction (Moore and Wade, 2013).

Stylolitic porosity

This type of porosity is less common in the studied rocks of the Khurmala Formation and is only observed in the lower part of Sheraswar outcrop. It is mainly formed by stylolites when they contribute to creating pores around their sutures owing to the passing of CO₂ a rich solution along them (Carrozi and Bergen, 1987). The identified pores were partially filled with calcite cement (Fig. 8c).

4.5. Cathodoluminescences Study of Carbonate Rocks

A modern and standard technique CL was developed in the last century as an excellent tool to provide information on the internal textures of minerals and determine the paragenetic history of carbonate rocks (Hiatt and Pufahl 2014). Richter et al. (2003) concluded that, red to orange luminescence in calcite with a maximum broad band peak at 605-620 nm response to Mn⁺², while red luminescence dolomite has a peak ~ 656nm. The CL investigation of the carbonate rocks of the Khurmala Formation, specifically microfacies and dolomite textures, showed that most of the dolomitized lime mudstone microfacies were characterized by light to red dull luminescence of very fine to fine non-planar dolomite crystals (Figs. 9a and b). Although dolomitized lime packstone microfacies characterized by red to orange luminescence with a destructive fabric of tightly packed fine-crystalline dolomite with no-planar to planar-s crystals size, are ranging from 7-45 µm, it exhibits homogenous red to dull luminescence and replacing the skeletal grains (Figs 9c and d). Gradually, there is change into larger crystals of planar-s with light red luminescence, generally occurring in vugs (Fig. 9d), the larger crystals commonly preserve zonation. This dolomite represents 50-70% of the total dolomite type in the Khurmala Formation. Omer et al. (2014) recognized two types of dolomites in the
Khurmala Formation based on a CL study, replacement dolomite and dolomite cement. The consequence of this type of dolomite is creation of secondary porosity by dissolution processes, such as vuggy, moldic and shelter porosity (Fig. 9d). Thus, most of the porosities in the Khurmala Formation are developed and controlled by these processes and are dominated by secondary porosity, which predates both replacement and dolomite cement. The identification of these features sometimes impossible under an optical microscope (Figs. 9c and d). Furthermore, integration of CL analysis revealed that dolomitized lime wackestone microfacies has two different cementations in the late stages of blocky calcite cement, a discontinuous light to dull orange luminescence of very thin to thin blocky calcite cement with thickness ranges between 45-62.5 µm without zonation, which cut-cross skeletal grains (Figs. 9e and f). The second type of pure calcite cement is characterized by coarse to very coarse blocky calcite cement with thickness ranging from 351 µm to -980 µm, with bright orange luminescence and tight zoning (Reeder and Paquette, 1989), which reduced most of the secondary porosity in these facies (Fig. 9f). Pure calcite cement is mainly comprised of high-Mg-calcite, this oscillatory zone has a variation in trace elements especially Mn+2 (Machel, 2000). Omer et al. (2014), distinguished two generations of oscillatory zoning of blocky calcite cement in the Khurmala Formation, G1 dark blue intrinsic or non-luminescence patterns are affected by oxidizing pore waters of a meteoric phreatic lens and, G2 showing bright orange luminescence zoning reflects redox conditions. Frequently, the diagenetic processes are facies-controlled and only observed in depositional units, as shown (Figs. 9d and f).
5. Discussion

5.1. Depositional Environment

The depositional environment of the Khurmala Formation in the Hujran section was determined by Tamar-agha et al. (2015) as a back reef. They did not infer a patch reef setting. The depositional environment of the Khurmala Formation in the Gomaspan and Sheraswar sections is back reef/lagoonal environment, including patches of reef. The back reef/lagoonal environment is equivalent to standard...

**Fig. 9.** Paired plane-light and cathodoluminescence photomicrographs of carbonate rocks of the Khurmala Formation with different microfacies and diagenetic phases. (a) Plane light photomicrograph of dolomitized lime mudstone microfacies of very fine to fine non-planar intensive dolomite; (b) Cathodoluminescence photomicrograph of (a) characterized by light to red dull luminescence of same dolomite; (c) Plane light photomicrograph of dolomitized lime packstone microfacies of fine non-planar to planar-s dolomite crystals (a-à), dash line(à) is replacing skeleton grains; (d) Cathodoluminescence photomicrograph of (c) representing fine crystals of non-planar to planar-s dolomite (a) shows homogenous red to dull luminesces, whereas planar-s dolomite crystals with zonation with light red luminescence at (b). Secondary porosity is a common pore in this microfacies; (e) Plane photograph of dolomitized lime wackestone microfacies of two features of blocky calcite cement discontinuous very thin to thin (x) and coarse to very coarse blocky calcite cement (Y); (f) Cathodoluminescence photomicrograph discontinuous light to dull orange luminescence of very thin to thin (x), coarse to very coarse blocky calcite cement with strong zonation, engulfing vugs (Y). Sk=skeletal grains; Vu=Vuggy; Sh= Shelter; Qtz=quartz; Che= Chert.
microfacies (SMF)8,9,18 and 19 of Flügel (1982) and facies zone (FZ)7 of Wilson (1975). The lower marl beds in the Sheraswar section are assumed to have been deposited at the quite sea bottom (Asaad and Balaky, 2018). Dolomitized lime mudstone which occurs in the lower part of the formation in the Sheraswar section is common in a subtidal-lagoonal setting in a restricted platform environment (Asaad, 2022). The dominance of poloids with miliolids and rare ooids indicate deposition in a shallow lagoonal environment with a poor connection to the open marine (Abdullah et al., 2019). Pelecypods, gastropods and echinoderms in lime wackestone microfacies are shallow lagoon with open circulation at or just below the fair-weather wave base (Flügel, 2010). Bryozoa in lime wackestone microfacies indicate low energy subtidal environment (Gallagheri and Somerville, 2003). Ostracods were found in many depositional settings from fresh water to deep marine settings, but their association with the mentioned fossils is supposed to be deposited in a lagoonal/back reef environment. Intraclasts red algae packstone microfacies occur in backshoal/lagoonal environments (Asaad and Omer, 2020). Monocrystalline quartz grains have several depositional environments, such as, intertidal, supratidal and subtidal. Moreover, it is associated with benthonic foraminifera, red algae and intraclasts, indicating a restricted lagoon setting (Ameen et al., 2019; Asaad, 2022).

The reef setting forms the interval in the lower part of the formation in the Sheraswar section and two intervals in the lower and middle parts of the in Gomaspan section. This corresponds to SMF7 of Flügel (1982) and FZ 5 of Wilson (1975), respectively. It is characterized by very thick to massive gray to yellow dolomitic marly limestone and massive brecciated limestone represented mainly by red algae and coral lime boundstone microfacies. The dominance of coral and red algae indicates the reef setting of this association, as Tucker (1992) mentioned that the dominant elements of reefs in the Paleogene and Neogene are coral and red algae. Scleractinian corals are regarded as basic reef builders in tropical and subtropical warm water zones (Flügel, 2010). Red algae encrusters are the dominant binding organisms in most Cenozoic to modern reefs (Flügel, 2010). The assemblage of ostracods, mollusks and intraclasts with corals and red algae boundstone is referred to as a reef setting. The above interpretation and the depositional environment of the Khurmala Formation in the Gomaspan and Sheraswar sections are shown in the schematic block diagram (Fig.10)

**Fig.10.** Depositional model of the Khurmala Formation in Gomaspan and Sheraswar sections, High Folded, Northeast Erbil City, Northern Iraq
5.2. Porosity Evolution

The carbonate rocks of the Khurmala Formation in the studied sections bear both primary and secondary porosities which were reduced by diagenetic agents such as; dolomitization and cementation. The sequence of pore formation in the Khurmala carbonates started with primary porosities. The interparticle porosity formed during deposition mainly with medium- to high-energy water and is associated mainly with lime grainstone and packstone microfacies in the upper part of the studied sections and reduced by sprite cement (Fig. 3b). Intraparticle porosity was formed by soft organic parts of the skeletal grain walls that were dissolved within the deposition. It is common within the foraminiferal chambers in the lime packstone and grainstone microfacies of the Khurmala Formation. Growth framework porosity, which occurs in lime boundstone microfacies of the Khurmala Formation formed by scleractinian corals that construct an open framework reef during the depositional phase (Moore and Wade, 2013) and partially filled by authigenic pyrites and calcite cements (Fig. 4d).

The dominant pore type in the Khurmala Formation in both studied sections was secondary porosity, which formed after deposition. The secondary porosity started in the early history of burial (eogenetic stage) of carbonate rocks of the Khurmala Formation by the dissolution of metastable minerals under the effect of meteoric waters particularly aragonite (Longman, 1980), which is indicated by the common occurrence of moldic porosity in different parts of the Khurmala carbonates in the studied sections (Figs. 7 and 8a). In the late history of burial or the (telogenetic stage) is the direct result of exposure to meteoric, vadose, and phreatic conditions. After minerals stabilized, the dissolution increased and cut across all fabric elements such as grains, cement, and matrix forming a large pore called vuggy porosity (Moore and Wade, 2013) and most vugs of Khurmala rocks were supposedly formed from the dissolution of replacement dolomite and dolomite cement as revealed by CL examination. It is associated with dolomitized lime mudstone and wackestone microfacies of the Khurmala Formation in the studied sections and was reduced mainly by blocky calcite cement (Figs 8c, d and 9f). Intercrystalline porosity is commonly formed between the coarse crystalline planar-c dolomite of the Khurmala Formation, which is supposed to have formed in the mesogenetic stage of diagenesis (Zadeh and Adabi, 2010). Stylolites formed by chemical compaction in the burial stage, sometimes develops into pores by dissolution when passing through of CO₂ rich solution, and it is only found within dolomitized lime mudstone in the middle part of the Khurmala Formation in the Sheraswar section. Paleogene rocks were subjected to folding and fracturing as a consequence of the Late Alpine orogeny in northern Iraq (Numan, 2001). Thus, most of the fracture porosity in the Khurmala Formation, especially in the lower and upper parts, is filled with blocky calcite and dolomite cement (Figs. 9e and f). Generally, the secondary porosity of the Khurmala Formation in the studied sections was reduced by two types of cementations in the late stages of blocky calcite cement, as revealed by CL analysis, which was discontinuous light to dull orange luminescence of very thin to thin blocky calcite cement without zonation, cut-crossing skeletal grains and coarse to very coarse blocky calcite cement with characteristic bright orange luminescence with tight zonation (Fig. 9f).

6. Conclusions

- The petrographic constituents of the Khurmala Formation (Paleocene-Early Eocene) in Gomaspan and Sheraswar sections, Northern Erbil, Kurdistan Region of Iraq, encompassing skeletal grains from shallow marine derivative fauna, which are: benthic foraminifera, coralline red algae, dacycladacean green algae, coral, ostracods, pelecypods, bryozoa, echinoderm spines, microgastropods, mollusks and bioclasts. Non-skeletal grains comprise of intraclasts, peloids, ooids and extraclasts (monocrystalline quartz).
Five major microfacies were recognized in the carbonate rocks of the Khurmala Formation in the studied sections. They were merged into two types of facies associations connected with their environmental interpretation, back reef, lagoon and patch reef.

Eight pore types of primary and secondary porosities were identified in the carbonate rocks of the Khurmala formation in the following sections: interparticle, intraparticle, growth framework, intercrystalline, moldic, vuggy, fracture and stylolitic porosities.

Primary porosity was reduced by compaction and cementation. Interparticle porosity occur within the packstone and grainstone microfacies. Additionally, growth frame works formed in reef setting within lime boundstone microfacies.

The petrographic inspection and CL investigations show that the secondary porosity is predominant in both studied sections and the most common is the moldic porosity associated with different microfacies fabrics. In contrast, vuggy porosity is dominant in dolomitized mudstone and wackestone microfacies, which are supposed to be from the dissolution of replacement dolomite and dolomite cements.

CL examination revealed that dolomitized lime wackestone microfacies has two different cementations in the late stages of blocky calcite cement which are discontinuous light to dull orange luminescence of very thin to thin blocky calcite cement without zonation. The second type is pure calcite cement of coarse to very coarse blocky calcite cement with characteristic bright orange luminescence and tight zoning.

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