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Cenomanian-Early Campanian Carbonate Reservoir Rocks of Northwestern Iraq: Diagenesis and Porosity Development

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ABSTRACT

The present work focuses on the upper Cretaceous (Cenomanian-early Campanian) carbonate successions in selected wells from northwestern Iraq. These successions are represented by Gir Bir (Cenomanian-early Turonian), Wajna (late Santonian) and Mushorah (early Campanian) Formations. The succession has affected by early burial near-surface, unconformity-related and deep burial diagenesis represented by cementation, neomorphism, dolomitization, dedolomitization, silicification, authigenesis of glauconite and pyrite, compaction, micritization, solution and porosity formation. The common porosity types are intergranular, fenestral, intercrystalline, moldic, vuggy, channel and fracture. Three porosity zones (I, II, and III) are identified depending on variation in gamma ray which reflects their shale content. The upper part of zone (II) is highly porous and regarded on the main reservoir unit in the middle and upper parts of the Gir Bir Formation. Fracture and moldic and vuggy dissolution features in addition to karstic and fissure features are responsible for the porosity increase in the fractured reservoir unit.

Keywords: Carbonate Reservoir, Porosity, Diagenesis, Upper Cretaceous, Iraq.

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الصخور المكمنية الجيرية (السينوماني–الكامباني المبكر) في شمال غرب العراق: العمليات التحويرية وتطور المسامية

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الملخص

يتركز البحث الحالي على دراسة التعاقبات الجيرية بعمر الكريتاسي العلوي (السينوماني–الكامباني المبكر) في ابار مختارة من شمالي غرب العراق. تتمثل التعاقبات بالتكاوين جير بير (السينوماني–التوروني المبكر)، وجنة (السنتوني المتأخر) ومشورة (الكامباني المبكر). تأثرت التعاقبات قيد الدراسة بالعديد من العمليات التحويرية من قرب السطح والدفن الضحل والفن العميق متمثلة بالسمنتة والتشكل الجديد والدلمتة والديدلمتة والسلكتة والنشوء الموضعي للكلوكونايت والبايرايت. أنواع المسامية هي بين الحبيبات واللوزية وبين البلورية والقالبية والفجوية ومسامية المكسر. انطقة المسامية والتي تم تشخيصها بناءا على التغير في اشعه كاما والتي تعكس المحتوى الطيني هي (I,II.III). الجزء العلوي من النطاق المسامي (II) هو عالي المسامية ويعد المكمن الرئيسي في الجزئين الوسطي والعلوي من تكزين الجير بير وان مسامية المكسر والقالبية والفجوية هي من أهم مظاهر الاذابة في هذا التكوين فضلا عن ظواهر التشقق والكارست والمسؤوله عن زيادة المسامية في هذه الوحدة المكمنية.

الكلمات الدالة: المكمن الكاربوناتي، المسامية، العمليات التحويرية، الكريتاس يالعلوي، العراق.

1. Introduction

The Mesozoic carbonate system of the Arabian Plate is one of richest hydrocarbon provinces of the world. This is mostly due to combination of their large-scale dimensions and the presence of source and seal rocks within the same depositional system [1].

Iraq's largest hydrocarbon reserves are hosted in the Cretaceous sediments, particularly in the Mesopotamian Basin [2]. The Cretaceous succession in Iraq is up to 3000 m thick [3] and comprises megasequences AP8 and AP9 of Sharland et al., 2001, [4]

The Cretaceous succession has been extensively studied because it contains abundant reservoir intervals. It is the most productive interval in Iraq and contains about 80% of the country's oil reserves [2].

The present work focuses on the upper Cretaceous (Cenomanian-early Campanian) successions in selected wells from northwestern Iraq. These successions are represented by Gir Bir (Cenomanian-early Turonian), Wajna (late Santonian) and Mushorah (early Campanian) formations. Carbonate rocks of the Gir Bir Formation are represented by limestones (mostly recrystalized), marly limestone and fractured dolomite. Limestones (locally silicified), thinly laminated dolomite with occasional anhydrite nodules and fractured limestones form the main lithology of the Wajna Formation. Whereas, Limestone and marly limestone dominate the lithology of the Mushorah Formation. The Mushorah carbonates are based on conglomerate and brecciate bed, poorly sorted with subrounded-subangular rock fragments in a green marl matrix.

Several microfacies were distinguished in each formation, they were grouped into facies belts and the depositional environment were identified [5]. The Gir Bir carbonates were deposited in outer shelf, slope/shoal, rudist build-ups, back-reef/shoal and protected lagoons in a regressive shallowing upward sequence. Shallow marine environment with facies belts; supratidal, protected lagoons and outer lagoonal (shoal) are distinguished for the Wajna

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rocks. The succession of the Mushorah Formation is considered to be deposited in a relatively deep marine environments ranging from outer shelf to upper bathyal [5].

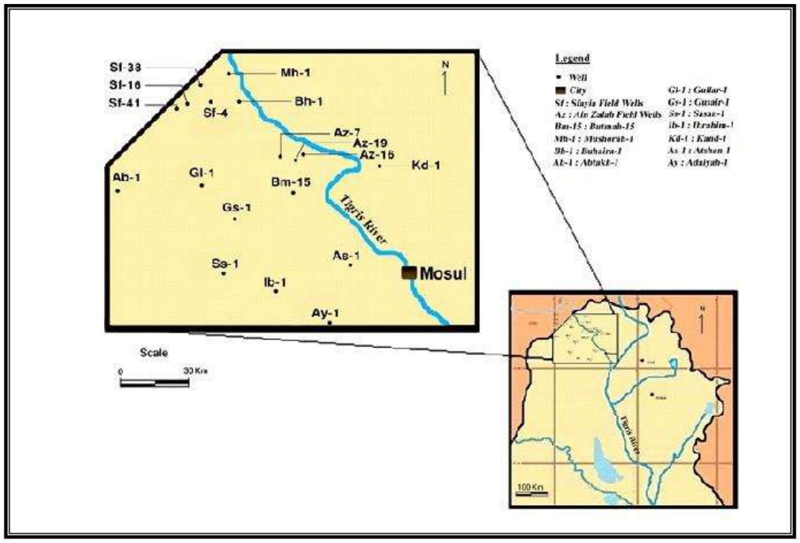

Fig. 1 Location map showing the studied wells from northwestern Iraq

The correlative rock successions in the north and eastern parts of Iraq were studied by Haddad and Ameen (2007), [6] who concluded that the Gulneri, Kometan and Mushorah formations (mid-Turonian- early Campanian) have been deposited in a flat-topped ramp that formed because of extensional tectonism.

The present work is conducted on several wells from northwestern (Figure 1) aiming to investigate the linking between diagenesis and porosity evolution of the studied formations.

2. Geologic Setting

The paleolatitudinal location of the Arabian Plate influenced Cretaceous stratigraphy in Iraq. Progressive northward drift placed the Arabian plate in equatorial tropical latitudes [7]. Carbonates rocks forming the main lithologies in the Cretaceous successions of Iraq and most of the Middle East region due to prevalence of warm equatorial climates [8].

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The upper Cretaceous successions in northwestern part of Iraq have been affected by several phases of tectonic movements [9], therefore, they are not completely documented from this part of the country. The study area was a part of the shelf during Cenomanian- early
Turonian and was separated from the main basin by the Mosul and Khleisia uplifts [10]. Prevailed warm and equatorial conditions on the Arabian Plate [11] promote the deposition of reefal and lagoonal facies of the Gir Bir Formation in the area. During Turonian- early Campanian, the area was still affected by uplifting with discontinuous and local subsidence that permit deposition of shallow lagoonal facies of the Wajna Formation. Transgression in the early Campanian led to deposition of shallow marine facies of the Mushorah Formation in the studied area.
According to Sharland et al. (2001), [4] , the studied formations present in two of the Arabian Plate Megasequences, Gir Bir Formation of the Cenomanian-early Turonian sequence which represents the upper part of the late Tithonian-early Turonian megasequence AP8 whereas, Wajna and Mushorah formations exist in the late Turonian-early Campanian sequence that represents the lower part of late Turonian-Danian AP9 megasequence. The studied formations and their correlative succession in other parts of Iraq and neighboring countries is illustrated in Figure (2).

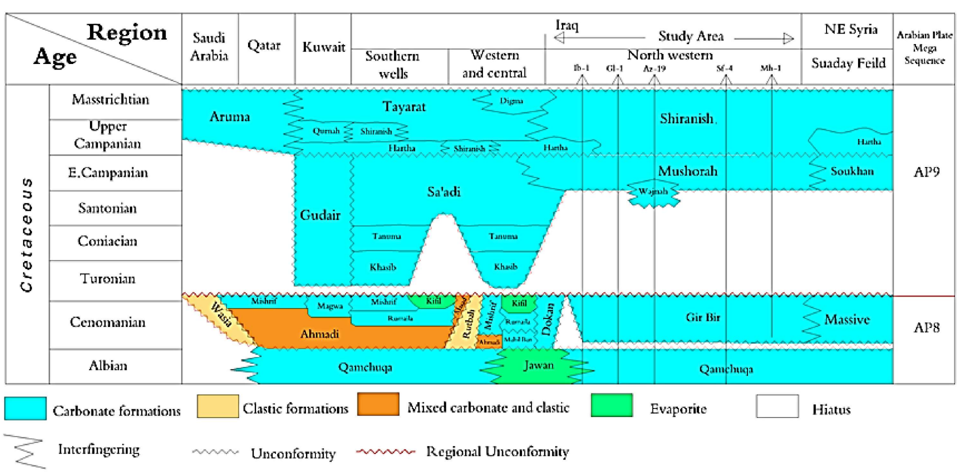

Fig. 2 Stratigraphic correlation of the studied formations within Iraq and some of the neighboring countries (modified from Al-Naqib, 1967), [12]

3. Materials and Methods

60 samples from the three studied formations Gir Bir, Wajna and Mushorah were investigated. Petrographic study is carried out for identification of the main components of the studied lithologies and to distinguish the main diagenetic events. Scanning electron microscopy is conducted at Steinman Institute of Bonn University, Germany and the Earth Sciences Department, Royall Holloway, University of London, UK for selected samples.

Pore types are identified according to Choquette and Pray (1970), [13] classification that based on the texture of rock matrix, visible pore structure, and typical petrophysical behavior that would be associated with the rock. The ages of the studied formations was considered according to biostratigraphic works of [14, 15].

For the study of porosity evolution, the studied successions are divided according to shale volume (V-Sh; [16]) into three porosity zones (A, B and C). Primary, total and effective porosities are measured from FDC, CNL and BHC logs of the three selected wells.

4. Results

Petrographic component

The main components of the studied carbonate successions are represented by skeletal and non-skeletal grains, micritic groundmass, sparry calcite cement and various types of pores (discussed separately).

The skeletal grains of the Gir Bir Formation are dominated by benthic foraminifera (Miliolids, Alveolina, and Orbitolina) and rudist while the non-skeletal constituents are represented by pelloids and lithoclasts. In the Wajna Formation, ostracoda, benthic foraminifera (Miliolids and Glomospira) and pelloids are the main constituents. Whereas, calcispheres, planktonic and benthic foraminifera and Inoceramus form the main constituents of the Mushorah Formation.

These components are distributed in a micritic groundmass that is composed mostly of calcite in addition to clay minerals that are dominated by kaolinite, illite, palygorskite and glauconite [5]. The micritic groundmass has been affected by dolomitization and recrystallization. The sparry calcite cement is dominated in most of the studied carbonates either as intergranular cement or as filling of voids and fractures

.Diagenetic processes

Carbonates of the studied formations have been affected by both early-and late-stage diagenesis. The observed diagenetic events can be divided into constructive (isochemical and allochemical constructive diagenesis) and destructive diagenesis (sensu Milliman, 1974), [17]

Isochemical constructive events (without modifications in chemical composition of the rocks) are represented by cementation and neomophism. Cementation has led to occlusion of primary porosity in carbonates. The following cement types were recognized; blocky, syntaxial rim, drusy mosaic, radiaxial fibrous, fibrous and granular filling inter-and intragranular pores and fractures (Figure 3 A-H). These cements are believed to be of later diagenetic origin, although the mosaic cement may have formed during two or more phases

.Neomorphism is the dominant diagenetic event affecting on the carbonate rocks of the Gir Bir and the upper parts of the Wajna formations, whereas, it is slightly affected on the Mushorah carbonates. This process is divided into recrystallization and inversion (Figure 3 I-K).

Allochemical constructive events (that show some modification in chemical composition of the rocks) are represented by dolomitization, dedolomitization, silicification and authigenesis. Aphanotopic, fine-grained dolomite rhombs, floating and contact rhombs, spotted, sieve and sutured Mosaic dolomite textures were recognized (Figure 4 A-F) according to classification of Randazzo and Zachos (1984), [18].

Dolomitization has slightly enhanced the reservoir quality particularly with the formation secondary intercrystalline micropores. Dedolomitization is observed in poikilotopic, composite calcite rhombs and rhombic pores textures (Figure 4 G). This event is commonly recorded in the Mushorah Formation. Silicification in the form of chert nodules and beds are sporadically exists in the lower part of the Mushorah Formation and in distinctive zones in the Gir Bir and Wajna formations. The process is diminished in the highly dolomitized beds and near stylolites rich in organic matter (Figure 4 H).

The authigenic minerals in the studied carbonates include glauconite and pyrite. Galuconite is observed as green rounded grains (Figure 4 I) in the upper part of the Mushorah Formation near the contact with Shiranish and Hartha formations and rarely occur in the lower and middle part of the formation. Pyrite occurs in various forms in all the studied formations. It exists either in planktonic foraminifera chambers or in calcispheres or in the pores of the micritic groundmass of the Mushorah Formation. Pyrite also found as euhedral cubics or in stylolites or in mollusca fragments of the the Gir Bir and Wajna formations (Figure 4 J)

.Destructive events include; compaction, micritization, bioturbation, dissolution and porosity formation (discussed separately).

Compaction generally decreases porosity due to the heavy sedimentary cover (>1000 m thickness) which gave the orientation property in their internal structure of the sediments [19]. The compaction has indirect relationship with the original primary cementation. It occurs in the studied carbonates in mechanical and chemical compaction. Mechanical compaction is observed by breakage in inoceramus shells (Figure 4 K) whereas, chemical compaction is recorded from various types of pressure solution or stylolitic textures (Figure 4 L and 5 A- B). Pressure solution has resulted in the formation of dissolution surfaces, clay seams, and stylolites Organic material and other relatively insoluble particles (dolomite rhombs, early calcite-cemented grains, and clay particles) commonly occur on the stylolite surfaces, indicating a late-diagenetic origin.

Micritization is an early diagenetic process that occurs in marine phreatic environments [20], and skeletal grains were micritized shortly after deposition due to fungi action and micritic envelops construction. In the present study, it seen in the successions of the Gir Bir and Wajna formations. Bioturbation is distinguished in mottled textures due to boring activities that lead to accumulation of organic matters and give darker color for the bioturbated zones. It is recorded in distinctive areas where dolomitization and pyritization dominate (Figure 4 J).

Dissolution is a more effective diagenetic process than cementation in most of the reservoir beds that improved the carbonates porosity. This process acts to destroy the internal structures for the skeletal grains, leaving the micritic envelope to form the moldic porosity, vuggy porosity or enlarging the presenting vugs to form cavern porosity or channel porosity, and sometimes, there are open space structures due to the effect of the selective dissolution. In the present work, dissolution is recorded as karst and fissures in the upper part of the Gir Bir Formation where conglomerate and breccias dominate or in different forms throughout the studied carbonates (Figure 5 C).

Porosity types

The following types of the porosities have been distinguished according to Choquette and Pray (1970), [13]

1. Solution enhanced inter-granular that form as a result of dissolution of the cement between carbonate grains and this pores is enlarged by dissolution processes and cementation between grains is further removed (Figure 5 D).
2. Fenestral porosity which is formed as a result of dissolution of evaporite grains and organic matter and is commonly distinguished in the middle part of the Wajna Formation (Figure 5E). The aforementioned porosity types are considered as primary porosity types that have insignificant contribution to overall porosity.

The following types of porosity are considered as secondary porosities with most significant contributors to overall pore volume in the studied carbonates .

3. Intercrystallline: This type of pores are associated with recrystallized and/or dolomitized beds. It is observed between dolomite crystals in the Gir Bir and Mushorah formations (Figure 5F and 4E).
4. Moldic: Molds and incomplete molds are formed from the diagenetic dissolution of metastable grains. Moldic pores exhibit sharp and distinctive outlines of leached grains, while incomplete moldic pore boundaries are less distinctive and

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adjacent to recrystallized remnants of the original grain. Moldic and incomplete moldic pores (Figure 5G) dominate the skeletal grains of most of the studied carbonates specially in the upper part of the Gir Bir Formation.

5. Vuggy: Vuggy pores occur as enlarged solution enhanced intra-matrix pores (Figure 5H and I). Pore outlines are irregular and pore shapes are typically blocky in nature. Vugs are fabric selective and do not resemble preexisting component grain shapes or sizes. Vugs may contribute to overall effective porosity when interconnected by sufficient intra-matrix porosity.
6. Channel: This porosity is distinguished as elongate vugs mostly filled with hydrocarbons in the upper parts of the Gir Bir and the lower part of the Mushorah formations (Figure 5J).
7. Fracture: It is the most effective and important secondary porosity generated by tectonic fracturing of the rocks and play as conduits for hydrocarbons in carbonate reservoirs. It is observed as an oblique fractures including sliken sides or as isolated or group of fractures (Figure 5 K and L) in various portions of the studied carbonates but commonly seen in the upper part of the Gir Bir Formation below the unconformity surface with the overlying Mushorah Formation.

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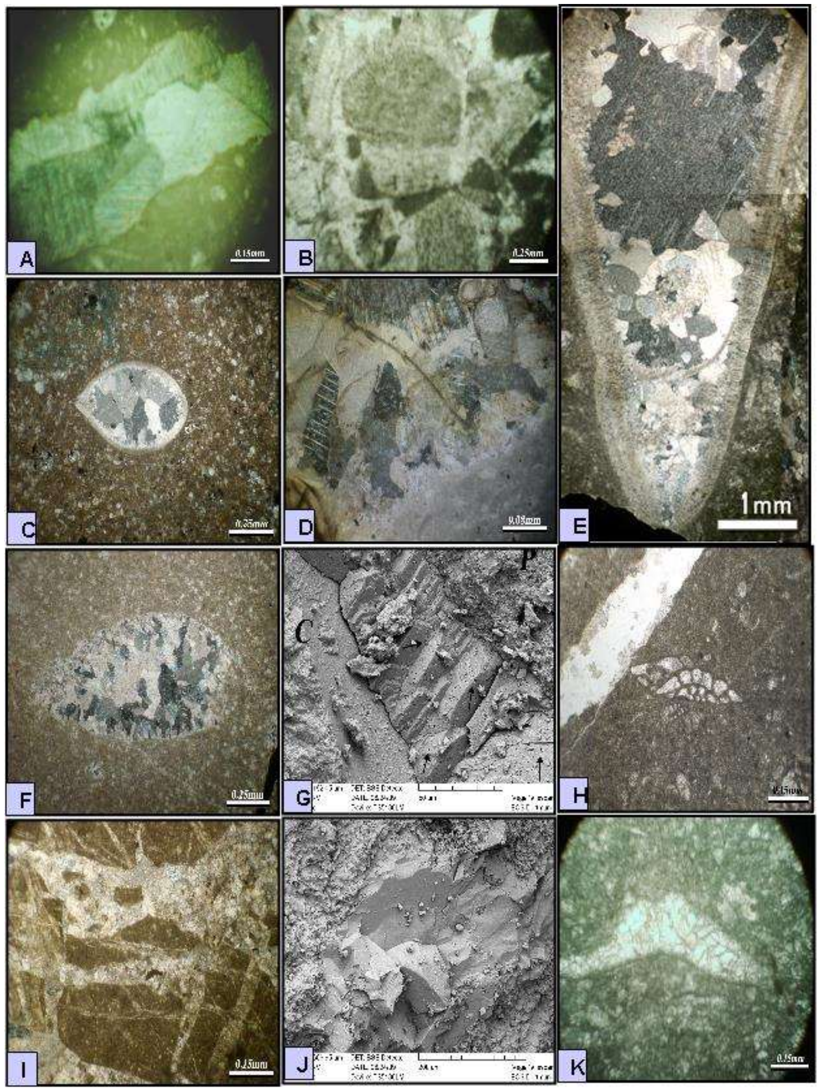

Fig. 3 Diagenetic features of the studied rocks, A, blocky cement in micritic groundmass, Gir Bir Formation. B, syntaxial rim cement around echinoderm fragment, Gir Bir Formation. C, fibrous cement in rim graded to drusy mosaic in center of ostracoda shell. Mushorah Formation. D, drusy mosaic cement in micritic groundmass, Gir Bir Formation. E, drusy cement in conical rudist shell, Gir Bir Formation. F, radaxial fibrous cement that develop to drusy cement in the center of a shell, Mushorah Formation. G, Scanning electron microscopic image (SEM) of radaxial fibrous cement with dissolution features and small pores (arrows), note calcispheres (C) and planktonic forams (P). Mushorah Formation. H, granular cement in Nezzazata benthic forams and vein filled with calcite, Gir Bir Formation. I, recrystallization of the micritic groundmass in the Mushorah Formation. J, SEM of recrystallization and microspar neomorphism, Gir Bir Formation. K, inversion of aragonite to calcite on a bioclast, Gir Bir Formation.

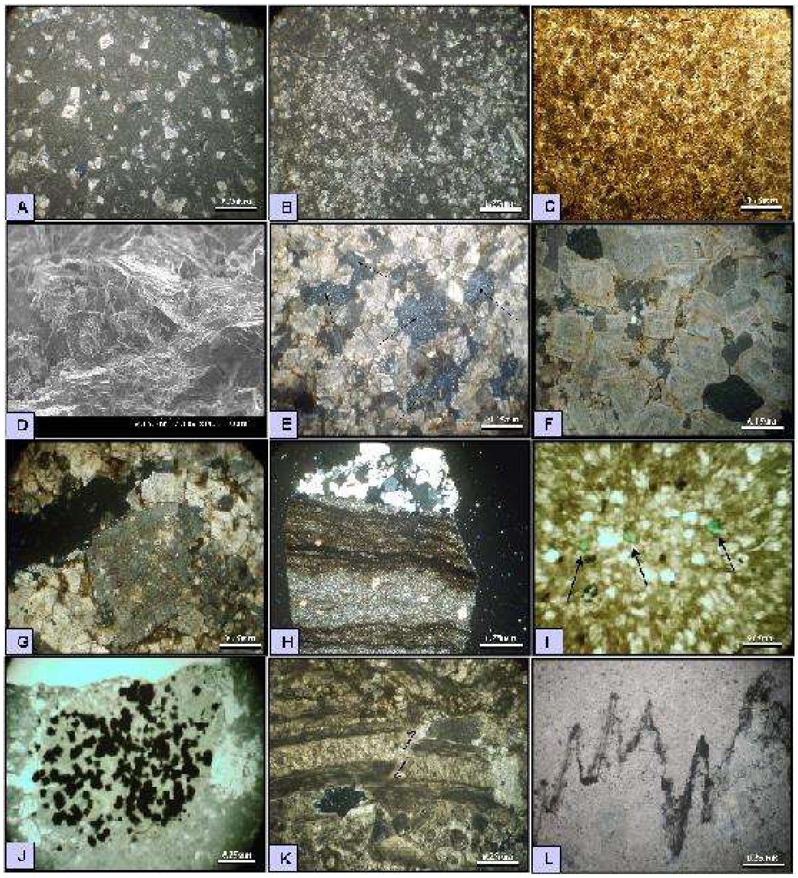

Fig. 4 Diagenetic features of the studied rocks. A, floating dolomite texture, Gir Bir Formation. B, contact rhomb fabric, Gir Bir Formation. C, drusy mosaic dolomite texture, Gir Bir Formation. D, SEM image of drusy mosaic dolomite texture, Gir Bir Formation. E, sieve mosaic texture with intercrystalline porosity (arrows), Mushorah Formation. F, zoned dolomite in contact rhomb structure, Gir Bir Formation. G, poikilotopic dedolomite texture, Mushorah Formation. H, silicification with growth of coarse quartz crystals, note inhabitation of silicification in the organic rich and dolomitized laminas (arrows refer to dolomite rhombs), Mushorah Formation. I, authigenic glauconite (arrows), Mushorah Formation. J, concentration of pyrite in bioturbated bed, Gir Bir Formation, K, mechanical compaction and breakage in Inoceramus shell, Mushorah Formation. L, low-amplitude stylolite filled with organic and clayey matters, Gir Bir Formation.

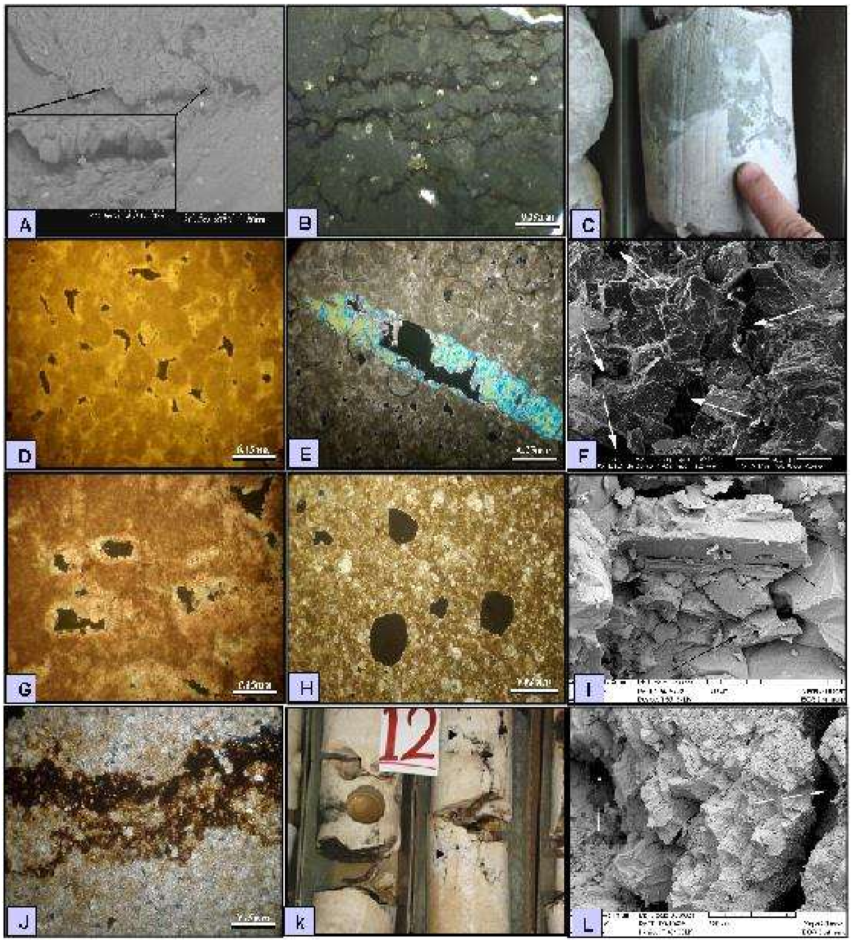

Fig. 5 Compaction features and porosity types in the studied rocks. A, SEM image of stylolite with enlarged view showing partial calcite growth in stylolite, Gir Bir Formation. B, irregular anastomosing stylolite, Gir Bir Formation. C, karstification in the upper surface of Gir Bir Formation, core sample. D, intergranular porosity in peloidal lime grainstone of Gir Bir Formation. E, fenestral porosity in lime mudstone that includes anhydrite nodules, Wajna Formation. F, SEM image of sieve mosaic dolomite with intercrystalline porosity (arrows), Mushorah Formation. G, moldic porosity after dissolution of skeletal grains and rimmed dolomite formation, Gir Bir Formation. H, vuggy porosity, Mushorah Formation. I, SEM image of differential dissolution in recrystallized limestone leaving micro-vuggy pores, Gir Bir Formation. J, channel porosity filled by organic matter, Mushorah Formation. K, high amplitude stylolite and fractures filled by hydrocarbons, core samples of Gir Bir Formation. L, micro-fracture porosity in SEM image of Gir Bir Formation.

Porosity Evolution

The studied succession was divided into three zones (A, B, and C) depending on variations in Gamma ray, which reflects their shale content (Figure 6).

The A zone is recorded in well Bh-1 only and has a funnel shape (Figure 6) with 103 meter thick and high shale content. This zone is represented by stratigraphic sequence A and the TST from sequence B (the lower and middle parts of the Gir Bir Formation).

Zone B is of bell shape (Figure 6) and low content of shale. It has approximately 109 meter and appears in BH-1 well and continues in the upper parts of wells Sf-16 and 41. It is revealed that the upper part of zone (B) which coincides with (HST) of sequence (B) is highly porous and regarded on the main reservoir in the middle and upper parts of the Gir Bir Formation.

The funnel shape is also observed for the zone C (Figure 6) with high thickness in Sf-16 and 41 whereas, while it decreases to 34 meter thick in Bh-1 well. It has high shale content as compared with other zones and is represented by sequence C (Mushorah Formation).

The primary, total and effective porosities are calculated from the well logs (BHC, CNL, and FDC). The values are plotted with depth for selected wells (Figure 7) to show distribution of porosity with depth and to delineate the locations of the effective porosity that reflect the fluid direction and the reservoir zones in the studied successions.

In zone A, the total porosity is 2-15% (see Figure 7), the effective porosity is generally low, while primary porosity is high in some levels due to effect of dolomitization. This zone is composed of limestone and dolomitic limestone that are highly affected by recrystallization, in general, it is of poor reservoir characteristics.

The total porosity in the zone B range between 5-25% but increases in the upper part of the zone (in the upper surface of Gir Bir Formation). The primary porosity increases also in the upper part of the zone reaching 30% in Bh-1 well and 10% in Sf-16 and 41 wells (Figure 7). This increase may reflect the effect of fracture porosity [21], or it due to hydrocarbon effect [22].

A Fracturing and dissolution feature in the upper part of the Gir Bir Formation is the cause of increase in primary porosity. The upper part of zone B could be regarded as a reservoir unit with total porosity (10-25%) and an effective porosity of 10% in addition to low shale content. This reservoir unit is of fracture reservoir type, which is formed of shallow marine facies with mud dominance.

In the zone C, the porosity is 3-5% with high shale content in the three studied wells except lower parts of the zone in Sf-41 where total porosity is relatively high (15%) and effective porosity of 10%. Core and petrographic investigations show that the studied rocks include intercrystalline porosity (Figures 4E and 5F) and saturated with hydrocarbons [5].

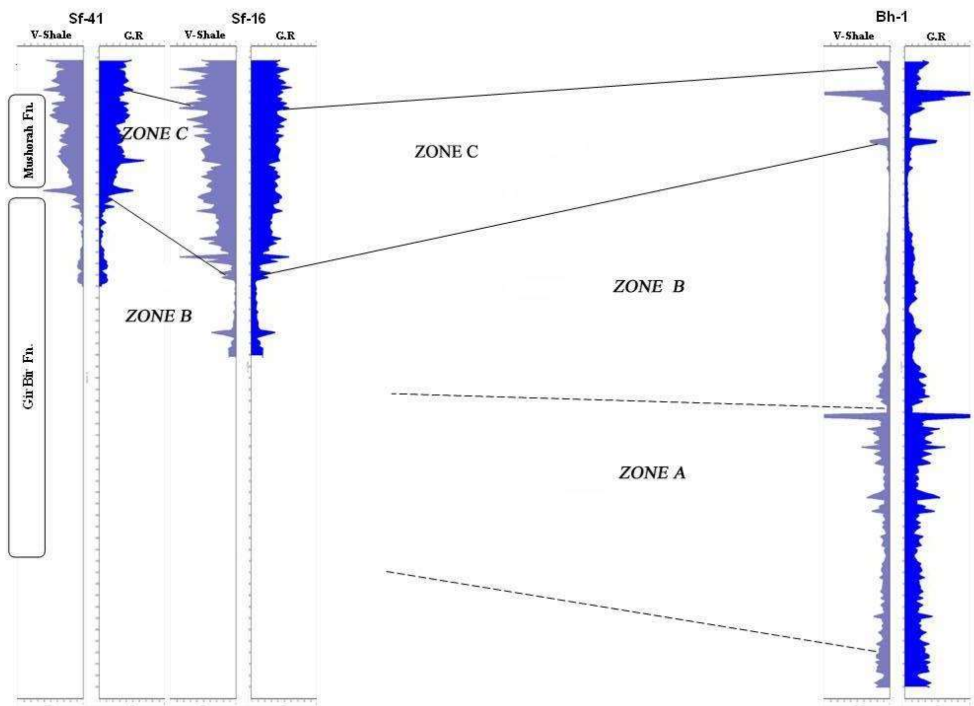

Fig. 6 Porosity zones based on gamma readings and shale volume.

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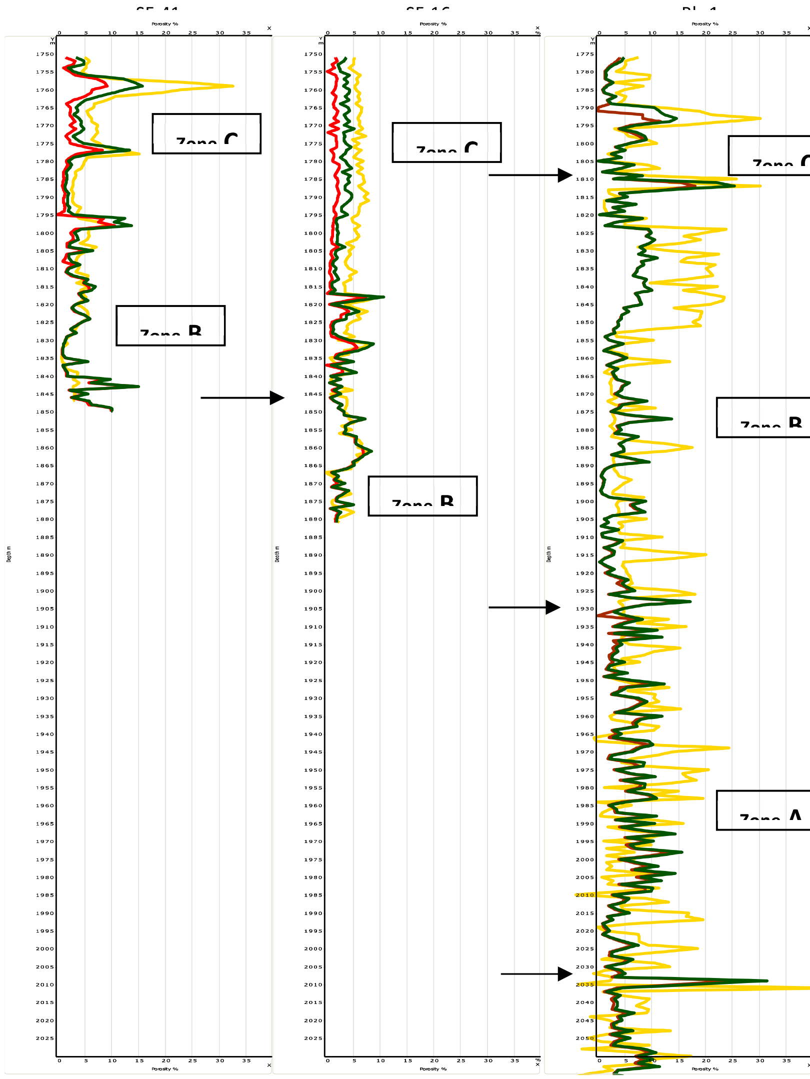

Fig. 7 Depth relation with total porosity (green), effective (red) and primary (yellow) in the wells Bh-1, Sf-16 and Sf-41.

5. Discussion and conclusions

The studied succession of the upper Cretaceous (Cenomanian-early Campanian) represented by Gir Bir, Wajna, and Mushorah formations of northwestern Iraq has affected by three types of diagenetic stages; early burial, unconformity-related, and deep burial diagenesis .

Early diagenesis is represented by precipitation of fibrous cement on the inner rims of skeletal grains (primary porosity). Secondary porosity could be formed during this stage through dissolution of aragonite and calcite precipitation, which has unequal distribution leaving intergranular secondary porosity. In general, this stage has little effect on the studied rocks.

The unconformity-related diagenesis dominates in the upper parts of the Gir Bir Formation near the unconformity with Mushorah Formation where dissolution features are common as indicated from dissolution of rudist and bioclasts leaving vuggy and moldic porosity and other karstic and fissure structures. The effect of cementation on porosity is mostly limited during this stage. The absence of meniscus cement may refer to phreatic and vadose conditions, whereas, presence of syntaxial rim cement around echinoderm and common dissolution refer to the effect of meteoric water on the limestone of the Gir Bir Formation. This stage is considered as the main reservoir unit in the area under study.

In the deep burial diagenesis, various processes have affected on the studied rocks that decrease porosity such as cementation (mostly drusy mosaic and blocky), recrystallization and compaction (stylolite formation). Dolomitization enhanced the reservoir characteristics by formation of intercrystalline porosity as indicated from increasing of porosity in the lower part of the Gir Bir Formation (see Figures 6 and 7) and the lower part of the Mushorah Formation where dolomites and dolomitic limestone dominate.

The Gir Bir Formation is formed of shallowing upward succession. The reservoir characteristics are low in the lower part of the formation where slope and outer shelf environments dominate while they improve toward upper part of the formation where rudist build-ups and other bioclasts are common (Figure 7). Although the upper part was deposited in back reef shoal environment, it is regarded as the main reservoir in the studied succession due to fracturing and common vuggy and moldic porosities. Fracturing porosity is also dominated in the lagoonal facies of the correlative Mishrif Formation in the Arabian Gulf region [23].

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