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MICROFACIES, DEPOSITIONAL ENVIRONMENTS AND DIAGENETIC PROCESSES OF THE MISHRIF AND YAMAMA FORMATIONS AT FAIHA AND SINDIBAD OILFIELDS, SOUTH IRAQ

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Key words: Microfacies; Diagenetic processes; Depositional environment; Oilfields; South Iraq

ABSTRACT

The Faiha and Sindibad oilfields are located in the northeastern part of the Basrah Governorate, south Iraq. More than 50 thin sections of limestone samples, collected from wells penetrating the Mishrif and Yamama formations in these oilfields, are examined in this work. Several microfacies are identified in the formations studied; four main facies and seven subfacies are found in the Yamama Formation and three main Formation. The main microfacies include lime mudstone, wackestone, packstone and grainstone. They were deposited in various marine sedimentary systems of open marine, foreslope, reef and lagoonal environments. Benthonic foraminifera, Mollusk shells, echinoids, and algae, are the fossils identified in the Mishrif and Yamama formations. Dolomite and calcite are the main minerals in the studied samples. Petrographic examinations revealed that diagenesis varied in intensity from microfacies to another. Dissolution and neomorphism (recrystallization) have created and controlled the development of porosity. The dominant pore types are vuggy, interparticles, intraparticles, channel and moldic. Whereas, cementation, micritization, and compaction processes have had destructive effects, by reducing porosity and permeability that led to reducing reservoir quality. Other processes, such as dolomitization and authigenic minerals (pyrite) do not have strong effects on the reservoir quality. The depositional basin model shows that the Yamama Formation was deposited in the ramp carbonate environment, whereas, the Mishrif Formation was deposited in the rimmed carbonate shelf environment.

السحنات المجهرية، البيئات الترسيبية والعمليات التحويرية لتكويني المشرف واليمامة في حقلي الفيحاء والسندباد، جنوب العراق

آمنة مال الله حنظل ، حسين عليوي جفيت و نوفل عدنان دحام

المستخلص

يتضمن هذه البحث دراسة توزيع السحنات المجهرية، البيئات الترسيبية والعمليات التحويرية لتكويني المشرف واليمامة في حقلي الفيحاء والسندباد الواقعين في الجزء الشمالي الشرقي من محافظة البصرة، جنوبي العراق تم فحص أكثر من 50 شريحة صخرية رقيقة من نماذج الحجر الجيري من ابار محفورة في الحقلين أعلاه. تم تشخيص عدة سحنات مجهرية في التكوينين اعلاه إعتماداً على المحتوى الحياتي (المتحجرات) في النماذج قيد الدراسة وأظهر الفحص السحني أن هناك أربع سحنات رئيسية وثمان

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سحنات ثانوية في تكوين اليمامة وأربع سحنات رئيسية وتسع سحنات ثانوية في تكوين المشرف وان السحنات الرئيسية هي الحجر الجيري الطيني، الحجر الجيري الواكي، الحجر الجيري المرصوص والحجر الجيري الحبيبي، والتي ترسبت في بيئات البحر المفتوح، أمام المنحدر، الشعاب المرجانية واللاغونية.تمثلت المتحجرات بالمنخربات القاعية، أصداف الرخويات، شوكيات الجلد (القنفذيات) والطحالب. الكالسايت والدولومايت هي المكونات المعدنية السائدة في عينات تكويني المشرف واليمامة. تبين من خلال فحص الشرائح الرقيقة وجود عمليات تحويرية تختلف في شدتها من سحنة إلى أخرى، مثل السمنتة، التشكل الجديد، الأحكام، الدلمتة، الإذابة (الذوبان العالي للحبيبات بسبب الخلط بالمياه الفرياتية)، المكرتة وبدرجة أقل من المعادن موضعية النشأة، والتي تؤدي إلى نشوء و تطور المسامية. أن المسامية الغالبة هي المسامية الفجوية، ما بين الحبيبات، ضمن الحبيبات، القنواتية والقالبية. بينت النتائج لنموذج الحوض الترسيبي أن تكوين اليمامة ترسب في بيئة المنحدرالكاربوناتي، في حين أن تكوين المشرف ترسب في بيئة حافة الرف الكاربوناتي المحصور.

INTRODUCTION

The Cretaceous rocks occupy a distinct position within the stratigraphic column in southern Iraq, where the content of this era represents good oil potential rocks. Some of these formations were considered as source rocks, while the others were reservoirs with high oil potentiality (Idan *et al.*, 2020). Many parameters can be applied to interpret depositional environment of the sedimentary rocks. The components commonly described in carbonate rocks, such skeletal and non-skeletal grains, are some common criteria in this respect. Likewise, microfacies study has a key role in the reconstruction of depositional environment. In sedimentology, facies are described based on depositional beds properties, such as texture, components compositions and sedimentary structures (Ahr, 2008).

This work is devoted to study the microfacies, diagenetic processes and depositional environment of the Mishrif and Yamama formations in two wells drilled in the Faiha and Sindibad oilfields. The petrographic and stratigraphic characteristics are described for more than 50 thin sections collected from Faiha-2 and Sindibad-3 to conclude the depositional model of the basin. The Mishrif Formation (Cenomanian-early Turonian) is one of the important carbonate reservoirs in central, southern Iraq and throughout the Middle East (Alsharhan and Nairn 1993; Alsharhan 1995; Aqrawi *et al.*, 1998). The formation contains up to 40% of the Cretaceous oil reserves in Iraq and about 30% of the total Iraqi oil reserves (Aqrawi *et al.*, 1998). The Yamama Formation is one of the most important oil producing reservoirs in southern Mesopotamian Zone, especially in the West Qurna, North Rumaila and Majnoon fields. It extends in age from Valanginian to Early Hauterivian within the main retrogressive depositional cycle (Berriasian-Aptian) in south of Iraq (Buday, 1980).

GEOLOGY OF THE STUDY AREA

Faiha and Sindibad oilfields are located in the Basrah Governorate, south Iraq. The Faiha field is located within the area of exploration (Block-9). This structure extends along the Iraqi-Iranian borders, about 20 Km towards northeast of the Basrah City. It is bordered from the north by Majnoon oilfield, from the south by Sindibad field, from the west by Nahr Bin Umr field and from the east by Hisainiya Iranian field. It is a convex fold which covers an area of 2866 Km, and lies approximately between the lines easting (215337.12 – 215502.00) m and northing (3425691.05 – 3432610.00) m as shown in (Fig.1).

Sindibad oilfield is located 18 Km east of Basrah City and approximately 5 Km of the Iraq – Iran borders, between the lines easting (785451 – 787500) m, and northing (3388161 – 3389000) m, (Basrah Oil Company). Many wells have been drilled in the Faiha field (Faiha-1, Faiha-2 and Faiha-3) and in the Sindibad field (Sindibad-1 and Sindibad-2) to determine the depositional environments and facies distribution of the reservoir rocks.

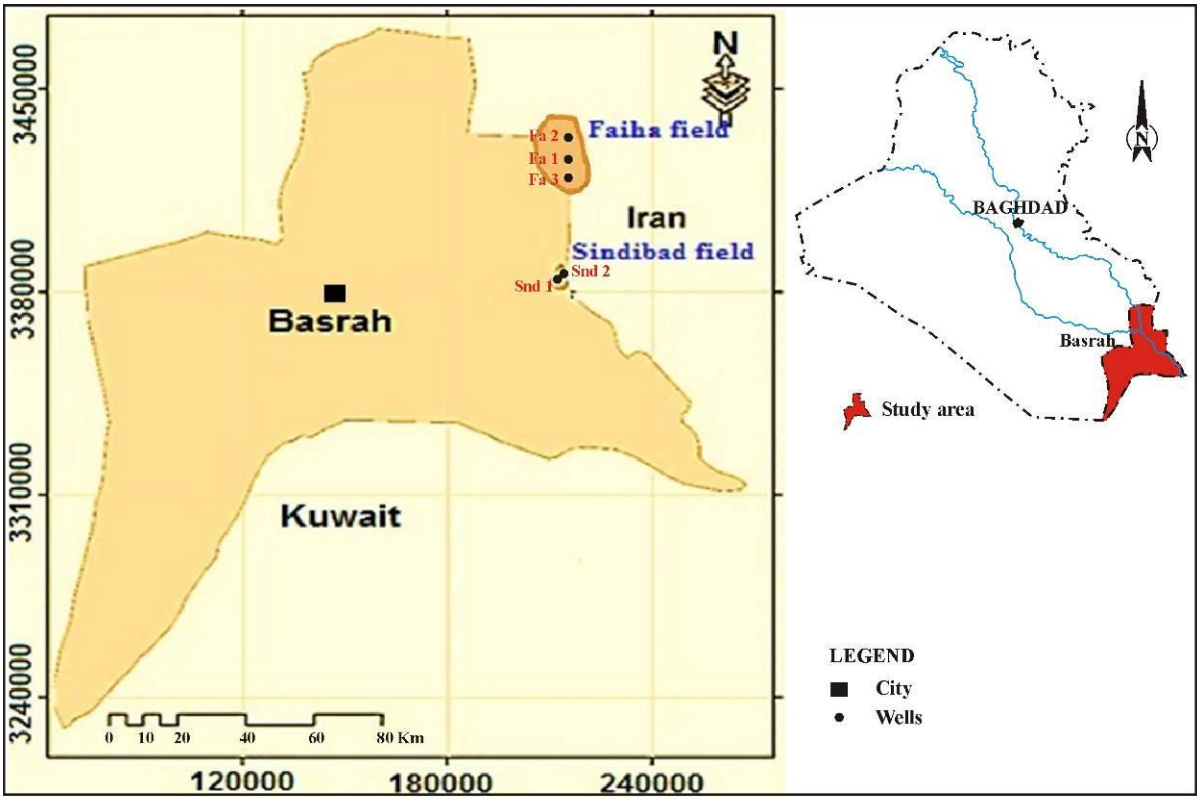
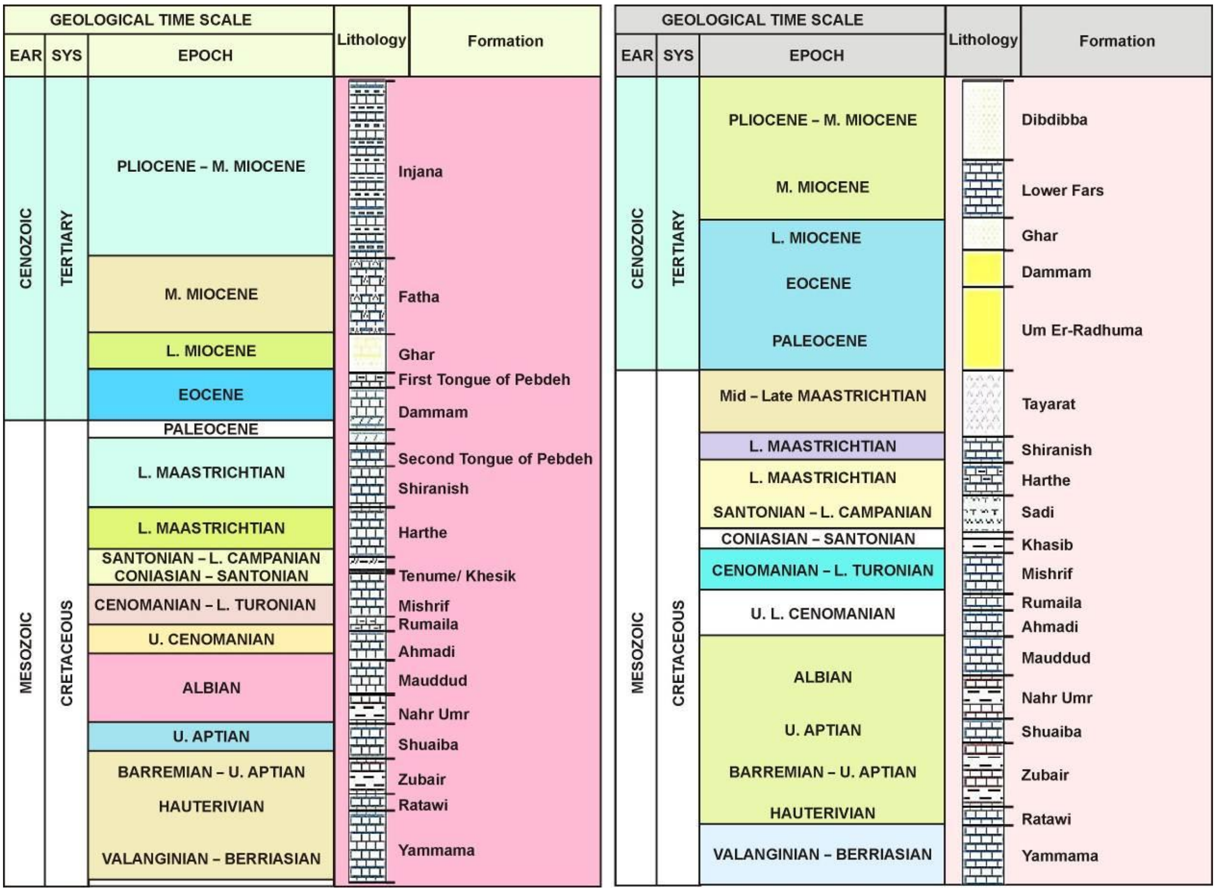


Fig.1: Location map of the studied oilfields

STRATIGRAPHIC SETTING

The Yamama Formation is one of the important reservoirs in southern Iraq, and it is deposited at the base of megasequence AP8 (Tithonian-Early Turonian) within the Tithonian-Hauterivian sequence (Jassim and Goff, 2006), while the Mishrif Formation is of Late Cenomanian age (Bellen *et al.*, 1959) and represents the most important oil reservoir in the Mesopotamian basin, southern Iraq (Reulet, 1982; Aqrawi *et al.*, 1998). The Yamama Formation takes the stratigraphic position between the Sulaiy Formation (Tithonian-Berriasian) at the lower part, and the Ratawi Formation (Valanginian-Hauterivian) at the upper part, reaching a thickness of about 400 m in the Zubair area (Jassim and Goff, 2006). The Mishrif Formation is widespread throughout the Arabian Peninsula (Al-Ameri *et al.*, 2009). The underlying Rumaila Formation consists predominantly of chalky and marly limestone. A conformable and gradational-junction with the Mishrif Formation are dark grey and greenish shales, alternating with grey, fine-grained marly limestone of the Khasib Formation (Bellen *et al.*, 1959) as shown in (Fig.2).

In SE Iraq, the Yamama Formation comprises three depositional cycles (Sadooni, 1993). Cycle tops are characterized by oolitic grainstone inner-ramp facies, which pass down to finer-grained peloidal facies and middle-ramp bioclastic/coral/stromoatoporoid pack-wackestones. Outer-ramp cycle bases comprise thick gray shales with stringers of chalky micrite (Roychoudhury and Handoo, 1980). Al-Siddiki (1977) divided the formation into three main lithofacies: the first represents a highly granular porosity and permeability limestone beds at the base of the formation, the middle represents compact limestone beds, whereas the upper part represents a high porosity and permeability Oolitic limestone beds. Al-Siddiki (1978) divided the Yamama Formation into five rock units with different petrophysical properties, three of which are reservoir units and the other two are cap rocks, depending on the interpretations of well logs, analysis of cores and study of depositional environment. These units are: First reservoir unit (YA), Second reservoir unit (YB) and Third reservoir unit (YC) separated by two units; first cap rock (CI) and second cap rock (CII). The depositional environment of the Yamama Formation alternates between shallow water environment and deep inter-reef environments and may be controlled by hidden structural heights within the carbonate ramp (Sadooni, 1993).



a- Faiha oilfield (Fa-2) **b-** Sindibad oilfield (Snd-3)

Fig.2: Stratigraphic sections of the studied oil wells (Basrah Oil Company)

The Mishrif Formation is the most important petroleum reservoir in the Mesopotamian basin, south of Iraq. The Mishrif Formation represents a heterogeneous limestone-bearing formation comprised of organic limestone with a group of algae, rudist and coral reef limestone (Bellen *et al*., 1959). The Mishrif Formation consists of a sequence of limestone complex structure and the lithology reflects the environment conditions that grade from open outer shelf/ shallow environments with reef-building organisms environments to open lagoonal environment. The thickness of the formation in south Iraq ranges between 150 – 200 m, it becomes thicker towards the Iraq–Iran borders, where the thickness of the formation is more than 350 m. In the study area the thickness of the formation is ranging from (250 – 350 m).

MITHODOLOGY

In this study, two wells from the Faiha and Sindibad fields are selected after careful study of available geological logs and related information. More than 50 thin sections of limestone samples are examined, using a polarizing microscope to determine the texture, microfacies and identify the components and diagenetic processes. The thin sections were prepared and stained with Alizarin Red Solution (ARS) following the procedure of Friedman (1959) to identify the calcite and dolomite. Well-preserved digital photomicrographs of grains and structures like stylolites were taken through a digital camera connected to the microscope and a computer program. The petrographic classification of Dunham (1962) is used in this study because it is easy and widely applied classification for microfacies. The interpretation of the sedimentary environment is compared with standard microfacies of Wilson (1975) and facies zones for Flügel (1982 and 2004).

RESULTS AND DISCUSSION

- **Microfacies Analysis**

Facies is defined as a lithic body has certain properties described according to the color, bedding and sedimentary structures, mineralogical composition, particle size, main constituents, texture and biological remains, and each facies represent certain geological event (Reading, 1986). The microfacies defined as completely sedimentological and paleontological standards that can be studied and classified in thin sections for environmental analysis and correlation (Flügel, 1982). Kendall (2007) defines facies according to structural, histological and synthetic properties that result from deposition processes and cause accumulation and modification within the depositional environment.

The important facies of the Mishrif and Yamama formations are determined in this study through the description of core and thin sections that were available for two selected wells in the study area. Microscopic examination of thin sections resulted s in the recognition of four major microfacies. These are:

– **Lime Mudstone Microfacies:** Lime mudstone was defined by Dunham (1962) as a kind of limestone that is composed of microcrystalline calcite, which corresponds to the term micrite that was launched by Folk (1965). Micrite represents more than 90% of this microfacies, and it also consists of allochems; by ratio ranging from (2 – 10 %) and represented by bioclasts or lithoclasts. Such facies is deposited in low energy environment (Bathurst, 1975). Depending on composition, this microfacies is further specified into:

a. Unfossiliferous Lime Mudstone Submicrofacies (**M1**)

This submicrofacies is found in the Yamama Formation in well Snd-3 (at depths 4063.10, 4119.60 and 4127.90) m, (Figs.3a and c; and 4e; Table 1), and in well Fa-2 within depths (4055.12, 4061.3, 4114.55, 4333.44, 4340.4 and 4351.39) m, (Fig.4b, c and d; Table 2). Generally, the term Muddiness refers to the quiet environment (Dunham, 1962). In addition, lime mudstone contributes to preventing living beings to gather and form grains inside. This facies could be compared with standard microfacies RMF-19 (SMF-23) that is deposited in Facies Zone FZ-8 according to Wilson (1975) and Flügel (1982 and 2004), which represents the peritidal and lagoonal zone in the inner carbonate ramp.

b. Fossiliferous Lime Mudstone Submicrofacies (**M2**)

This submicrofacies is characterized by being fossiliferous (not exceeding 10%) including echinoderm and algae. This submicrofacies is observed in well Fa-2 in Yamama Formation (at depths 4259.82, 4264.54 and 4344.41) m, (Fig.3e; Table 2). This microfacies represents deposition in peritidal zone in the inner carbonate ramp as compared with the RMF-23 (SMF-21) that is deposited in Facies Zone FZ-8 according to the models of Wilson (1975) and Flügel (1982 and 2004).

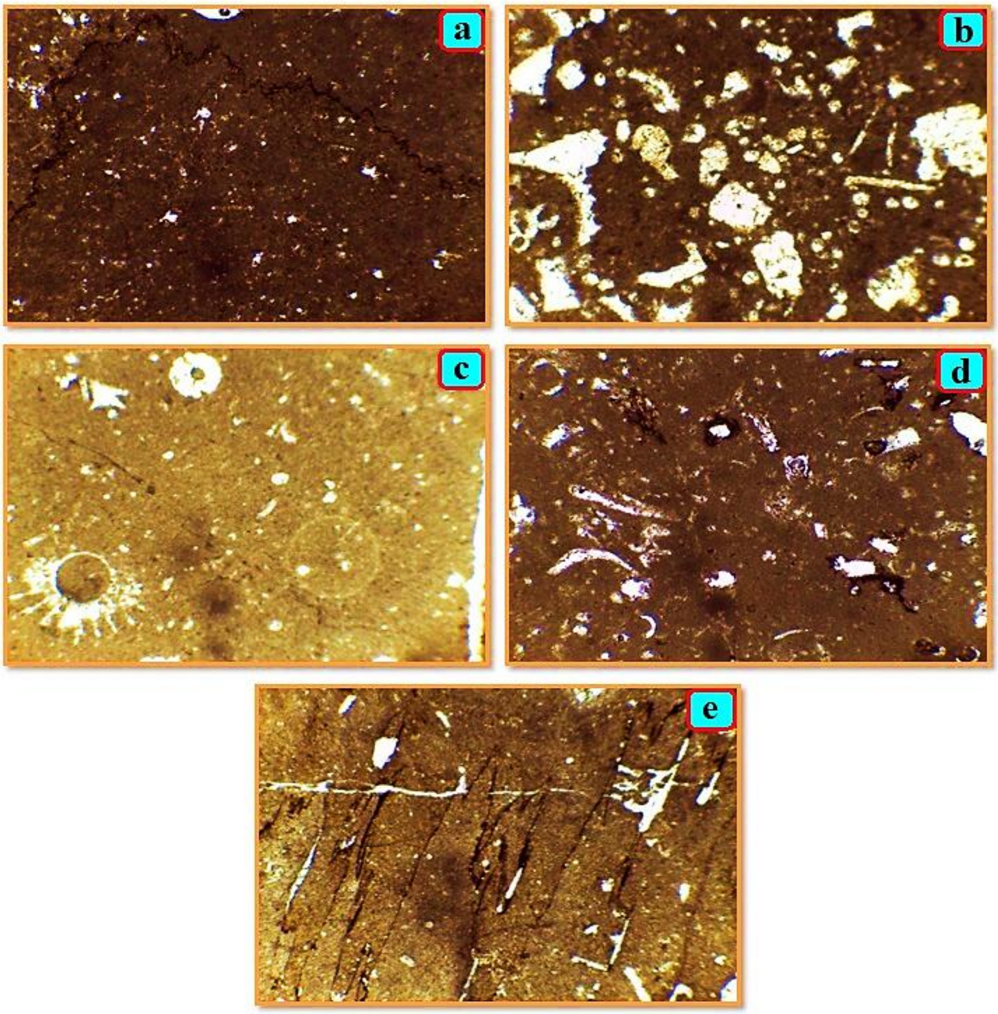


Fig.3:

a. Bioclastic Wackestone Submicrofacies with coral (Co), green algae (Ga) and benthic foraminifera (Bf), Snd-3, depth 4059.60, 40x, PPL.

b. Peloidal Packstone Submicrofacies with benthic foraminifera (Bf) and green algae (Ga), in addition to the clarity of the compaction effect, which generates dissolution channel, Snd-3, depth 4068.50, 40x, PPL.

c. Bioclastic Wackestone Submicrofacies with *Gastropoda*, echinoderm, *Pelecypoda* and green algae (Ga), in addition to the high compaction which generates cracks and solution channels filled with blocky cement, Snd-3, depth 4079.80, 40x, PPL.

d. Bioclastic Wackestone Submicrofacies with *Miliolidae*, echinoderm and green algae (Ga), in addition to the solution channels which appearance associated with pyrite, as well as appearance syntaxial rim cement, Snd-3, depth 4166.25, 40x, PPL.

e. Bioclastic Wackestone Submicrofacies with coral (Co), *Gastropoda*, echinoderm, *Miliolidae*, *Pseudocyclamina*, benthic foraminifera (Bf) and green algae (Ga), as well as presence of high granular mosaic cement and oil shows, Snd-3, depth 4171.30, 40x, PPL.

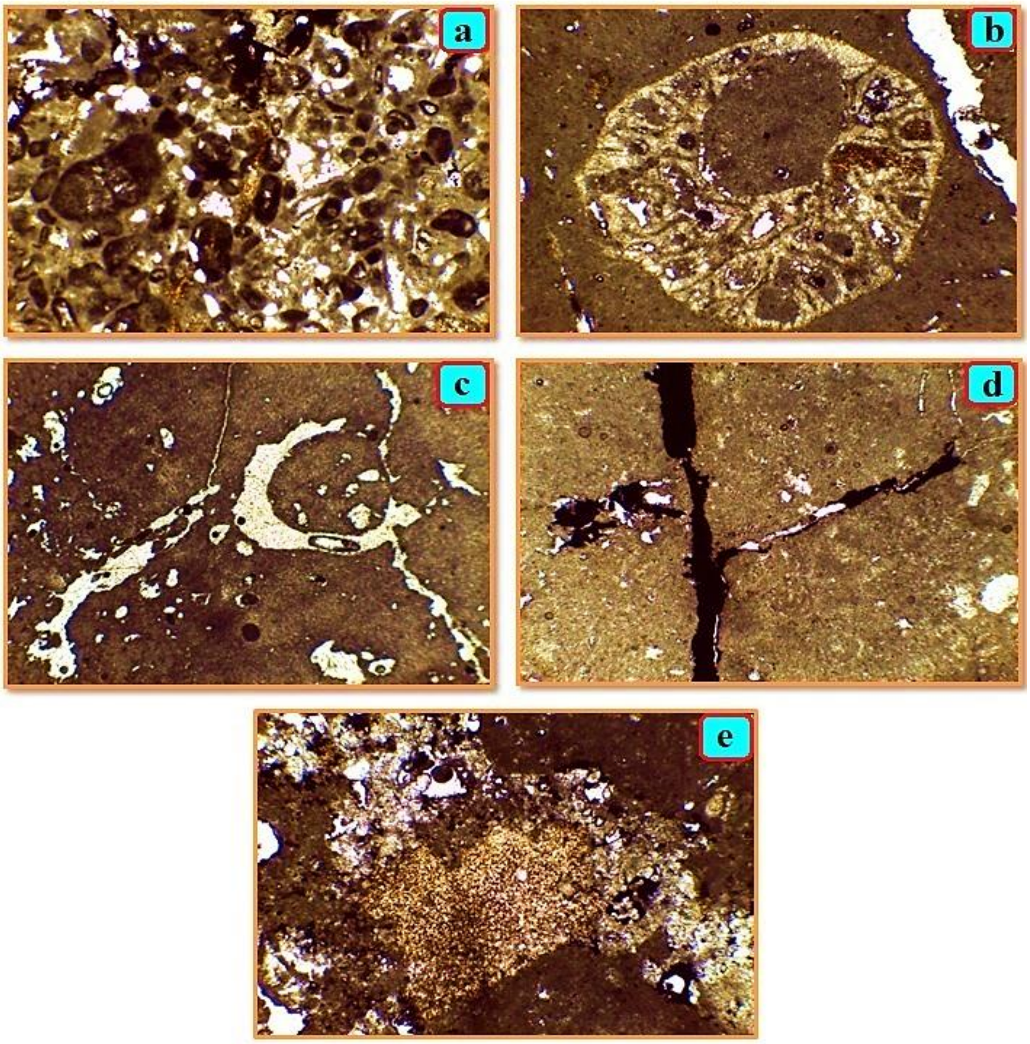


Fig.4:

a. Unfossiliferous Lime Mudstone Submicrofacies with *Pseudocyclamina*, benthic foraminifera (Bf) and green algae (Ga), with solution channels and stylolite, Snd-3, depth 4063.10, 40x, PPL.

b. Algae Wackestone Submicrofacies with *Pseudocyclamina*, *Pelecypoda,* echinoderm and green algae (Ga), with high argillaceous content and appearance of granular mosaic cement, Snd-3, depth 4114.75, 40x, PPL.

c. Unfossiliferous Lime Mudstone Submicrofacies, showing granular mosaic cement, Snd-3, depth 4119.60, 40x, PPL.

d. Algal Wackestone Submicrofacies, characterized by vuggy and moldic porosity enhanced by dissolution process and appearance of granular mosaic cement, Snd-3, depth 4146.76, 40x, PPL.

e. Fossiliferous Lime Mudstone Submicrofacies with red algae (*Permocalculus*), *Pelecepods,* Oil shows and stylolite, Fa-2, depth 4259.82, 40x, PPL.

Table 1: Petrographic description, distribution of microfacies and diagenesis for the Yamama Formation in well (Snd-3)

Age	Depth (m)	Cement Types	Fossils									Fabric	Pore Types	Structure
			Coral	*Gastropoda*	*Echinoderm*	*Heteroporla*	*Pseudocyclamina*	*Pelecypoda*	*Green Algae*	*Benthic Foram.*	*Miliolidae*			
Berriasian – Valanginian	**4059.6**		•						•	•		W	M & V	
	4063.1						•		•	•		M	M & V	sty.
	4068.5								•	•		P	V & Ch	sty.
	4079.8	Blk		•	•			•	•			W	M & V	sol.
	4086.4				•		•		•			W	M & V & Sh	
	4114.75	Gr			•		•	•	•			W		
	4119.6	Gr				•			•			M	Fr	
	4127.9						•	•		•		M		
	4146.76	Gr							•			W	M & V	sol.
	4158.5								•	•		W	Ip & Ia	
	4166.25	Blk			•				•		•	W	V & Ip & Ia	
	4171.3	Gr	•	•	•		•		•	•	•	W	M & Ch	
	4176.65				•				•	•		W	M & V	

Legend		
Fabric	**M**	Mudstone
	W	Wackestone
	P	Packstone
	G	Grainstone
Pore Types	**Ip**	Interparticles
	M	Moldic
	V	Vuggy
	Ch	Channel
	Fr	Fracture
	Ia	Intraparticles
	Sh	Shelter
Structure	**sty.**	Stylolite
	sol.	Solution channel
Cement Types	**Gr**	Granular
	Blk	Blocky

Table 2: Petrographic description, distribution of microfacies and diagenesis for the Yamama Formation in well (Fa-2)

Age	Depth (m)	Cement Types	Fossils: *Textularia*	Fossils: *Algae (Permocalculus)*	Fossils: *Echinoderm*	Fossils: *Coral*	Fossils: *Gastropoda*	Fossils: *Actinopoda*	Fossils: *Bryozoa*	Fossils: *Pelecypoda*	Fossils: *Benthic Foram.*	Fabric	Pore Types	Structure
Berriasian – Valanginian	4055.12				•							M	V	
	4061.3				•							M	M	
	4064.35				•		•					W	M & V	
	4070.45				•	•			•	•	•	W	V & Ia	sol.
	4088.75	Gr			•	•						W	K	
	4097.35				•	•						W	Ip & V	
	4114.55											M	M & V	
	4119.70	Gr & Blk		•	•						•	W	M & Ip	sty.
	4130.6	Gr			•					•	•	G	M & Ip	sol.
	4132.55	Gr	•	•		•				•		W	M & V	sty.
	4137.6				•							W	Ch	sty.
	4259.82			•						•		M	M	sty.
	4264.54			•	•							M	Ia.	
	4277.4		•	•				•			•	W	M & V	
	4333.44								•	•	•	M	M & V	sty.
	4340.4	Gr							•	•	•	M	V	sol.
	4344.41			•	•		•	•	•		•	M	M & V	
	4348.42										•	W	Ia & Ip	
	4351.39		•	•							•	M	M & V	sol.

Legend		
Cement Types	Blk	Blocky
	Gr	Granular
Structure	sol.	Solution channel
	sty.	Stylolite
Pore Types	Ia	Intraparticles
	K	Cavern
	Ch	Channel
	V	Vuggy
	M	Moldic
	Ip	Interparticles
Fabric	G	Grainstone
	P	Packstone
	W	Wackestone
	M	Mudstone

– **Wackestone Microfacies:** In this microfacies type, the percent of skeletal and non-skeletal grains ranges between (10 – 40 %). It is considered as the main common microfacies in the Yamama Formation in well Snd-3 (at depth 4158.5 m.) and in well Fa-2 at three depths (4132.55, 4277.40 and 4348) m. This microfacies contains abundant skeletal grains, mainly comprised of benthic foraminifera, Mollusca shells, Echinodermata and algae; with their structures intact and their parts clear and buried in the micrite matrix (Dunham, 1962). The non-skeletal grains are represented by red algae (*Permocalculus*) fragments and debris of echinodermata.

This main microfacies was subjected to a range of diagenetic processes, which were observed as: **1)** cementation which is represented by several types, such as blocky, granular and mosaic cement, **2)** dolomitization which has partial effect and appear as small dolomite crystals without facets, **3)** compaction and **4)** dissolution. Depending on the ratio of dominant grains and diagenetic processes, the wackestones are further divided into five submicrofacies listed below:

a. Bioclastic Wackestone Submicrofacies (**M3**)

This submicrofacies represents the most common submicrofacies in the studied samples and is comprised of microbioclasts in varying levels, such as fragments and debris of green and red algae, *Miliolidae* and Mollusca (*Gastropoda*) with few Echinoid and *Pseudocyclammina*. In addition, there are fragments of rudist in the Mishrif Formation in well Fa-2. In addition to the presence of *Alveolina* genus such as (*Cisalveolina, Praealveolina Quinqueloculina, Cycledomia* and *Pseudoloftuoinal*). The most important diagenetic processes, found only in this submicrofacies especially in the Yamama Formation (at depth 4166.25 m), is the appearance of Syntaxial rim cement.

This submicrofacies is widely observed in the Yamama Formation in well Snd-3 at depths: (4059.60, 4079.80, 4086.40, 4166.25, 4171.30 and 4176.65) m, (Figs.5a, c, d and e; and 9a; Table 1). While in well Fa-2, this submicrofacies is found in the Yamama Formation within depths (4064.35, 4070.45, 4088.75, 4097.35 and 4137.60) m. In addition, the submicrofacies is found in the Mishrif Formation in well Fa-2 at depths: (2779.17, 2956.65, 2973.64, 2977.75 and 2981.50) m, (Fig.6a, c, d and e; Table 3). This submicrofacies correlates with the Standard Microfacies RMF-20 (SMF-9) deposited in Facies Zone FZ-7 according to the models of Wilson (1975) and Flügel (1982 and 2004), and represents the lagoonal zone in the inner carbonate ramp.

b. Algae Wackestone Submicrofacies (**M4**)

This submicrofacies is comprised of red and green algae of various sizes and shapes. It is mostly soluble filled with more than one type of cement, fragments of shells and fragments of large benthic foraminifera such as (*Pseudocyclammina*), in addition to fragments of (Echinoderms). This submicrofacies is observed within two depths in well Snd-3 (4114.75 and 4146.76) m, (Fig.3b and d; Table 1). This facies could be compared with the Standard Microfacies RMF-17 (SMF-18) that is deposited in Facies Zone FZ-7 according to Wilson (1975) and Flügel (1982 and 2004), which represents the restricted zone in the inner carbonate ramp.

c. Dolomitic Wackestone Submicrofacies (**M5**)

This submicrofacies is found in well Fa-2 (Figs.4a and 7d; Table 2), within depth (4119.70) m. Such submicrofacies is characterized by being highly argillaceous and contains fragments of red and green algae and fragments of echinoderm. The most important digenetic process that affected this microfacies is cementation, which appears as blocky, granular and mosaic cement, whereas, dolomite appears as a scattered microcrystalline form. It is also observed that there are stylolites associated with the dolomite. This microfacies correlates with Standard Microfacies RMF-3 (SMF-8) that is deposited in Facies Zone FZ-7 according to the models of Wilson (1975) and Flügel (1982 and 2004), which represents the outer carbonate ramp.

d. Benthic Foraminifera Wackestone Submicrofacies (**M6**)

This submicrofacies is found only in the Mishrif Formation in well Fa-2 and is dominated by large broken fragments of foraminifera and echinoderm embedded in lime mud. In addition to small fragments of rudist such as (*Praealveolina*, *Ovalveolina*, *Nezzazata* and *Textularia)* which are observed at depths: (2961.55 and 2997.78) m. As for the depth (2986.56 m) this facies is overlapping with dolostone microfacies. The dominant *Peneroplidae* with *Miliolidae* families has an indication of the back-reef facies (Fig.7a, b and c; Table 3). This facies could be compared with Standard Microfacies SMF-9 that is deposited in Facies Zone FZ-7 according to Wilson (1975) and Flügel (1982 and 2004), which represents the open circulation, open marine zone in the platform interior.

e. Rudist Inplace Wackestone Submicrofacies (**M7**)

This submicrofacies is characterized by predominant bioclasts of large size rudist shells. It also contains benthic foraminifera and fragments of amyloid and a proportion of biocrumbs. This submicrofacies shows high proportion of cementation and muddiness. Moreover, there are set of micro-fracture channels with oil show. Small *Hermatypic* corals are represented by the source of debris transported over the isolated platform (Kendall and Schlager, 1981). The presence of *Dyscladic* is unique for the foreslope environment (Al-Hashmi and Amer, 1985). This submicrofacies is observed in the Mishrif Formation at depth: (2787.61) m. This facies could be compared with the Standard Microfacies SMF-6 that is deposited in Facies Zone FZ-4 according to Wilson (1975) and Flügel (1982 and 2004), which represents reef foreslope environment.

– **Packstone Microfacies:** This microfacies consists mainly of grains, which represent a ratio between (40 – 90 %) when it is compared with the micritic matrix, in addition to the presence of fragments or bioclasts debris in little proportion including peloids and pellets. This microfacies is found within micritic matrix partially or totally converted into sparite or microsparite in neomorphism process and contains stains of oil. This submicrofacies is characterized by the appearance of very high ratio of rudist in well Fa-2, within the depth (2992.50) m, (Fig.8b; Table 3). This microfacies is similar in characteristics to SMF-16 that was deposited in FZ-8 according to the models of Wilson (1975) and Flügel (1982 and 2004). The Packstone Microfacies is further subdivided into two submicrofacies:

a. Bioclastic Packstone Submicrofacies (**M8**)

This submicrofacies is characterized by the presence of bioclasts represented by fragments and debris of (Echinoid, Mollusca, *Cisalveolina*, *Praealveolina*, *Quinqeloculina* and *Cycledomia*). The most important diagenetic process, observed in this microfacies is cementation having the appearance of blocky, equigranular, drusy and granular mosaic cement. Moreover, there are stains of oil within the investigated thin sections. This submicrofacies is found in the Mishrif Formation in well Fa-2 in the depths (2781.95, 2782.88, 2783.70 and 2860.9) m, (Figs.5f; and 9b and c; Table 3). This submicrofacies correlates the Standard Microfacies SMF-12 that is deposited in Facies Zone FZ-6 according to Wilson (1975) and Flügel (1982 and 2004), which represents the platform-margin environment.

b. Peloidal Packstone Submicrofacies (**M9**)

This submicrofacies is mainly formed from peliods with the presence of bioclastic debris represented by fragments and debris of (*Nezzazata*, *Miliolidae*, *Pseudocyclomina* and *Biloculina foraminifera*) as well as presence rudist debris and stains of oil with micritic matrix. The peliods are generally difficult to determine their origin. They are formed with skeletal grains, represented by benthic foraminifera exposed to the micritization process or formed from non-skeletal grains, such as incomplete oolites or pseudo-oolites having no appropriate conditions for being complete. This facies is exposed to the cementation process in all observed thin sections, especially in one thin section in well Snd-3 at depth (4068.50) m, (Fig.3b; Table 1) and in the Mishrif Formation in well Fa-2 at depths (2784.77, 2796.95, 2819, 2827.88 and 2856) m, (Figs.6b and 8a; Table 3). By comparing this submicrofacies with Wilson' standard microfacies (Wilson, 1975) and Flügel (1982 and 2004) it shows similarities with the Standard Microfacies (SMF-16) located in Facies Zone (FZ-7:6). This facies could be compared with the Standard Microfacies RMF-14 (SMF-16) that is deposited in Facies Zone FZ-8 according to Wilson (1975) and Flügel (1982 and 2004), which represents the open marine zone in the inner carbonate ramp.

– **Grainstone Microfacies:** Grains, whether skeletal or non-skeletal, form about 90% of the basic structure of this microfacies; it contains only about 10% or less of matrix which consists of microsparite texture and pseudosparite texture. The most important digenetic processes that affected this microfacies are the cementation, dolomitization and neomorphism. The Grainstone Microfacies is further subdivided into three submicrofacies:

a. Peloidal Grainstone Submicrofacies (**M10**)

This submicrofacies consists of peloids that have relatively large size and are connected with each other by cement which is found in high proportion. The most important digenetic process that affected this microfacies is cementation present as blocky, drusy and granular mosaic cement. It is characterized by fragments and fossils of bioclast debris such as (Rudist, *Miliolids*, Echinoid and *Cisalveolina*). This submicrofacies is found at two depths in the study area; in the Yamama Formation at depth (4130.60) m, (Fig.7e; Table 2) and in the Mishrif Formation in Fa-2 at depth (2849) m, (Fig.7f; Table 3). This facies could be compared with Standard Microfacies RMF-16 (SMF-18) that is deposited in Facies Zone FZ-7 according to Wilson (1975) and Flügel (1982 and 2004), which represents the restricted zone in the inner carbonate ramp.

b. Oolitic Grainstone Submicrofacies (**M11**)

This submicrofacies is dominated by the presence of oolites. It is found in large proportions, poorly sorted and reduced in size. It is considered as good reservoir zone, because of the porosity created by these grains. Dissolution processes by the action of high currents, energy and cementation are the most abundant diagenetic processes affecting the porosity. High cementation rates have affected the upper parts of this submicrofacies where sparite is developed. This submicrofacies is found in well Fa-2 in Mishrif Formation only within the depths (2808, 2843 and 2843.95) m, (Figs.8c and d; and 9d; Table 3). This facies could be compared with Standard Microfacies SMF-15 that is deposited in Facies Zone FZ-6 according to Wilson (1975) and Flügel (1982 and 2004), which represents the platform-margin environment.

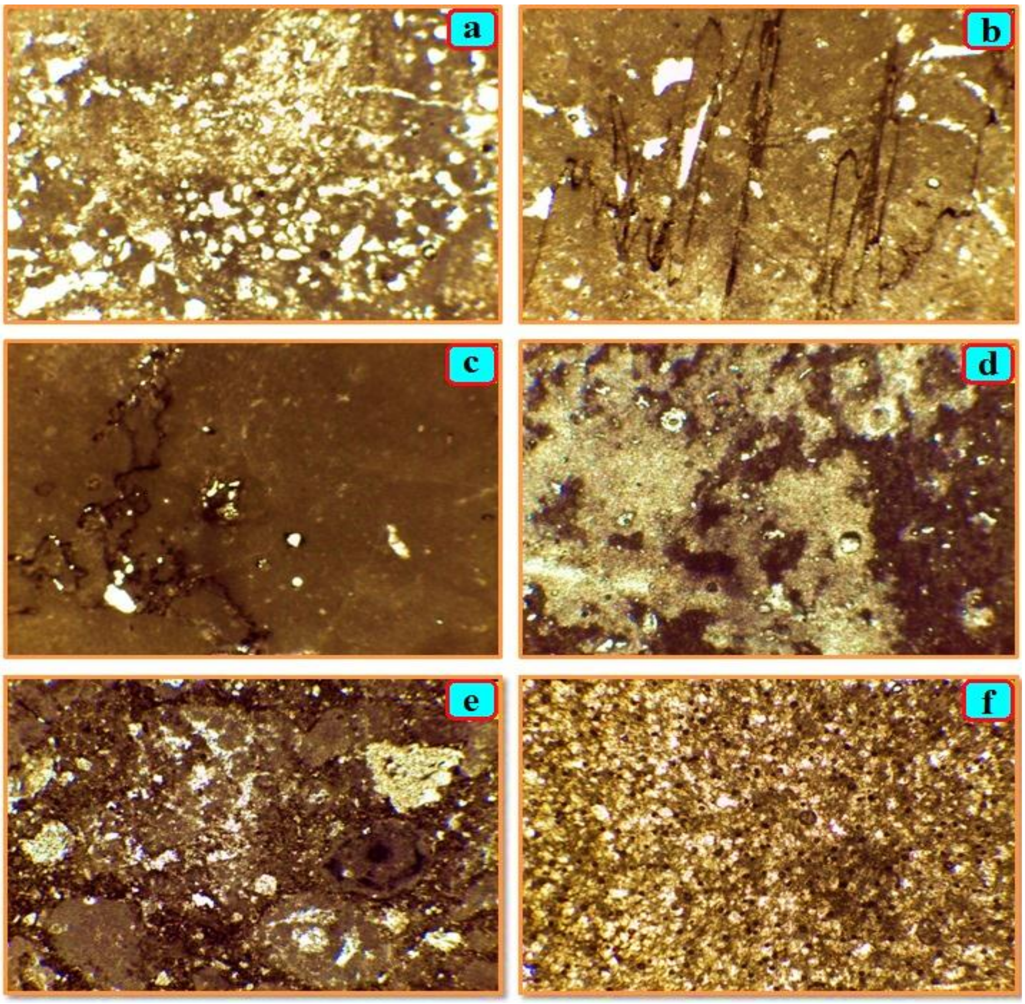


Fig.5:

a. Dolomitic Wackestone Submicrofacies with benthic foraminifera (Bf), echinoderm and algae fragments, characterized by moldic porosity enhanced by dissolution, Fa-2, depth 4119.70, 40x, PPL.

b. Unfossiliferous Lime Mudstone Submicrofacies with benthic foraminifera (Bf), *Pelecypoda* and Bryozoa, with abundant stylolites, Fa-2, depth 4333.44, 40x, PPL.

c. Unfossiliferous Lime Mudstone Submicrofacies with benthic foraminifera (Bf), *Pelecypoda* and Bryozoa, showing solution channel, oil shows and granular cement, Fa-2, depth 4340.4, 40x, PPL.

d. Unfossiliferous Lime Mudstone Submicrofacies with *Textularia*, benthic foraminifera (Bf) and Algae fragments, showing high dissolution process, Fa-2, depth 4351.39, 40x, PPL.

e. Unfossiliferous Lime Mudstone Submicrofacies with *Pseudocyclamina*, *Pelecypoda* and benthic foraminifera (Bf), overlapping with Peloidal Packstone Submicrofacies. Observe the convertion of micrite into sparite, Snd-3, depth 4127.9, 40x, PPL

f. Bioclastic Packstone Submicrofacies with *Miliolidae* and benthic foraminifera (Bf) and Dolostone Microfacies, showing blocky cement, Fa-2, depth 2860.9, 40x, PPL.

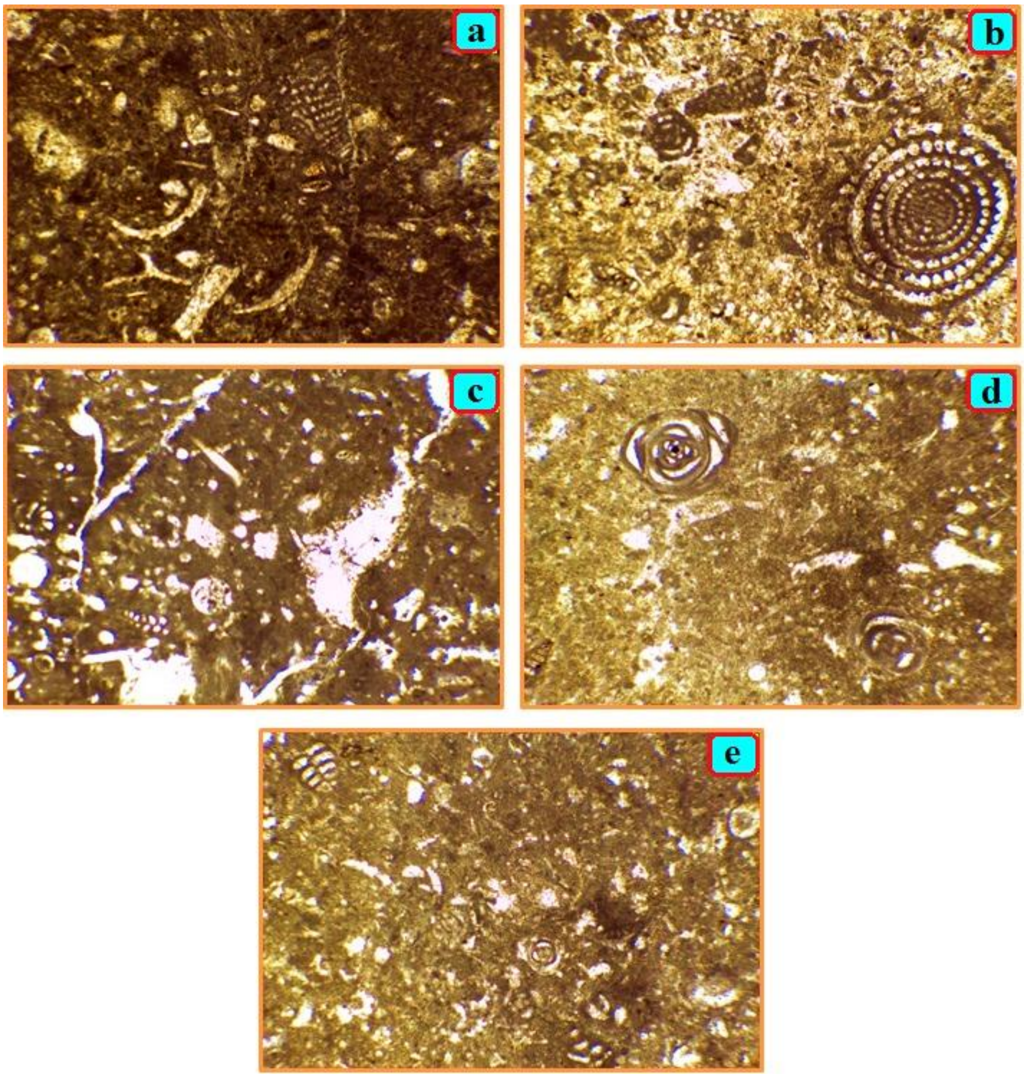


Fig.6:

a. Bioclastic Wackestone Submicrofacies with *Praealveolina* and mollusca, showing micro-granular cement, Fa-2, depth 2779.17, 40x, PPL.

b. Peloidal Packstone Submicrofacies with large benthic foraminifera (Bf) and *Cisalveolina*, showing high cementation, neomorphism and recrystallization, Fa-2, depth 2856, 40x, PPL.

c. Bioclastic Wackestone Submicrofacies with green algae (Ga) and benthic foraminifera fragments (Bf), in addition to the presence of very high proportion of blocky mosaic, cement, and showing channel and moldic porosity enhanced by dissolution, Fa-2, depth 2973.64, 40x, PPL.

d. Bioclastic wackestone submicrofacies with *Miliolidae* and benthic foraminifera (Bf), Fa-2, depth 2977.75, 40x, PPL.

e. Bioclastic Wackestone Submicrofacies with *Thaumatoporella parvovesiculifera*, *Chrysalidina* and *Quinqueloculina*, Fa-2, depth 2981.5, 40x, PPL.

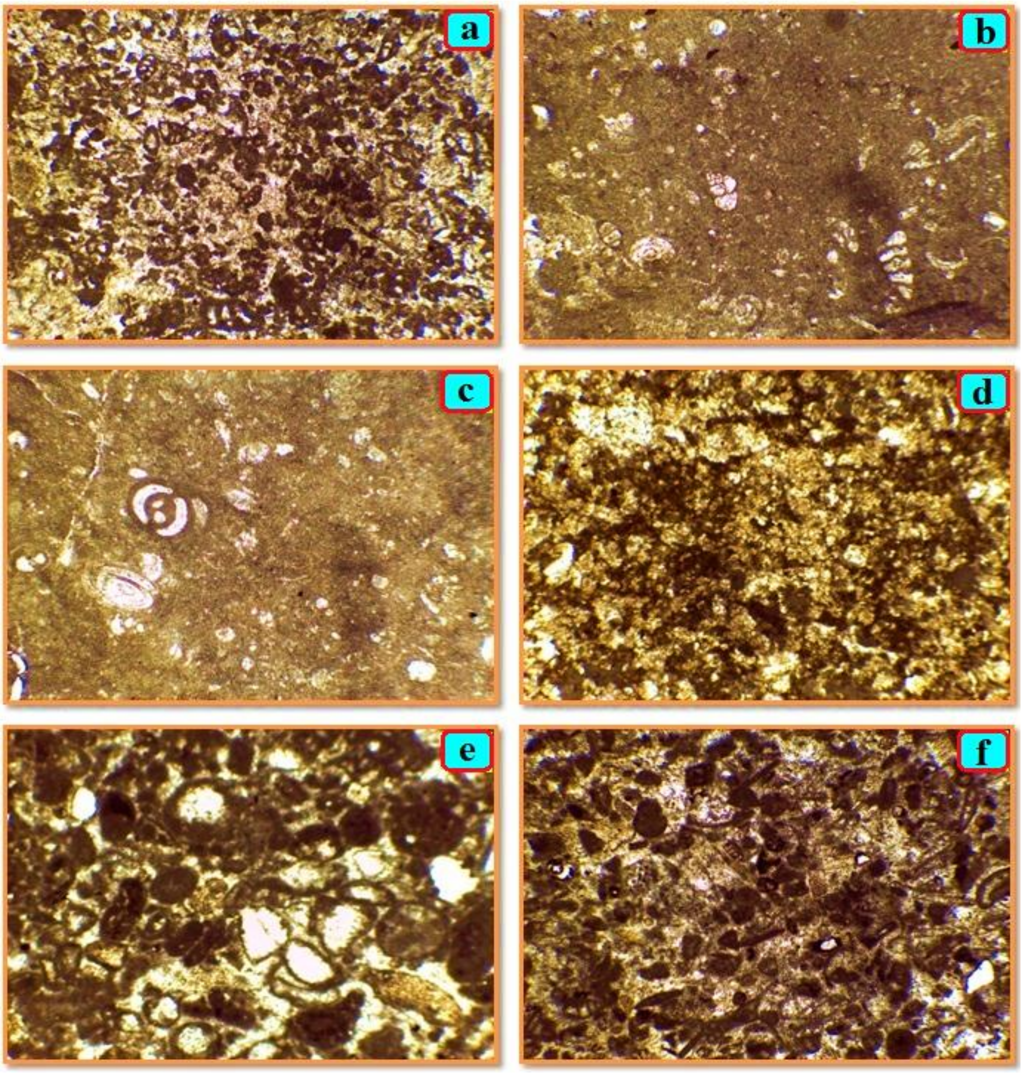


Fig.7:

a. Benthic Foraminifera Wackestone Submicrofacies with *Miliolida*, *Nezzazata* and *Cisalveolina*, in addition to small rudist fragments. Highly micritic, Fa-2, depth 2961.55, 40x, PPL.

b. Benthic Foraminifera Wackestone Submicrofacies with *Permocalculs ampullaceus*, *Chrysalidina* and echinoderm, Fa-2, depth 2986.56, 40x, PPL.

c. Benthic Foraminifera Wackestone Submicrofacies, showing compaction effect with the presence of blocky cement, Fa-2, depth 2997.78, 40x, PPL.

d. Dolomitic Wackestone Submicrofacies highly cemented, showing blocky and granular mosaic cement, Fa-2, depth 4119.70, 40x, PPL.

e. Peloidal Grainstone Submicrofacies with benthic foraminifera (Bf), echinoderm and *Pelecypoda*; characterized by moldic and intraparticles porosity enhanced by micritization, Fa-2, depth 4130.60, 40x, PPL.

f. Peloidal Grainstone Submicrofacies with *Pelecepods*, benthic foraminifera (Bf) and oil shows, Fa-2, depth 2849, 40x, PPL.

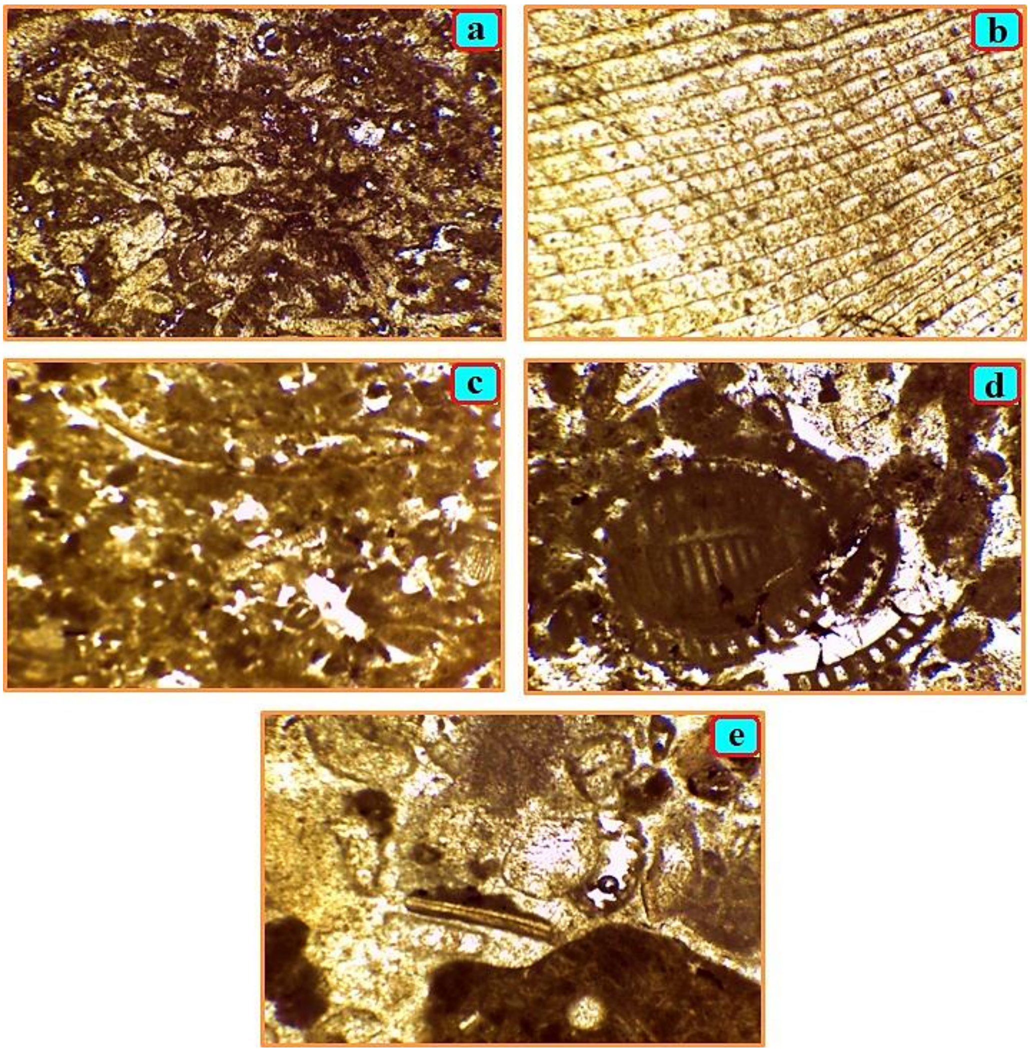


Fig.8:

a. Peloidal Packstone Submicrofacies with *Nezzazata, Bryozoa*, benthic foraminifera (Bf), echinoderm and small rudist fragments, Fa-2, depth 2819, 40x, PPL.

b. Rudist Packstone Microfacies, showing benthic foraminifera fragments, Fa-2, depth 2992.50, 40x, PPL.

c. Oolitic Grainstone Submicrofacies with mollusca, echinoderm and rudist, characterized by high blocky cement, Fa-2, depth 2808, 40x, PPL.

d. Oolitic Grainstone Submicrofacies with *Cisalveolina*, showing blocky cement, Fa-2, depth 2843, 40x, PPL.

e. Rudist Peloidal Grainstone Submicrofacies with *Nezzazata* and *Miliolida*, in addition to the presence blocky cement, Fa-2, depth 2865, 40x, PPL.

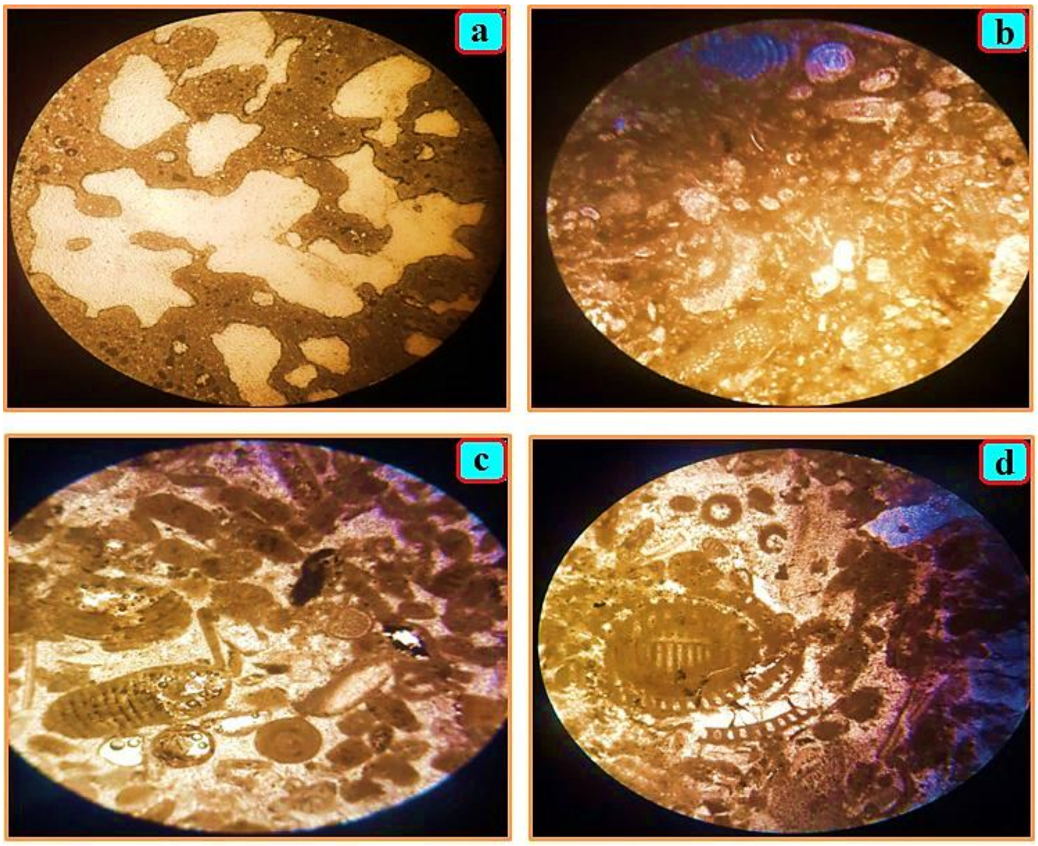


Fig.9:

a. Bioclastic Wackestone Submicrofacies with echinoderm, benthic foraminifera (Bf) and green algae (Ga), in addition to the presence of micritization and convertion of micrite into sparite, Snd-3, depth 4176.65, 40x, PPL.

b. Bioclastic Packstone Microfacies with *Chrysalidine*, *Ataxophrgium* and *Praealveolina*, showing blocky cement, Fa-2, depth 2781.95, 40x, PPL.

c. Bioclastic Packstone Submicrofacies with *Spiroplectammina*, *Cisalveolina, Peneroplidae* and *Qatariadukhani*, in addition to the presence of oil shows, Fa-2, depth 2782.88, 40x, PPL.

d. Oolitic Grainstone Submicrofacies with *Cisalveolina, Pelecepods,* echinoderm and rudist fragments, in addition to the presence blocky cement, Fa-2, depth 2843.95, 40x, PPL.

Table 3: Petrographic description, distribution of microfacies and diagenesis for the Mishrif Formation in well (Fa-2)

Age: Late Cenomanian – Early Turonian

Depth (m)	2997.78	2996.83	2992.5	2986.56	2981.5	2977.75	2973.64	2966.5	2961.55	2956.65	2952	2865	2860.9	2856	2849	2843.95
Cement Types	Blk		Gr				Blk					Blk	Blk		Gr	Blk
Fossils: *Nezzazata*			●						●			●				
Fossils: *Rudist*							●					●	●			●
Fossils: *Mollusca*													●			
Fossils: *Cisalveolina*		●							●							
Fossils: *Praealveolina*																●
Fossils: *Quinqueloculina*		●			●											
Fossils: *Cycledomia*		●														
Fossils: *Miliolidae*											●	●	●			
Fossils: *Qatariadukhan*														●		
Fossils: *Chrysalidina*				●												
Fossils: *Pseudocyclamina*				●												
Fossils: *Gastropoda*																
Fossils: *Echinoderm*													●			●
Fossils: *Pelecypoda*															●	●
Fossils: *Bryozoa*																
Fossils: *Benthic Foram.*	●	●	●		●	●	●	●		●	●		●	●	●	●
Fossils: *Textularia*						●	●							●		
Fabric	W	W	P	W	W	W	W	W	W	W	W	G	P	P	G	G
Pore Types			Ia		V & Ia		M & Ch	V			M & V	M		Ip & V	M & V	
Structure									sty.			sty.		sol. & sty.		

Depth (m)	2832.9	2827.88	2819	2816	2812	2809.06	2808	2806	2802	2796.95	2787.61	2784.77	2783.70	2782.88	2781.95	2779.17
Cement Types		Gr		Gr	Gr	Gr	Blk	Gr		Gr		Gr			Blk	Gr
Fossils: *Nezzazata*			●													
Fossils: *Rudist*	●		●	●	●	●	●		●		●		●			
Fossils: *Mollusca*						●	●	●								●
Fossils: *Cisalveolina*	●		●											●	●	
Fossils: *Praealveolina*		●												●	●	●
Fossils: *Quinqueloculina*														●	●	●
Fossils: *Cycledomia*														●	●	●
Fossils: *Miliolidae*	●			●							●					
Fossils: *Qatariadukhan*				●							●	●		●		
Fossils: *Chrysalidina*																
Fossils: *Pseudocyclamina*											●	●				
Fossils: *Gastropoda*								●								
Fossils: *Echinoderm*			●	●	●		●	●								
Fossils: *Pelecypoda*		●	●					●								
Fossils: *Bryozoa*			●													
Fossils: *Benthic Foram.*		●	●	●		●					●					
Fossils: *Textularia*			●													
Fabric	G	P	P	P	P	P	G	W	W	P	W	P	P	P	P	W
Pore Types	M & V	M & V	Ia & V	M & V	M & V	M & Ip			V	M & Ip	Ip & K		Ip	Ip & Ia	M & Ip	Ch
Structure						sol.	sol.	sol.	sol.	sol.	sol.	sol.	sty.	sol. & sty.		

Legend

Fabric		Pore Types		Structure		Cement Types	
M	Mudstone	**Ip**	Interparticles	**sty.**	Stylolite	**Gr**	Granular
W	Wackestone	**M**	Moldic	**sol.**	Solution channel	**Blk**	Blocky
P	Packstone	**V**	Vuggy				
G	Grainstone	**Ch**	Channel				
		K	Cavern				
		Ia	Intraparticles				

c. Rudist Peloidal Grainstone Submicrofacies (**M12**)

This submicrofacies is one of the facies that rarely appeared in the studied samples; observed only at depth (2865) m, in well Fa-2 of the Mishrif Formation (Fig.8e; Table 3). The most important diagenetic processes observed in this submicrofacies are high cementation and neomorphism. Some bioclasts are present represented by debris of benthic foraminifera, Echinoderm and *Textularia*. This microfacies represents deposition in the reef slope environment as compared with the SMF-5 that is deposited in Facies Zone FZ-4 according to Wilson (1975) and Flügel (1982 and 2004).

- **Diagenetic Processes**

The most important diagenetic processes observed in the Mishrif and Yamama formations are cementation, neomorphism, compaction, dolomitization, dissolution, micritization and to a lesser degree authigenic mineral growth (pyrite). The following is a brief summary of these processes:

– **Cementation:** Cementation of the carbonate sediments is an important diagenetic process, which gives strength and stability to the rock. Early diagenetic cement precipitates as fibrous aragonite while granular mosaic cement, drusy cement, blocky cement and syntaxial rim cement precipitate as later diagenetic cements. It was observed in the Mishrif and Yamama formations especially in the Wackestone and Bioclastic Packstone microfacies where prevalence of the granular mosaic cement is noticed (Figs.8b and c; and 9d). Crystals of high transparency and large size characterize this type of cement with straight edges to semi-zigzag. With continuous sedimentation and increased mechanical pressure, as a result of increased sedimentation load, another generation of cement is generated which is the blocky cement, characterized by large size euhedral-subhedral crystals (Flügel, 1982), the late diagenetic cementation also indicates that these two types of cement could occure in deep and shallow environments during late diagenesis processes. Blocky textures can also originate from the recrystallization of pre-existing cements (Flügel, 2004). It should be noted that all types of cement in the Mishrif and Yamama formations are calcareous; silica cement is absent due to sea water composition filling the cavities which is saturated with calcite and aragonite.

– **Neomorphism:** The term Neomorphism was first introduced by Folk (1965) to involve all transformations between one mineral and itself or a polymorph. Meteoric phreatic conditions are thought to be a lineage of neomorphism in marine sediments (Longman, 1980). Most of the neomorphism is of aggrading type; i.e. leading to increase in crystal size and this occurs chiefly in fine-grained limestone. On the other hand, degrading neomorphism; i.e. leading to decrease in crystal size is also present in the studied rocks. It has affected the shells of most types of fossils in the carbonate rocks of the Mishrif Formation (Fig.8b) and extended to the micritic groundmass, either as inversion of the aragonite into calcite or changing the calcite to another calcite that is called recrystallization. Both types are completed during dissolution and re-precipitation processes (Longman, 1982). In shallow marine environments, the neomorphism process intensifies greatly by the solution under higher temperature and pressure conditions (Flügel, 1982).

– **Compaction:** The compaction is regarded as of the latest diagenetic processes of physical origin. In the initial stages, the process of compaction involves the expulsion of liquids that occupy the pores between the grains and therefore reduce the primary porosity of the sediments and the volume of the rocks. There is another type of compaction called compaction of solutions, dissolution of lime materials may occur during or along with grain edges or crystals forming dissolution surfaces (stylolites) which represent the late stage of the diagenetic processes (Friedman, 1975). Stylolization process occurs after at the end of compaction process and the lithification of rocks and as a result of impressed forces on contact surfaces between grains leading to dissolving the calcite mineral which will be redeposited as cement materials filling the pore space. Stylolites have been observed in well Fa-2 at depths (4119.70 and 4333.44) m, (Fig.9a and b) and in well Snd-3 at depth (4171.30 m), (Fig.7e).

– **Dolomitization:** It is a process by which the dolomite is formed when magnesium ions replace calcium ions in calcite. This process is described by the equivalent equation:

$$8CaCO_{3\,(calcite)} + Mg^{2+} \leftrightarrow CaMg\,(CO_3)_{2(dolomite)} + Ca^{2+}$$

Early dolomitization occurs by the replacement of precipitated micrite from sea water rich in magnesium ions and contact sediments before their lithification, where the calcium ion is replaced by magnesium ion present in the sea water, or through the mixing of interstitial water between the particles with fresh water after the exposure of sediments to the air, resulting in increased magnesium ion and decreasing of calcium ion, leading to dolomite formation.

This corresponds to the dolomite formed at the Wackestone Microfacies (Dolomitic Wackestone Submicrofacies) in well Fa-2 of the Mishrif Formation at depth (2860.9) m, (Fig.7f) and in the Yamama Formation at depth (4119.70) m, (Fig.9d), which reflects the shallow conditions where mixing of the cosmic fresh water and the marine water can occur in the pores of the rocks causing the process of complete dolomitization.

– **Authigenic mineralization of pyrite:** Authigenic pyrites in limestones are usually developed in the form of cubic euhedral crystals. Pyrite attracts the attention of sedimentologists; being a valuable indicator of chemical processes (Wilkin *et al.*, 1996 in Flügel, 2004) and diagenetic stages (Hudson, 1992 in Flügel, 2004). Fossils preserved in pyrite show morphological details revealed and preserved by pyritization. Most of the pyrite in sedimentary rocks is of diagenetic origins, although detrital and synsedimentary pyrite occurs, too. Authigenic pyrite commonly forms under reducing conditions replacing organic material or in close proximity to organic material. Pyrite is formed in normal marine, euxinic and freshwater environments (Flügel, 2004). Pyrite is frequent in the Yamama carbonate rocks in well Snd-3 at depths (4146.76, 4166.25 and 4171.30) m, (See Figs.7e, 8d and 9d).

– **Dissolution:** It is a process of dissolving the skeletal and non-skeletal components that exist in the tissue of carbonate rocks due to their mixing with fresh water or may be with sea water (Flügel, 1982). The moldic and vuggy pores form as a result of dissolution which occurs in low stability minerals such as aragonite and high magnesium calcite. As the size of the crystal is small, the dissolution increases (Flügel, 1982). The dissolution occurs within vadose environment and the upper part of fresh phreatic environment (Longman, 1980). That is to say, it occurs in shallow environments due to the increase of carbon dioxide which results in the formation of weak acid solutions that dissolve the carbonate components during the passage of this water through the vadose zone. Some researchers (Giles and Marshall, 1986) have reported that this process can occur in deep burial environments due to the concentration of CO_2 which is produced as a result of decay and decomposition of organic materials in clay-rich facies, in addition to the increase of hydrostatic pressure. Thus, the dissolution process can occur in shallow environments during early diagenesis processes and in deep burial environments. Dissolution was observed in the Mishrif and Yamama formations (Figs.7e; and 9a and d), especially in the Biolistic Wackestone and Lime Mudstone microfacies through dissolving of the fossils skeleton forming moldic porosity.

– **Micritization:** Organisms participate in a variety of ways in generation carbonate deposits. After carbonate sediment are deposited, however, organisms may breakdown skeletal grains and other carbonate materials. This organic degradation is actually a kind of sediment-forming process because it results in the production of finer-grained sediment. Nonetheless, it is included here as a type of very early diagenesis because it brings about modification of previously formed sediment. The most important kind of biogenetic modification of sediment is caused by the boring activities of organisms. Boring by algae, fungi and bacteria is a particularly important process for modifying skeletal material and carbonate grains (Boggs, 2009).

If boring activities are prolonged and intense, the entire surface of a grain may become infested by this aragonite or Mg-calcite filled boring, resulting in the formation of a thin coat of micrite around the grain. This coating is called a micritic envelope (Bathurst, 1966 in Boggs, 2009). Even more intensive boring may result in complete micritization of the grain, with the result that all internal textures are destroyed and a kind of peloid is created. This process has affected widely the Mishrif Formation in well Fa-2 and affected the Yamama Formation in well Snd-3 (Figs.7e and 9a) which led to destroy the skeletal grains of most fossils.

- **Depositional environments**

The microfacies analysis is used in the current study to identify the depositional environments of the Mishrif and Yamama formations in the localities covered by sampling. Based on our study the depositional environment of the Mishrif Formation corresponds to Rimmed Carbonate Platform and depositional environment of the Yamama Formation corresponds to Ramp Carbonate model (Fig.10). This is achieved by following the concepts of standard microfacies of Wilson model (1975) and facies zones for Flügel (2004). These models illustrate the inferred paleoenvironmental conditions of the Mishrif and Yamama formations at Faiha and Sindibad oilfields, south Iraq.

CONCLUSIONS

- Several main microfacies have been identified in the studied formations; which are: lime mudstone, wackestone, packstone and grainstone. They were deposited in open marine, foreslope, rudist and lagoonal environments.
- The allochems in the Mishrif and Yamama formations are dominated by bioclasts, peloids, ooids, and intraclasts. Benthonic foraminifera, mollusk shells, echinoids, and algae, represent the main fossils in the Mishrif and Yamama formations. Dolomite and calcite are the main minerals components of the formations.
- Based upon the fossils observed and the type and number of the recognized microfacies, the depositional basin models are constructed and show that the Yamama Formation was deposited in the ramp carbonate environment, while the Mishrif Formation was deposited in the rimmed carbonate shelf environment.
- Seven diagenetic processes are identified in the Mishrif and Yamama formations which have had variable effects on the reservoir quality. Dissolution and neomorphism (recrystallization) have created, developed and improved the porosity which led to improving the reservoir quality. The dominant pore types are vuggy, interparticles, intraparticles, channel and moldic. On the other hand, cementation, micritization, and

compaction processes have had destructive effects, by reducing porosity and permeability and consequently reducing the reservoir quality. Other processes such as dolomitization and authigenic minerals (pyrite) have no strong effects on the reservoir quality.

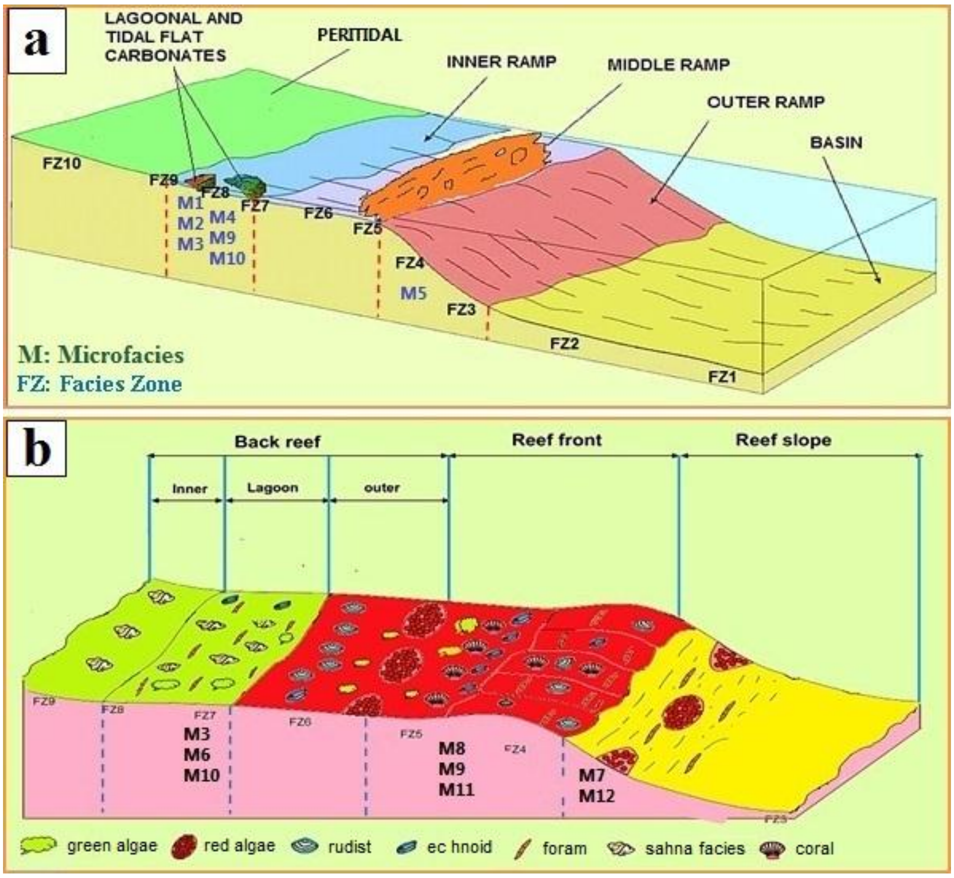


Fig.10: Schematic block diagrams showing depositional environments and distribution of microfacies of the formations in the studied wells: **a)** Yamama Formation, **(b)** Mishrif Formation

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