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Microfacies Analysis and Depositional Environments of Lower Sa'adi Formation, Southern Iraq

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Abstract

The Sa'adi Formation is a part of the late Cretaceous period in the Santonian-Campanian stage that represents a potential hydrocarbon-bearing reservoir across many oilfields in the Mesopotamian Basin, South of Iraq. The Formation was divided into two main parts as a stratigraphy sequence. It consists of chalky limestone with argillaceous limestone in the upper part and limestone with marly limestone in the lower part. The lower part is considered an important stratigraphic unit marked by petroleum shows. Thus, current research constructs the depositional environment, evaluates the reservoir, and predicts the best zones with good reservoir quality. The microfacies analysis was carried out on thirty-five thin sections to reveal the primary depositional environment, and well logs data were used to evaluate the petrophysical properties of the lower Sa'adi Formation. Four microfacies appeared related to the carbonate ramp, which identified the depositional system track from mid to inner ramp. These are; mudstone, wackestone, packstone, and grainstone. Twelve sub-microfacies were identified and interpreted in the lower Sa'adi Formation. These are pelagic lime mudstone to benthic foraminiferal-argillaceous wackestone in middle ramp experienced burial diagenesis and syngenetic diagenesis with intra-fossil pores. The results characterize the bioclast echinoderms, bivalves, and algae packstone to grainstone in inner ramp (open marine and shoal environments) experienced marine pore-water diagenesis, meteoric freshwater dissolution, and burial diagenesis. Shoal facies with open marine facies are the best favorable microfacies in the lower Sa'adi Formation. Diagenesis processes were represented by dissolution that improved the porosity and permeability with higher reservoir quality in the inner ramp; besides that, it was recognized that cementation and micritization reduced the reservoir quality in the middle ramp.

Keywords: Sa'adi Formation; Microfacies; Planktonic; Depositional environment; Porosity

1. Introduction

The Sa'adi Formation is an important hydrocarbon-bearing stratigraphic formation. It has oil accumulations in the south of oilfields in Iraq (Al-khayanee, 2015), but the production rate is not commercial in the study area due to the low permeability. The studied oilfield is located in the southern part of Iraq (Fig. 1). The area was covered by alluvial deposits and recent clay material (Dawd and Hussien, 1992). Sa'adi Formation is the highest, youngest, thickest, and most widespread compared with the other formations (Khasib and Tanuma) in Late Cretaceous in Iraq. The formation was first described

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by Rabanit (l952). Owen and Nasr (1958) introduced the description as a type section of the formation based on the Zubair-3 well data in the Mesopotamian zone. The definition and age determination of the formation underwent several changes later, mainly due to the revisions made by Chatton and Hart (1961) and the Iraqi-Soviet Team (1972). Alshawosh (2002) and Aqrawi et al. (2010) have suggested the middle shelf as a primary depositional environment for the whole sequence, with the apparent influence of the outer shelf or open marine. The abundance of petrophysics, microfacies evaluation, paleoenvironments and sequence stratigraphy of the Turonian-Lower Campanian (Khasib, Tanuma and Sa'adi) formations have been discussed by researchers (Al-Edani, 2017 and Alkhaykanee, 2015). Current research aims to identify the depositional environment by microfacies analysis, and the effects of diagenetic processes on reservoir properties of Sa'adi Formation from the drilling wells data distribution in the studied Oilfield (Fig. 2). The core samples in the upper part of the Sa'adi Formation are missing, therefore, this study focuses on the lower part of the formation.

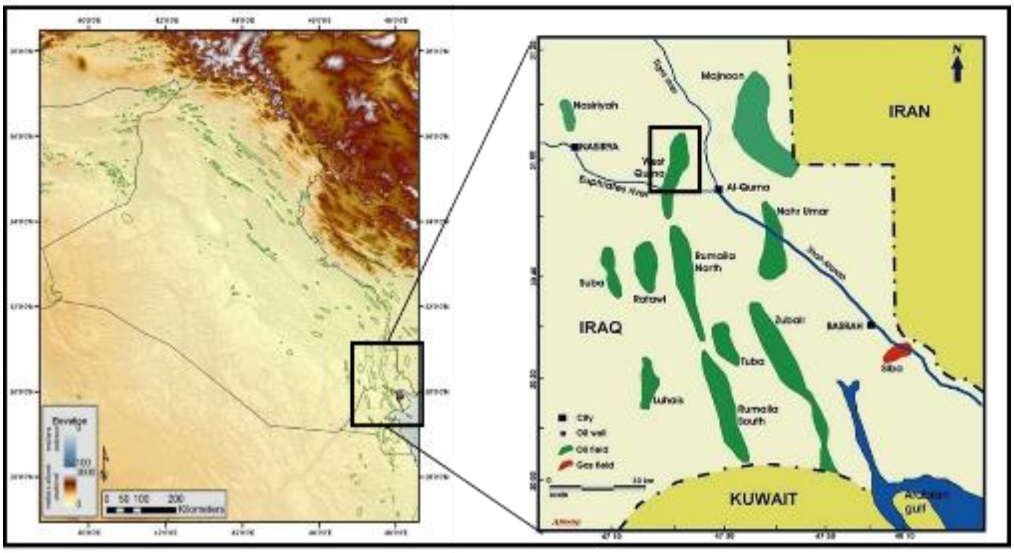

Fig.1. Location map of the study area showing the location southern fields of Iraq (Chafeet, 2016)

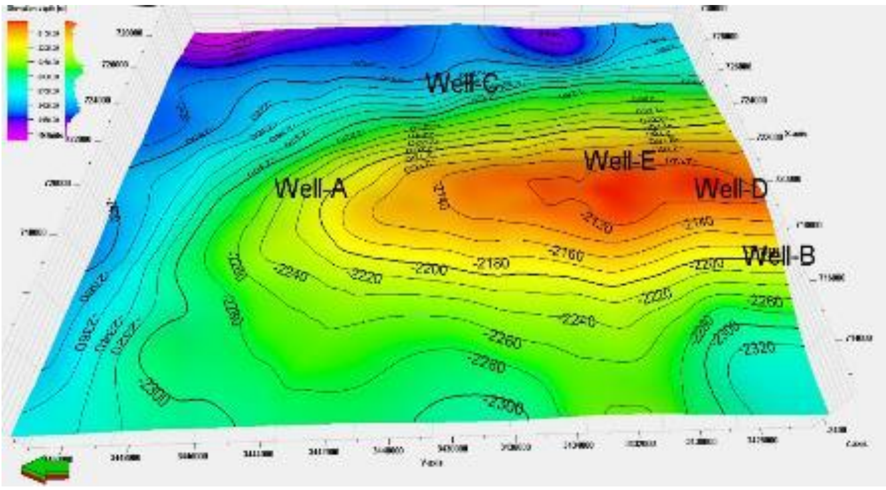

Fig.2. A Structural map of the top Sa'adi Formation, it shows distribution of wells understudy in West Qurna Oilfield

2. Geological Setting and Stratigraphy

The Sa'adi Formation is a part of the Santonian-Campanian cycle that belongs to the mega sequence AP9 (Sharland et al., 2001). In the study area, the formation was subdivided into two parts; the upper part is chalky limestone rocks, sometimes overlapping with marly limestone, and the lower part is limestone overlapping with marly limestone (Buday,1980. The lower part can be further divided into three units (A, B and C) according to wells logs and petrophysical properties (Fig. 3). The contact of the Sa'adi Formation with the underlying Tanuma Formation is conformable at the top of black calcareous shale and the base of white chalky limestone. The contact with the overlying Hartha Formation is an erosional unconformity corresponding (Buday, 1980), as shown in Fig. 4.

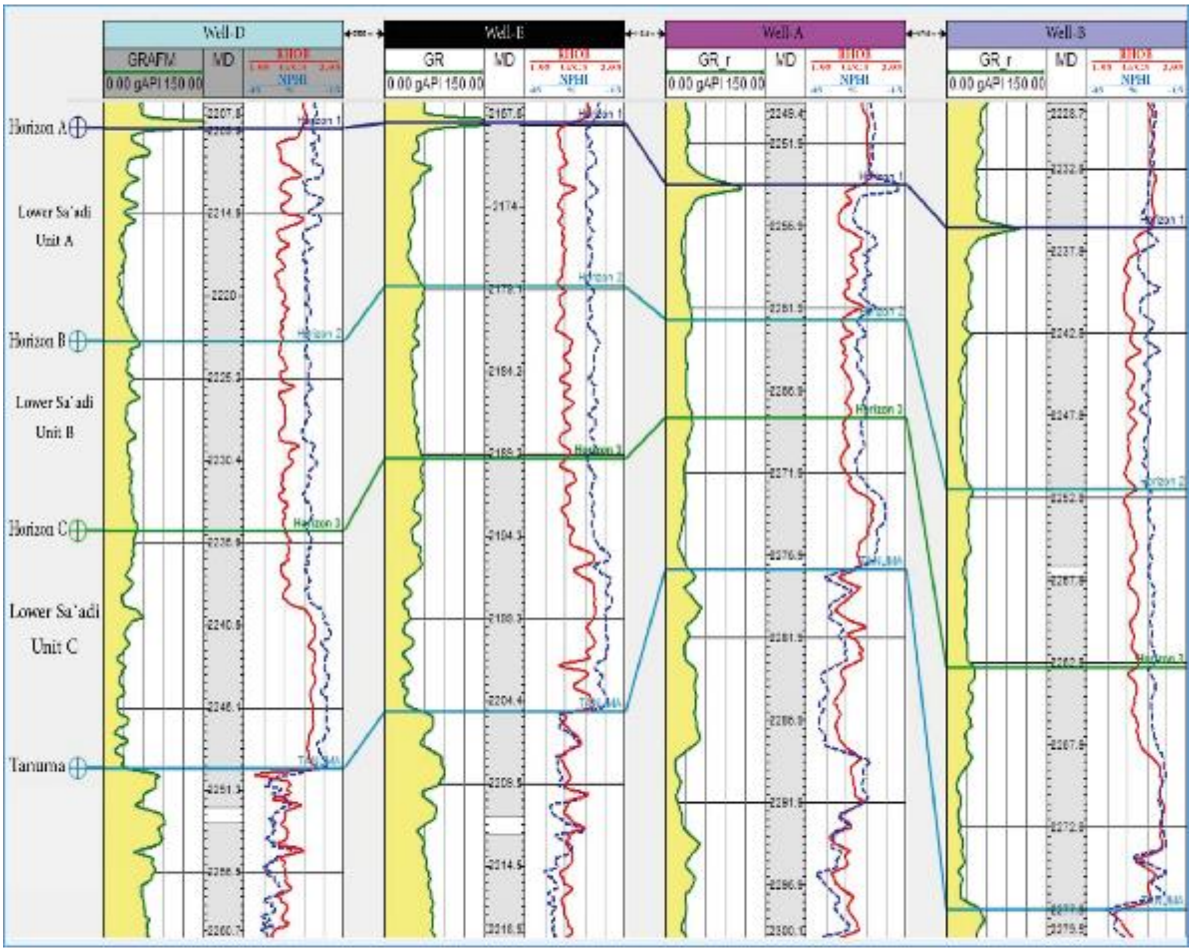

Fig.3. Three units of lateral variation (A, B, and C) for the lower Sa'adi Formation in the studied oilfield.

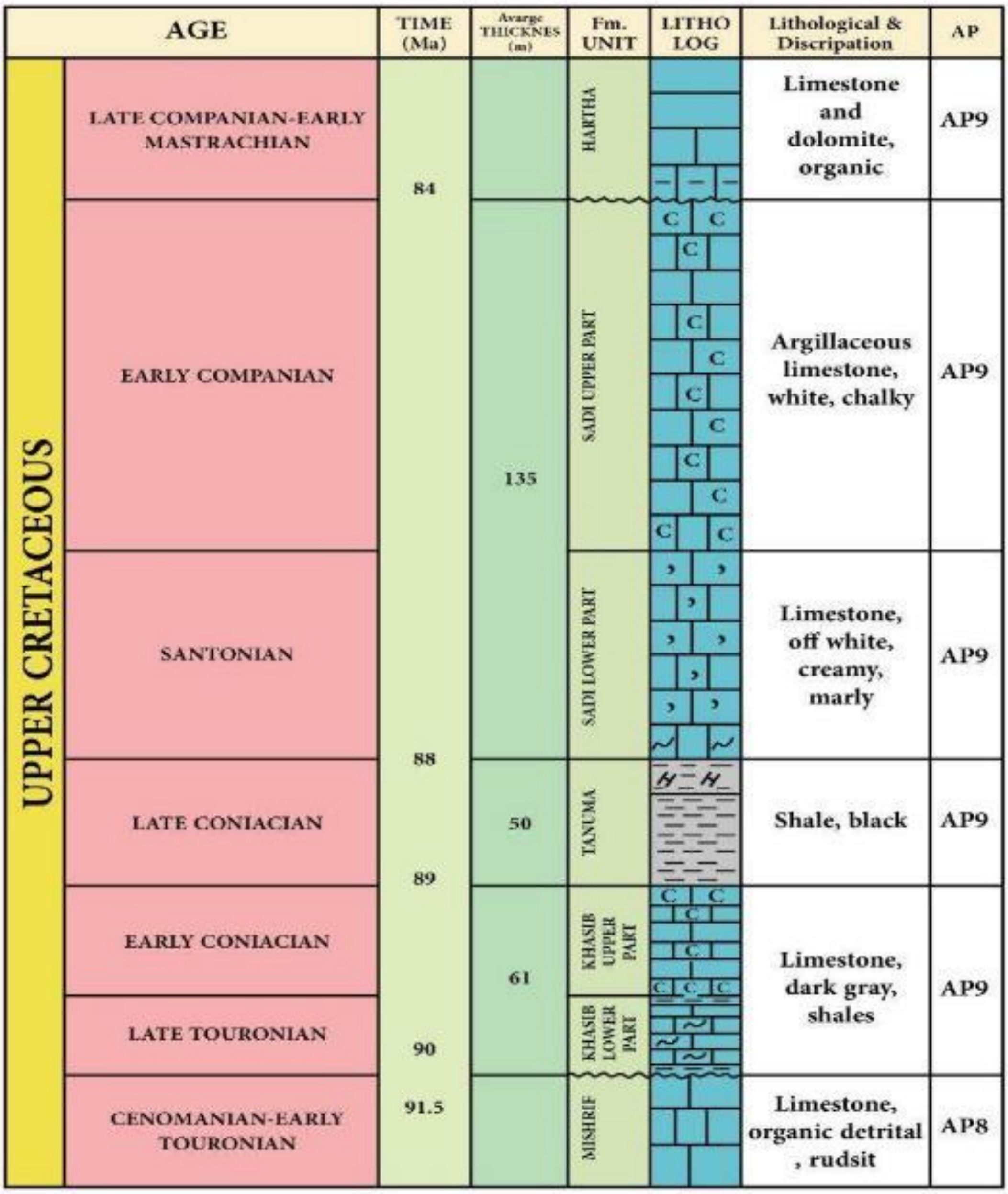

Fig.4. Lithostratigraphic column of the upper Cretaceous age in the West Qurna oilfield, modified from (Almohsen, 2019)

3. Materials and Methods

The current study used fieldwork to collect thirty-five core samples, which were then characterized to identify the lithology of the lower Sa'adi Formation. Thirty-five thin sections have been prepared in the laboratory of the Geology Department, University of Baghdad, and the analysis and description of thin sections have been applied in the laboratory of the Department of Geology, University of Basrah in which the microfacies analysis, depositional model, and diagenetic processes were investigated. The different facies will be classified based on Dunham's classification (1962) of carbonate rocks, and the depositional environment determination, standard depositional environment models and facies distribution were compared with the micofasices of Wilson (1975) and Flugel (2010). Machine work by

Petrel software (Version-2018) was applied to export the structural map of the top Formation and the correlation between the wells through the area of interest. The Excel sheet application was used to create the porosity and permeability values relation obtained from core analysis data and compare the results with the depths led to determine the best facies environment in the Lower Sa'adi Formation.

4. Results and Discussion

4.1. Facies Characteristics

Lower Sa'adi Formation in the studied wells consists of the following three facies belts facing the sea from the coast: Shoal, Open marine, and Middle ramp.

4.1.1. Inner ramp (Shoal facies group)

This facies comprises skeletal packstone to grainstone, bioclast packstone to grainstone, and rudist debris grainstone. The major allochems in these microfacies are skeletal grain and a few matrices, and the matrix is sparite. They contain more than 90% grain fossiliferous, millimeters to centimeters bioclast grains abundant rudist fragments and algae. The sub-microfacies reflected a high-energy environment in upper unit A (Fig. 4). This sub-microfacies corresponds to RMF-26 microfacies of Wilson (Wilson, 1975). It is found in the well-D at a depth of 2211.8m and well-E at a depth of 2170m. (Plate 1e, 1f).

4.1.2. Inner ramp (Open marine facies group)

- Algal wackestone sub microfacies

The bioclast wackestone consists mainly of skeletal fragments, and the dominant allochems are algae with rudist debris, micrite and Sparite filled algal shell fragments. This microfacies is distinguished by using a rate of grains of about 45%. This facies represents a low-moderate energy environment. It is located well-E at a depth of 2172m. This sub-microfacies corresponds to RMF-15 microfacies of Wilson (Wilson, 1975), that deposited in open marine zone FZ5 (Plate 1a).

- Bivalves packstone sub microfacies

The main component of microfacies is bivalves, with benthonic foraminiferal fragments and debris, such as Rotalia, algae, and a little echinoid. These facies are typically graining in texture with fewer than 20% micrite. Bioclastic packstone is representative of a shallow open marine environment. The sub microfacies is located within FZ-5. This sub-microfacies corresponds to RMF-14 microfacies of Wilson (Wilson, 1975), Well-E depth 2174m (Plate 1b).

- Fossiliferous packstone sub microfacies

This microfacies is characterised by abundant benthonic foraminifera and few planktonic with other shell fragments. The fossiliferous are highly cemented by fine to coarse crystalline calcite cement. These microfacies reflected a high-energy environment. This sub-microfacies corresponds to RMF-13 microfacies of Wilson (Wilson, 1975), facies are typical in well-E at a depth of 2172.8m (Plate 1c).

- Fragmental mollusca packstone sub-microfacies

The microfacies is hosted by various fragmental mollusca, algae, and pelecypods. This sub-microfacies corresponds to RMF-27 microfacies of Wilson (Wilson, 1975) and located in an open marine zone, as very clearly in well-D at a depth of 2214.8m (Plate 1d).

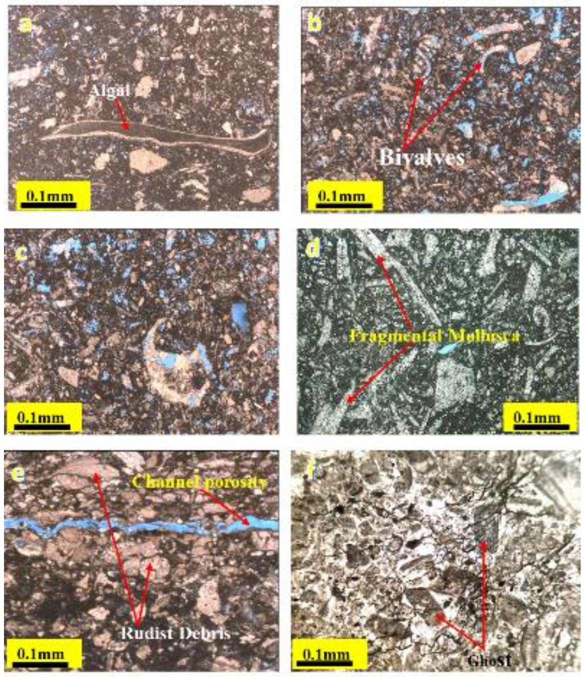

Plate.1. Photomicrographs of microfacies in the carbonates of the lower Sa'adi Formation. (a) Algal-bioclast Wackstone in well-E at a depth of 2172m. (b) Bivalves-Bioclast Packstone with dissolution (moldic and intraparticle porosity) in well-E at a depth of 2174m. (c) Fossiliferous Packstone with dissolution (vuggy porosity) and cementation (druzy cement), in well-E at a depth of 2172.8m. (d) Fragmental Mollusca Packstone sub-microfacies, in well-D at a depth of 2214.8m. (e) Echinoderms Packstone-Grainstone with rudist and bioclast, also appearance channel porosity and cementation in well-E at a 2171.8m. (f) Bioclast Grainstone submicrofacies in well-D at a depth of 2211.8m.

- Middle ramp facies group
- Pelagic lime mudstone submicrofacies

Based on Dunham's classification, these facies were distinguished. They consist of 5% fossils and fragments and contain foraminifera in micrite. These sub-microfacies are observed in the lower Sa'adi well-E at a depth of 2195m (Plates 2a). It is reflected low energy, which is characteristic of mid ramp environment facies zone (FZ-3); these microfacies have similarity to RMF-5 and its location in unit C was found by comparing the microfacies with the standard Wilson model microfacies (Wilson, 1975). (Fig.4).

- Fossiliferous wackestone submicrofacies

The microfacies are distinguished by the high proportion of fossilized material (20%) that consists primarily of Echinoderm, and benthonic foraminifera, with a rare presence of planktonic foraminifera and algae. These sub microfacies are observed in well-A, well-B and well-E at 2186.1m (Plate 2b). These facies showed similarity to RMF-3 of Wilson (1975). and it is located within unit B (Fig.4).

- Benthonic foraminifera wackestone sub microfacies

This facies consists of about 20-40% of components' total of texture and percentage of benthonic foraminifera. In the thin section, increased bioclastic relative to echinoderm and bryozoan. These facies showed similarity to RMF-13 of Wilson (1975). These sub-microfacies are observed in lower unit B of the lower Sa'adi Formation (Fig.4), clearly in well-E at 2184.4m. (Plate 2c).

- Echinoderms wackestone with diverse fossils Sub microfacies

This microfacies matrix is dark brown micrite (microcrystalline calcite); the most significant allochems are echinoderms and benthic foraminifera with pellet grains, fragments of benthic foraminifera as Textularids and *Ammonia*. It is similar to RMF-3 compared to typical Wilson model microfacies (Wilson, 1975), as clearly in well-E, well-B and well-A at 2259.60 m (Plate 2d).

- Bryozoan wackestone sub microfacies

This microfacies criterion micrite has many bryozoandepth of and some echinoderm fragments. This sub-microfacies corresponds to RMF-9 microfacies of Wilson (Wilson, 1975). These facies are located in well-A, well-B, well-D, and well-E of the study area as typical facies in lower Sa'adi Formation Well-E at 2174.3 m (Plate 2e).

- Argillaceous wackestone sub microfacies

These microfacies mainly consist of benthic foraminifera at the base of the formation. They contain skeletal grains of about 40%, although they may reach 70%, becoming packstone. The groundmass is micrite and shell fragments of foraminifera. These sub microfacies were observed in well-E at 2178.2 m (Plate 2f). This sub-microfacies corresponds to RMF-2 microfacies of Wilson (Wilson, 1975).

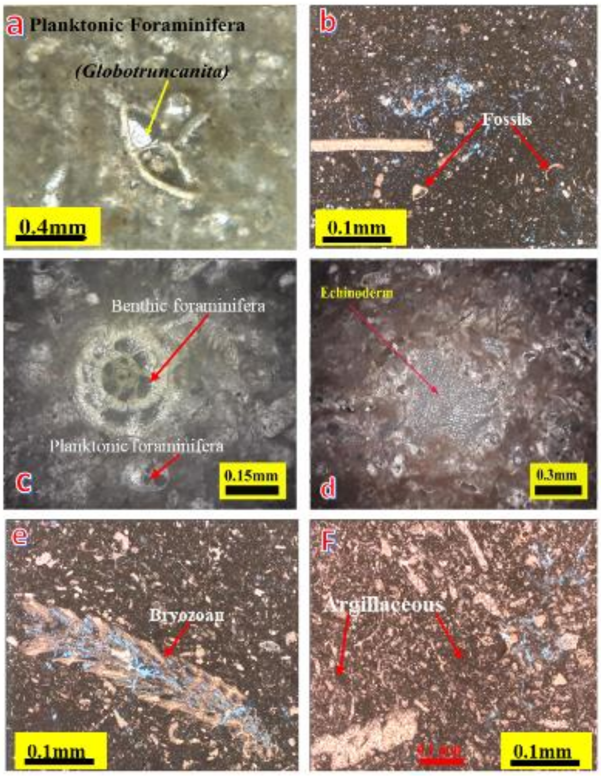

Plate.2. Photomicrographs of microfacies in the carbonates of the lower Sa'adi Formation. (a) Pelagic lime mudstone with planktonic foraminifera *Globotruncanita* (well-E at a depth of 2195m). (b) Fossiliferous wackstone, benthonic foraminifera *Rotalia* and *Ammonia* with rare planktonic appear as vuggy porosity and micritization. In well-E at a depth of 2186.1m. (c) Fossiliferous-Benthonic Foraminifera wackestone in well-E at a depth of 2184.4 m. (d) Echinoderms wackestone with diverse fossils. In well-E at a depth of 2182m. (e) Bryozoan wackestone containing a fragment of benthic foraminifera, the porosity within the intraparticle of the wackestone is visible at a depth of 2179m in the well-E (f) Argillaceous Wackestone with bioclastic, as cementation processes (granular cement) appear clear in well-E at a depth of 2178.2 m.

4.2. Diagenetic Processes

All diagenetic processes have affected the lower Sa'adi Formation, including cementation, micritization, compaction, dissolution, dolomitization, recrystallization, stylolitization, and pyritization (Table 1). Dissolution and cementation are the principal diagenetic processes that affect the sediments, whereas micritization and compaction are second-order diagenetic processes that affect the sediments of the lower Sa'adi Formation.

- Micritization: Micritized grains are prevalent in the bioclastic wackestone/packstones of the lower Sa’adi Formation. Mainly occurs in the middle ramp, it is an early diagenetic process, and skeletal grains were micritized shortly after deposition. (Plate 1b,1c).
- Cementation: this process has led to primary mineral porosity and secondary porosity precipitation in Sa’adi Formation carbonates. There are many types of cement, such as granular cement, blocky cement, and durzi cement. Early cement mainly took place in inner ramp shoals and open marine, and late cement primarily took place in fossils sediments deposited in the middle ramp (Plate 3e).
- Compaction is the dominance of mud-supported fabrics in the Sa’adi Formation; compaction increases when sediment is overburdened and fine grains increase, resulting in a general reduction of rock volume and porosity and mechanical failure of grains (Plate 4f). The stylolite and fracture are the most mechanical and chemical compaction diageneses. The boundary usually accumulates oxides, and organic matter is irregular surfaces formed due to different vertical movements under burial conditions (Friedman, 1975). Compaction also resulted in microfractures in bioclastic packstone in the inner ramp and pressure seams in lime mudstone/wackestone in the middle ramp. Stylolitization indicates a late-diagenetic origin (Plate 3a, 3f).
- Dissolution is an essential diagenetic process, especially in packstones/grainstone developed in the inner ramp. It is generally characterized by fabric selection represented by vuggy pores and molding of skeletal grains (Moore, 2013) (Plate 3b, 3e).
- Dolomitization: Most Fe-dolomitic crystals occur within wackestone in the middle ramp. It indicates the late diagenetic origin (Bathurst, 1975) (Plate 3b).
- Recrystallization; The micrite matrix material is often recrystallized, resulting in the inversion of micrite to microsparites and microspar. It is an early-stage diagenetic in the inner ramp in grain-supported microfacies (Plate 3d). By recrystallization and processes acting during burial diagenesis and thermal history, the original depositional microfacies and diagenetic textures of limestone are often altered or destroyed.
- Pyritization diagenetic marked in decreased environments abundant of aerobic bacteria. It is an indicator of low oxygen percentage (Flugel, 2010). Pyrite is autogenic when H_2S increases with an abundance of iron. Pyritization is rare in the lower Sa’adi Formation; it was found in the middle ramp (Plate 3c).

4.3.2. Porosity and permeability

Porosity and permeability in every unit were studied. Reservoir properties (porosity of permeability) for each unit are summarized in Table 2. Sa’adi A is a shallower environment than Sa’adi B and Sa’adi C. The porosity and permeability in Sa’adi A are higher than in Sa’adi B and Sa’adi C, which indicates that as the seawater deepens, the quality of the reservoir in the middle ramp becomes poorer in the studied oilfield. The porosity of Sa’adi C is lower than Sa’adi B. It is also certificated by the cross plot of porosity and permeability (Fig. 5). The Sa’adi A is dominated by bioclast packstone/grainstone, indicating that shoal facies with open marine facies are the best favourable environments for reservoir quality in the lower Sa’adi Formation.

Table 1. Diagenetic paragenesis of the lower Sa'adi Formation, from the petrographic study in the studied wells

Diagenetic environments	Diagenetic processes	Diagenetic fabrics	Diagenetic stages		
			Early	Middle	Late
Marine phreatic	Micritization	Micritic envelope	–		
	Cementation	Blocky cement	–	–	
Mixing zone	Dolomitisation	Dolomite		–	
Meteoric phreatic zone	Leaching	Leaching skeletal grains		–	
	Neomorphism	Recrystallization		–	–
	Cementation	Drusy cement		–	–
	Dissolution	Pores and Vugs			–
Vadose zone	Compaction	Fracture	–	–	–
Burial	Pressure Solution	Stylolites			–
	Burial Cementation	Blocky and granular			–
	Dolomitization				–
	Authigenic	Pyrite	–		–

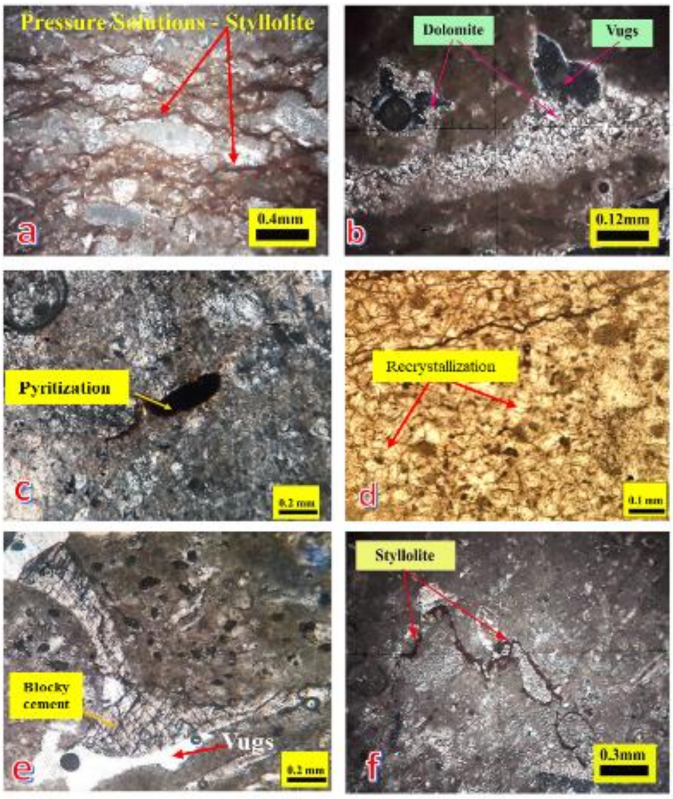

Plate.3. Digenesis's processes (a) Chemical compaction (Pressure solution-parallel stylolite) in well-B at depth of 2236.5m. (b) dolomitization diagenesis around dissolution vuggy porosity, in well-C at a depth of 2366.3m. (c) Pyritization diagenesis, in well-A at a depth of 2258.62m. (d) Recrystallization with the presence of mechanical compaction (Low-Amplitude Stylolite), well-D at a depth of 2212m. (e) Drusy mosaic cement and Blocky cement with dissolution, well-B at a depth of 2237.5m (f) Chemical compaction (Peak-High Amplitude Stylolite) in well-B at a depth of 2236.5m.

4.3. Reservoir Characteristics

Reservoir evaluation has been conducted by using core analysis and thin sections. Pore types have been studied. It revealed that the reservoir in the Sa'adi Formation is of medium porosity and moderate to low permeability. Permeability and porosity in inner ramp sediments are higher than in middle ramp sediments.

4.3.1. Pore ypes

Six types of pores are distinguished from the lower Sa'adi Formation by using thirty-five thin sections:

- Intergranular porosity was distinguished in intraclasts skeletal packstones, grainstone located at inner ramp facies. This porosity is rarely observed in thin sections (Plate 4b).
- Intragranular dissolved pores are common in skeletal and intraclasts; in foraminifera, bryozoan and Brachiopoda, it was formed in the freshwater environment (Plate 4d).
- Moldic porosity was primarily found in skeletal packstones within the inner-ramp facies and in wackestones within the middle-ramp facies, almost in the form of shall fragments, pelecypods, and benthonic foraminifers (Plate 4a).
- Abundance of channel pores in lime mudstone in middle ramp facies and packstone in inner ramp (shoal) facies (Plate 4c).
- Fractures pores, particularly in foraminifera wackstones in the middle ramp and rudist packstones in the inner ramp (open marine) (Plate 4f).
- Vuggy and cavern pores are mainly at the middle and inner ramps (Plate 4e).

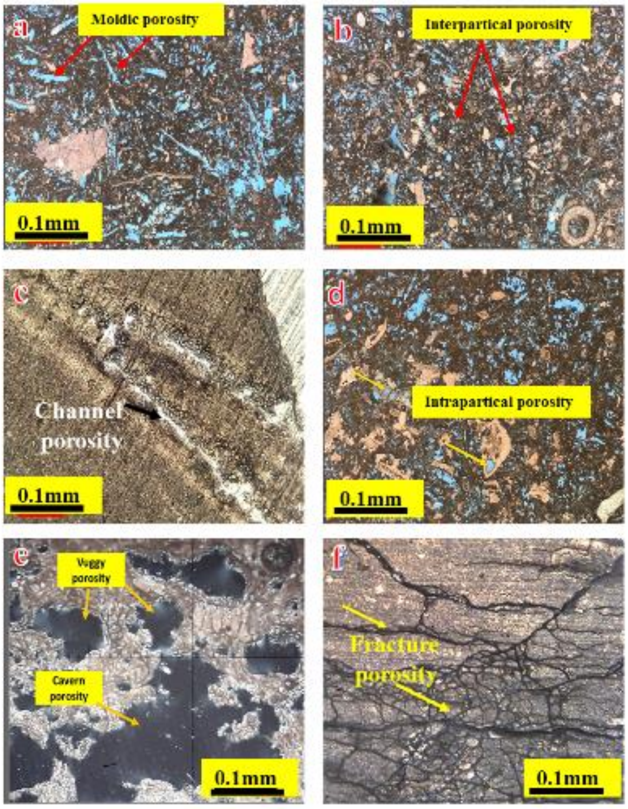

Plate 4. Porosity type in lower Sa'adi Formation, (a) Moldic and intraparticle porosity in well-E at a depth of 2169.7m. (b) Interparticle porosity and vuggy porosity in well E at a depth of 2171m. (c) Channel porosity in well-E at a depth of 2194m. (d) Intraparticle porosity and vuggy porosity in well-E at a depth of 2170m. (e) Cavern and vuggy porosity in well-C at a depth of 2365.8m. (f) Fracture in well-A at a depth of 2259.60m.

Table 2. Porosity and permeability measurements.

Lower Sa'adi	Porosity %			Permeability MD		
Units	Min	Max	Average	Min	Max	Average
Unit A	6.996	25.433	17.135	0.02	100.800	22.215
Unit B	4.836	25.961	15.618	0.116	52.950	20.366
Unit C	3.768	18.439	8.117	0.09	95.380	6.765

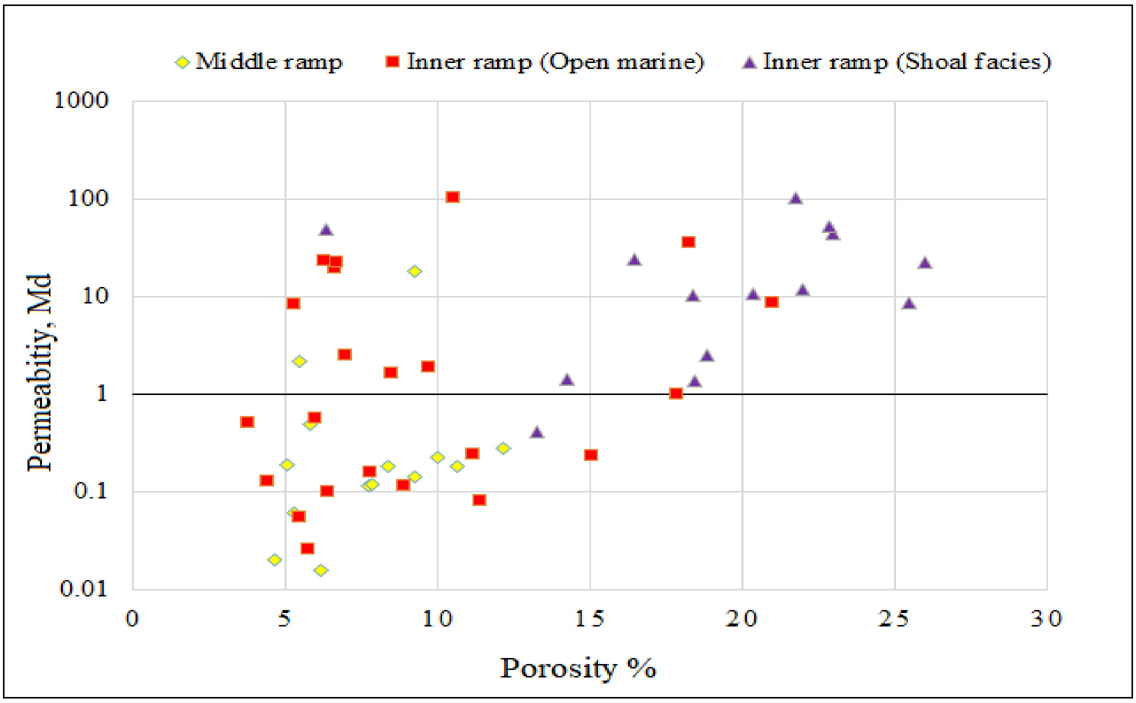

Fig.5. The cross plot of porosity and permeability in the lower Sa'adi Formation shows that the porosity and permeability are good in the inner ramp facies of the lower Sa'adi Formation.

4.4. Depositional Environments

The primary depositional setting of the lower unit was the shallow marine carbonate environment. Types of organisms determined the evidence of marine carbonate environment and the energy from wave currents, the source of the carbonate material is predominantly biogenic. Comparing them with recent and ancient sedimentary environments indicates that the Sa'adi Formation in the study area is deposited on a carbonate ramp platform. Most of the lower Sa'adi Formation microfacies were deposited in the mid ramp zone and the inner ramp zone (open marine and shoal). Mid-ramp's common environmental deposits (FZ-4 and FZ-3) contain skeleton lime mudstone-wackestone, fossiliferous wackestone, and argillaceous wackestone-packstone. The skeletal are more common in the proximal part of the mid-ramp association, wherever in the distal portion of the mid-ramp, the skeletal fragments are more minor. These fragments are debris of green algae, bryozoan, echinoderms, bivalves, and benthic foraminifera with few planktonic. The dominant texture in these associations is wackestone and wack-packstone textures, which means the energy level ranges from low to moderate. Bioclast wackestone-packstone reflected shallow open marine (FZ-5) in the inner ramp, and rudist debris packstone-grainstone reflected shoal deposition (FZ6) in the high-energy environment. Also, this environment contains bioclasts of debris and rudist represented by large algae, echinoids, shell Mollusca and benthic foraminifera (Schlager, 2005). According to the Facies Zone (FZ), the study area is FZ-3, FZ-4, FZ5 and FZ6 (Fig. 6).

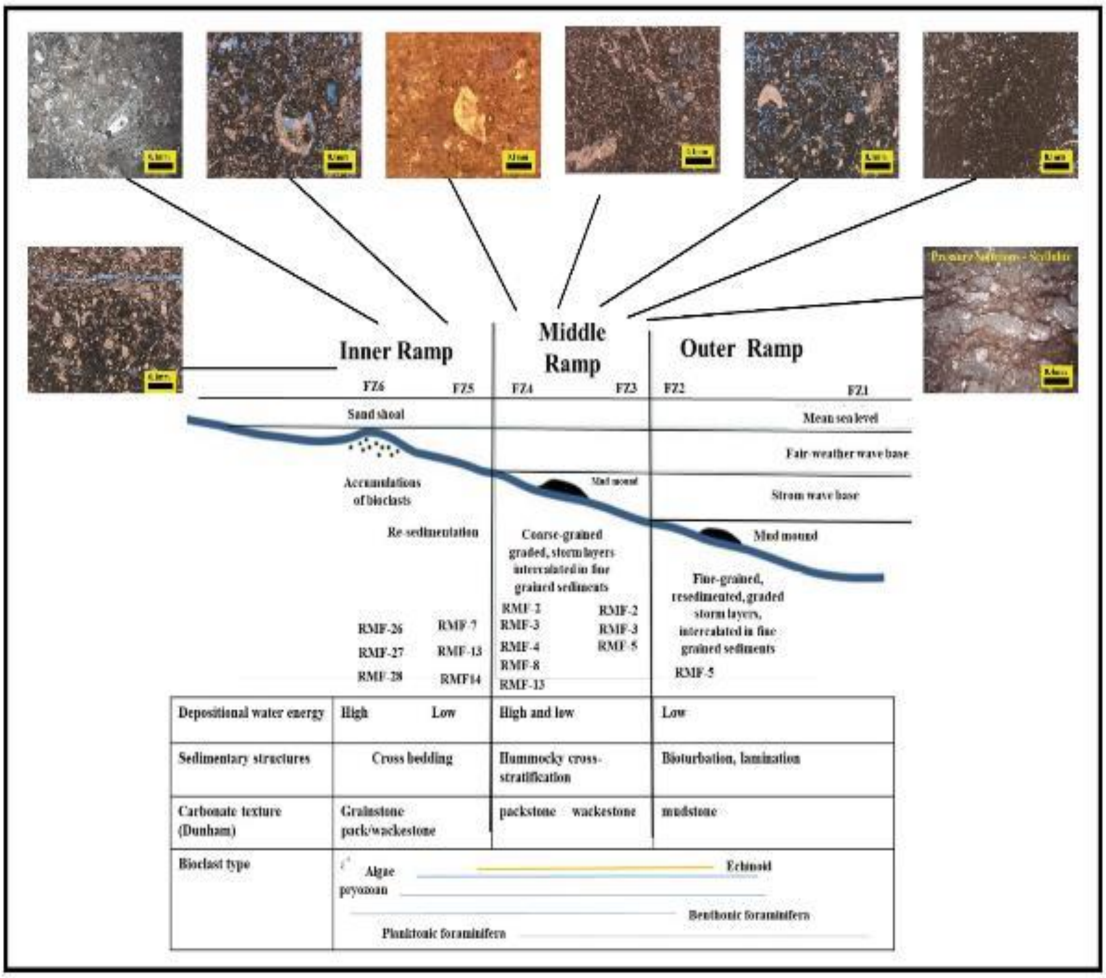

Fig.6. Schematic ramp deposition of the studied facies modified from Flugel (2010)

5. Conclusions

- The diagenetic processes in the lower part of the Sa'adi Formation have both positive and negative effects on reservoir quality; cementation and micrization have a detrimental impact on reservoir quality by reducing the porosity and permeability that decreased the reservoir quality, dissolution and recrystallization create and increase the petrophysics properties, resulting in improved reservoir quality. Other processes also exist but to a lesser extent, such as pyritization and dolomitization, which have no significant impact on reservoir quality.
- Most of the porosity within the lower part of the Sa'adi Formation was formed by diagenesis processes. The inner ramp facies of the lower Sa'adi Formations have the best reservoir quality in terms of porosity and permeability distribution.
- The Sa'adi Formation is divided into three units (A, B and C). The lower Sa'adi Formation has 12 carbonate sub-microfacies deposited in three facies associations: six sub-microfacies were identified and interpreted to be deposited in the middle ramp in unit C, and lower unit B. Four sub-microfacies were deposited in the inner ramp open marine in upper unit B and lower unit A. Two sub-microfacies were deposited in the inner ramp shoal in upper unit A. Thus, these facies reflected the system of shallowing upwards, which these facies of this paleoenvironment are evidence of the regression in the lower Sa'adi Formation. The deposition environment was articulated as part of the homoclinic ramp.

- The fossils of benthonic Foraminifera with rare planktonic, Echinoids, Bryozoan, and Algal were represented in the Formation's lower part. That skeletal granules are the most dominant facies in the inner ramp environment than in the middle ramp environment. With the more significant influence of the digenetic processes represented by dissolution (secondary porosity), unit A were incubators of organic matter represented by hydrocarbon. Still, it is considered a tight reservoir due to the moderate-low permeability resulting from disconnected pores.

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