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IMPACTS OF THE DIAGENETIC HISTORY ON THE PETROPHYSICAL FEATURES OF THE JURASSIC MARINE FACIES IN GEBEL EL MAGHARA MASSIF, NORTH SINAI, EGYPT

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تأثير التغيرات اللاحقة على الخصائص البتروفيزيقية للسحن البحرية الچوراسية بمنطقة جبل المغارة بشمال سيناء، مصر

الخلاصـة: خضعت عينات السحنات البحرية الچوراسية بمنطقة جبل المغارة لتحليل بتروفيزيقي كامل (نمطى وخاص)، وتم استخلاص تأثيرها بتاريخ التغيرات اللاحقة من خلال تحليل السحن الدقيقة. ويمثل تتابع السحنات البحرية الچوراسية بمنطقة جبل المغارة بثلاثة تكاوين تبدأ بتكوين رجبية (٢٩٢ م) ويتكون من عدد من السحن الدقيقة من حجر رملى جيرى به أكاسيد حديد وحجر جيرى دقيق التحبب، و كذلك تكوين بئر المغارة (٤٤٢ م) الذى يتكون من حجر جيرى دقيق التحبب وينتهى القطاع البحرى بتكوين المساچد (٥٧٥ م) الذى يتكون من حجر جيرى فورامنيفرى دقيق التحبب وحجر جيرى بطروخى وحجر جيرى دقيق التحبب فورامنيفرى به بقايا لطحالب قديمة. وقد ترسبت هذه التكاوين الثلاثة فى بيئات شاطئية محصورة.

ويتضح من الدراسات البتروجرافية أن معظم المسام المسجلة هى مسام دقيقة للغاية مع عدد بسيط من الشروخ والقنوات الفراغية التى تم ملؤها لاحقاً بمادة لاحمة جيرية وسيليسية. كما يتضح أنه لم يتم تسجيل مسامية أولية جيدة لهذا القطاع عدا الجزء السفلى منه. ويعتبر التلاحم بالسيليكا من أهم العوامل المضادة للمسامية، وعلى الجانب الآخر لم يتم تسجيل تأثير واضح للتضاغط الناتج عن الحركات الأرضية التى سادت بالمنطقة إلا فى الجزء السفلى من القطاع وتم تلاشى هذا التأثير بعمليات الإذابة اللاحقة.

ومن الناحية البتروفيزيقية نجد أن الكثافة الكلية للعينات تعتمد إلى حد كبير على المسامية، بينما تعتمد نفاذيتها على المسامية وقطر القنوات الفراغية وكمية الماء المحصور، وكذلك يعتمد معامل التكوين الكهربى على المسامية، وقد وجد أن التأثير الكهربى للطين المسمى بتأثير الطين–الجير لم يسجل سوى فى بعض عينات تابعة لتكوين المساچد. وأخيراً نجد أن الصفات الخزانية للتكاوين البحرية الچوراسيةالثلاثة بمنطقة جبل المغارة متدنية جداً عدا الجزء السفلى من القطاع وينصح بالتعامل مع هذه التكاوين بما تتمتع به من صلادة عالية ومسامية ضعيفة كمصدر لأحجار البناء والرخام.

ABSTRACT: *Routine and special core analyses were conducted for the Jurassic marine sediments in Gebel El Maghara massif whereas the impacts of the diagenetic effects have been identified from a detailed microfacies analysis. The Jurassic marine sediments in Gebel El Maghara are represented by the Rajabiah Formation (292 m) is composed mainly of ferruginous calcareous quartz arenite (clastic microfacies) at its lower parts and mudstone microfacies (SMF 23) at the other parts, Bir El Maghara Formation (442 m) is composed of mudstone microfacies (SMF 23), whereas the Masajid Formation (575 m) is composed of foraminiferal and molluscan mudstone microfacies (SMF 19), oolitic grainstone microfacies (SMF 16) and foraminiferal and algal sparitic mudstone microfacies (SMF 19 & 21). These microfacies were deposited in restricted platform conditions (Fz. 8) with some oscillation into shelf lagoon conditions (Fz. 7) in the middle parts of the Masajid Formation.*

The petrographical description of the pore spaces indicates that most of the studied pore spaces are matrix porosity with few channels and vug porosity filled later by microsparite and silica cement. Primary intergranular porosity was restricted to the lower parts of the Rajabiah Formation.

Cementation by microsparite and later by silica is the main porosity dishancing factor through the whole parts of the studied samples, whereas dissolution and leaching out is the sole porosity enhancing factor at the lower parts of the section. Grain compaction and fracturing are restricted to the clastic ferruginous calcareous quartz arenite microfacies in the lower parts of the Rajabiah Formation.

From the petrophysical point of view, the bulk density is dependent mainly porosity, whereas permeability on the channel diameter, porosity and the irreducible water saturation.

The formation resistivity factors were measured at 10 and 50 kppm, both are affected mainly by the effective porosity and electric tortuosity. A lime-mud effect could be recorded for some Masajid samples, with no effect for the other samples.

The Jurassic marine sediments in Gebel El Maghara complex have poor storage capacity properties except for the lower parts of the Rajabiah Formation, so it is recommended to deal with the present rocks as a source of building and ornamentation stones.

INTRODUCTION

The Gebel El Maghara massif is the highest topography of the northern part of Sinai. It is the first salient massif about 50 km south of the Sinai Mediterranean Coast, situated between longitude 33°10' and 33°35' E and latitude 30°35' and 30°50' N. It is an asymmetrical doubly plunging anticline about 54 km long and 30 km wide, its longest axis runs in a NE–SW direction, and has a total area of approximately 1300 km^2 (Fig. 1).

The core of El Maghara area is a dome-like; its northwestern flank dips with about 25°, while the southeastern flank is very steep, nearly vertical, or overturned, where it is bounded by a major thrust fault with Jurassic rocks riding over the Lower Cretaceous section (Moustafa and Khalil, 1990; Kassab, 2004). The Jurassic sediments are exposed at the core, whereas the Cretaceous and Eocene sediments at the flanks.

The area is one of the most important structural features in Egypt, since it represents one of the major Jurassic outcrops in North Sinai; it is the type section of the Jurassic exposures in North Sinai.

The area has been subjected to many geological and palaeontological studies initiated by Farag (1959), and continued by Kostandi (1959), Al-Far (1966), Jenkins et al. (1982), El Manawi (1986), Yussef (1986), Jenkins (1990), Moustafa and Khalil (1990), Said (1990) and Kassab (2004).

METHODOLOGY

The marine sequence in Gebel El Maghara area has been representatively sampled. A total of 132 core plugs were obtained out of these samples for the petrophysical and petrographical routine and special core analyses. The sampled Jurassic marine rocks were drilled and prepared for the petrophysical measurements as plugs of 1 inch diameter / 1 inch length.

To determine volume of the connected pore spaces in the lab., it is necessary to determine only two of three volumes namely, bulk volume (Vb), connected pore volume (Vc) and grain volume (Vg), where

$$Vb = Vg + Vc$$

One of the most known and simple methods for pore volume determination is the saturation method which was mentioned by Koithara et al. (1968), and used in the present study for measuring both the porosity and the bulk density of the drilled core samples. The method is based on determination of the pore volume and the bulk volume. The bulk density (σb) is then determined as:

$$\sigma b = Wd / Vb$$

where, Wd: is the dry weight.

and porosity could be calculated using the following equation:

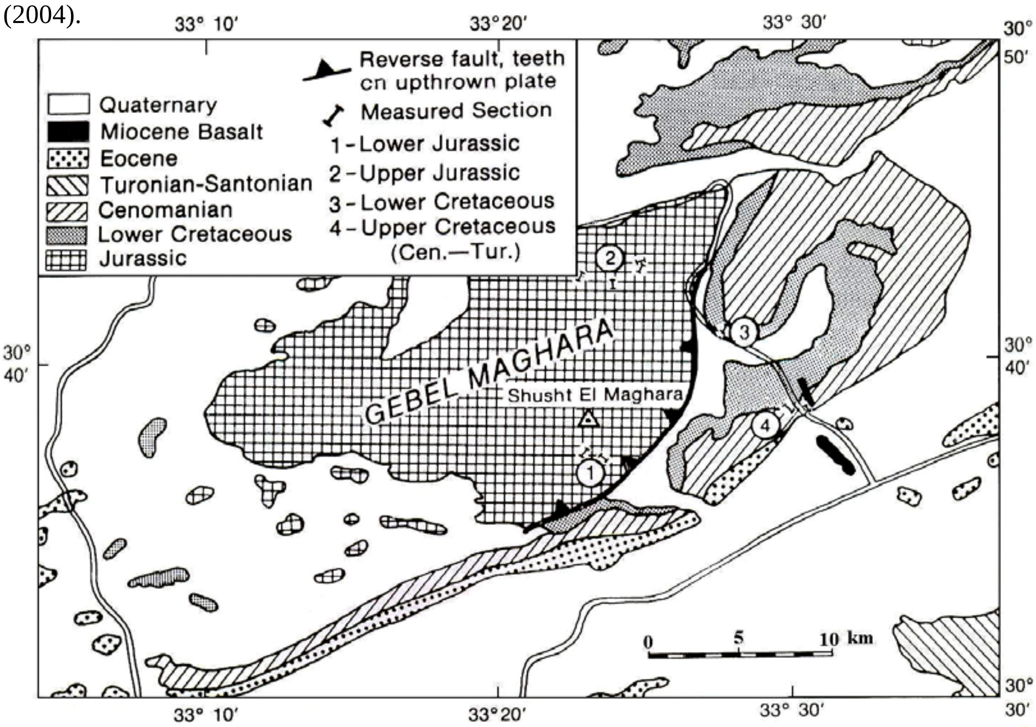


Fig. 1 Geologic map of Gebel El Maghara area (Al Far, 1966; Eyal et al., 1980; and EGSMA, 1992).

$$\varnothing = 100^* (Ws-Wd) / Vb$$

where, Wd: is the dry weight, and

Ws: is the sample weight fully saturated.

Levorsen (1967) classified the rocks which have porosity less than 5 % as negligible, so the permeability was estimated only for samples having more than 5 % porosity by applying Timur's equation (1968):

$$k = 0.136\ \varnothing^{4.4}.Sw_{irr}^{\ -2.0}$$

where; k = Permeability, in md,

$\varnothing$ = Porosity, in %, and

Sw_{irr} = Irreducible water saturation, in %.

The pore channel diameter (D) of the studied samples was calculated for each sample using the equation presented by Rzhevsky and Novik (1971) as follows:

$$D = (32\ K / \varnothing)^{0.5}$$

where; K = Permeability, in μm^2; and

$\varnothing$ = Porosity, %.

After that, the electrical resistivity measurements were carried out for the core samples by using A-C bridge at two successive cycles of brine saturations (10 and 50 kppm) with NaCl solutions (R_w = 0.56 ohm.m and 0.14 ohm.m, respectively) to investigate the effect of the conductive pore volume of the pore phase and the fine conductors within the solid rock phase.

The formation resistivity factor for each rock sample at the two brine concentrations was then calculated, as:

$$F = R_o / R_w \qquad \text{(Amyx et al., 1960)}$$

Values of the electric tortuosity factor (T) of the studied rocks were calculated for the first formation resistivity factor using the following equation (Gür, 1976; Ragab et al., 2000):

$$T^2 = F.\varnothing \qquad \text{(Gür, 1976)}$$

To investigate the lime-mud effects, the mounce potential was then calculated for the first and second formation resistivity factor following the equation of Perkins et al. (1954):

$$\Delta\phi = \ln (F_2/F_1) \qquad \text{(Perkins et al., 1976)}$$

where, F_2 measured at brine concentration higher than that of F_1

The applied methods and techniques were carried out in the Department of Geophysical Sciences, National Research Centre.

On the other hand, the petrography of the Jurassic marine sediments microfacies associations and their diagenetic history have been studied through a total of 50 thin sections stained by Alizarin Red-S for detecting of dolomite crystals and dyed for porosity studies following Dickson's technique (1966). The carbonate microfacies were classified according to their depositional textures' of Flügel (1982) which is based on Dunham classification (1962) and its modification by Embry and Klovan (1972). The paleoenvironment was then defined by using Standard Microfacies (SMF) analysis technique of Wilson (1975) and Flügel (1982).

On the other hand, the majority of sandstone classifications are based on texture and / or mineralogy; therefore, microscopic studies are required with accurate determination of the mineral components. The widely used classification of Pettijohn et al. (1973) is used in this study. On the other hand, the nomenclature and classification of porosity was carried out following Choquette and Pray's classification (1970).

LITHOSTRATIGRAPHY

The Gebel El Maghara area is covered mainly by Jurassic and Cretaceous rock sequences. The Jurassic rocks are the thickest and most complete Jurassic exposures in Egypt. They range in age from Liassic to Kimmeridgian and are approximately 1850 to 1900 m thick. According to Al Far (1966), the Jurassic rocks in Gebel El Maghara area are classified into six formations; namely, Mashaba at the base, Rajabiah, Shusha, Bir El Maghara, Safa and Masajid Formation at the top. The studied sequence represents three cycles of intercalated sea regressions and transgressions. Three of them have been deposited in continental environments, whereas the others in marine conditions. The marine formations are the scope of these studies; they are Rajabiah, Bir El Maghara and Masajid Formation (Fig. 2).

1) Rajabiah Formation (292 m)

Rajabiah Formation (Liassic age) is well exposed at its type section in Wadi Rajabiah and Wadi Sad El Mashaba, and composed of greyish dense, hard, coralline algal limestones in the lower part, intercalated with thin sandstone and sandy limestone interbeds, marly upward. The Rajabiah limestones are dark grey with white veinlets and algal nodules (Al Far, 1966).

2) Bir El Maghara Formation (442 m)

According to Al Far (1966) Bir El Maghara Formation (Bajocian-Bathonian age) is assigned at Bir El Maghara and Bir Mowerib areas, and could be subdivided into three members;

a) Mahl Member (Bajocian age, 94 m), its type section is located at Wadi Mahl. It is composed of hard coralline, massive limestones intercalated with few marls and clays (Youssef, 1986),

b) Bir Mowerib Member (Bajocian age, 132 m), its type section is located in Bir Mowerib. It is composed mainly of clays intercalated with hard coralline greyish algal limestone, and

c) Bir El Maghara Member (Bathonian age, 216 m), its type section is situated at Bir El Maghara, and composed of clays intercalated with hard coralline greyish algal limestone.

3) Masajid Fm. (Bathonian-Oxfordian age, 575 m)

Masajid Formation forms the top most parts of the Jurassic sequence in Gebel El Maghara. It could be classified into two members; namely,

1) Kehailia Member (132 m), its type section is located between Wadi Kehailia and Ras Abu Saqaa, and composed mainly of marly glauconitic limestones, and

2) Arousiah Member (443 m), its type section is located at Wadi Masajid; and consists of hard stylolitic coralline and algal limestone.

RESULTS AND DISCUSSION

MICROFACIES ANALYSIS

1) Rajabiah Formation

From the petrographical studies, it is achieved that Rajabiah samples are composed mainly of:

i) Ferruginous calcareous quartz arenite (clastic microfacies)

It represents the lower most parts of Rajabiah Formation. It is composed of medium sorted fine to very fine angular quartz grains cemented together by pseudo to microsparite. The quartz grains are frequently corroded by the cement and compacted together through point, straight and concave-convex contacts (Plate 1, Fig. A). Very fine to silt-sized iron oxides are found scattered within the pores and attached at their sides.

The total pore spaces can be differentiated into: 1) intercrystalline porosity, 2) micro to mesovugs, sometimes filled with iron oxides and 3) micro to mesointergranular porosity (Plate 1, Fig. B). The total pore spaces are around 20 % in most of the studied samples.

ii) Mudstone microfacies (SMF 23)

The studied mudstone microfacies are well represented at the topmost parts of Rajabiah Formation. Petrographically, it is composed mainly of micrite with rare neomorphic microsparite patches, which can be considered as an initial stage of a pseudo porphyritic fabric. Some silt-sized iron oxides are disseminated within the matrix (Plate 1, Fig. C).

The pore spaces can be described as: 1) micro intercrystalline pore spaces, 2) mesochannels, frequently filled microsparite (Plate 1, Fig. C), and 3) micro to meso fossil molds (Plate 1, Fig. D). The percentage of the total pore spaces is low to very low and doesn't exceed 8 %.

2) Bir El Maghara Formation

Petrographically, Bir El Maghara Formation is composed mainly of the following microfacies:

i) Mudstone microfacies (SMF 23)

The studied mudstone microfacies are representative for most parts of the Bir El Maghara Formation. It is composed of micrite to microsparite with some neomorphic microsparite patches. Some microsparite patches are found filling foraminifera moldic pores (Plate 1, Fig. G).

The pore spaces can be described as: 1) micro intercrystalline pore spaces, 2) mesovugs frequently filled with microsparite and silica cement (Plate 1, Figs. E & F), 3) micro to mesofossil molds (Plate 1, Fig. G), and 4) mesochannels frequently filled with silica cement and dolomicrosparite (Plate 1, Fig. H). The percentage of the total pore spaces is low and doesn't exceed 5 %.

3) Masajid Formation

From the present petrographical studies, Masajid Formation is composed mainly of the following microfacies:

i) Foraminiferal and molluscan mudstone microfacies (SMF 19)

The studied bioclastic mudstone microfacies are represented in the Kehailia Member**,** the lower member of Masajid Formation. It is composed mainly of micrite containing some foraminifera tests and molluscan shell fragments of micritic to microsparitic composition (Plate 2, Figs. A & B).

The pore spaces can be described as: 1) microintercrystalline or matrix pore spaces, and 2) mesofossil and test molds filled with microsparite. The percentage of the total pore spaces is low and doesn't exceed 8 %.

ii) Oolitic grainstone microfacies (SMF 16)

The oolitic grainstone microfacies are presented only for the Kehailia Member. The oolites are well sorted and well developed, composed mainly of micritc shells compacted together or cemented by microsparite and/or silica cement (Plate 2, Fig. C).

The pore spaces can be described as: 1) micro intercrystalline pore spaces, and 2) micro to mesointergranular porosity filled with microsparite and/or silica cement (Plate 2, Fig. C). The total porosity is low and doesn't exceed 10 %.

iii) Foraminiferal and algal sparitic mudstone microfacies (SMF 19 & 21)

The studied foraminiferal and algal mudstone microfacies are representative for Arousiah, the Upper Member of Masajid Formation**.** It is composed mainly of some foraminifera tests and algae remains cemented together by micrite matrix containing micro sparitic patches. (Plate 2, Figs. D & E).

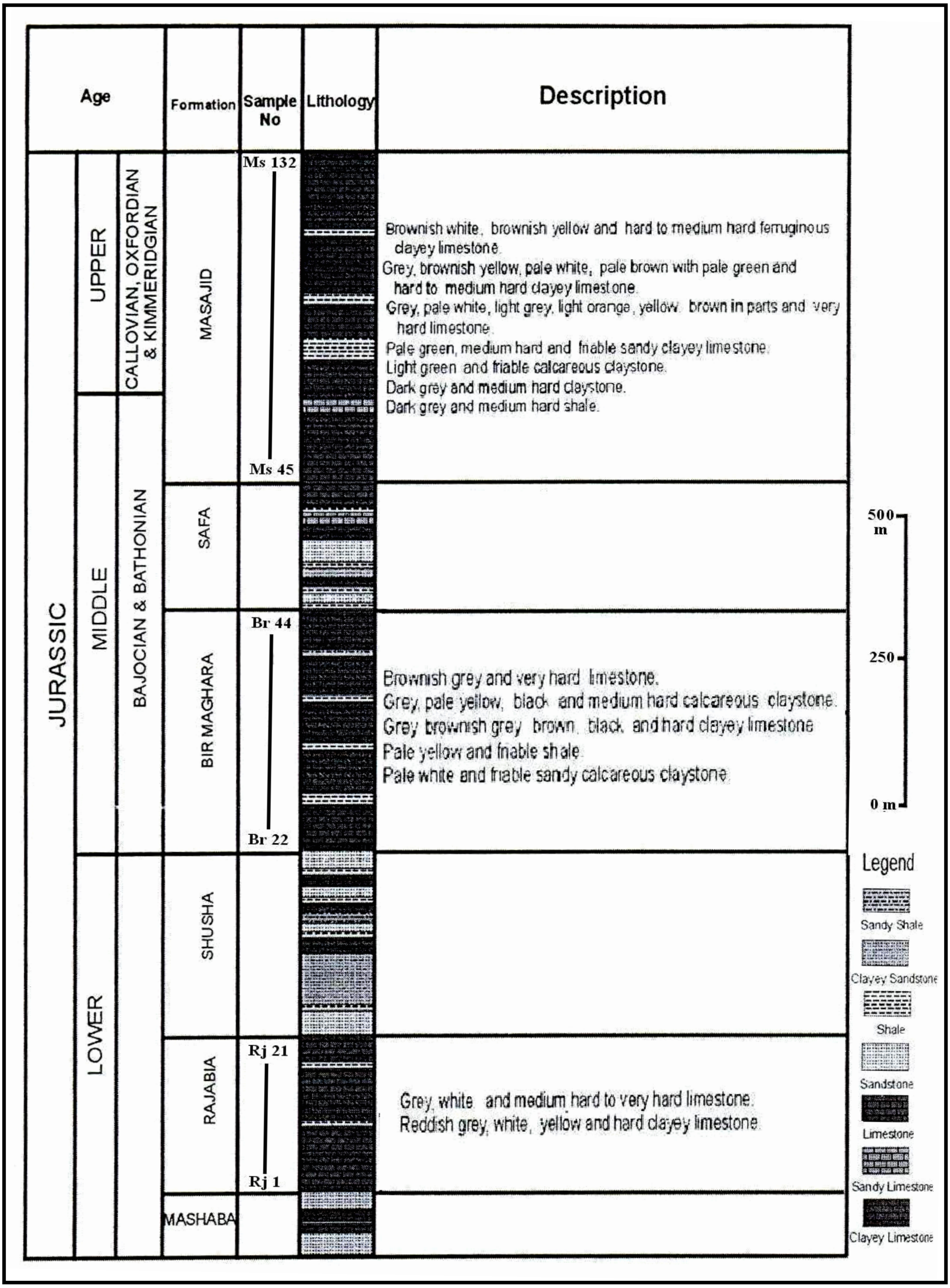
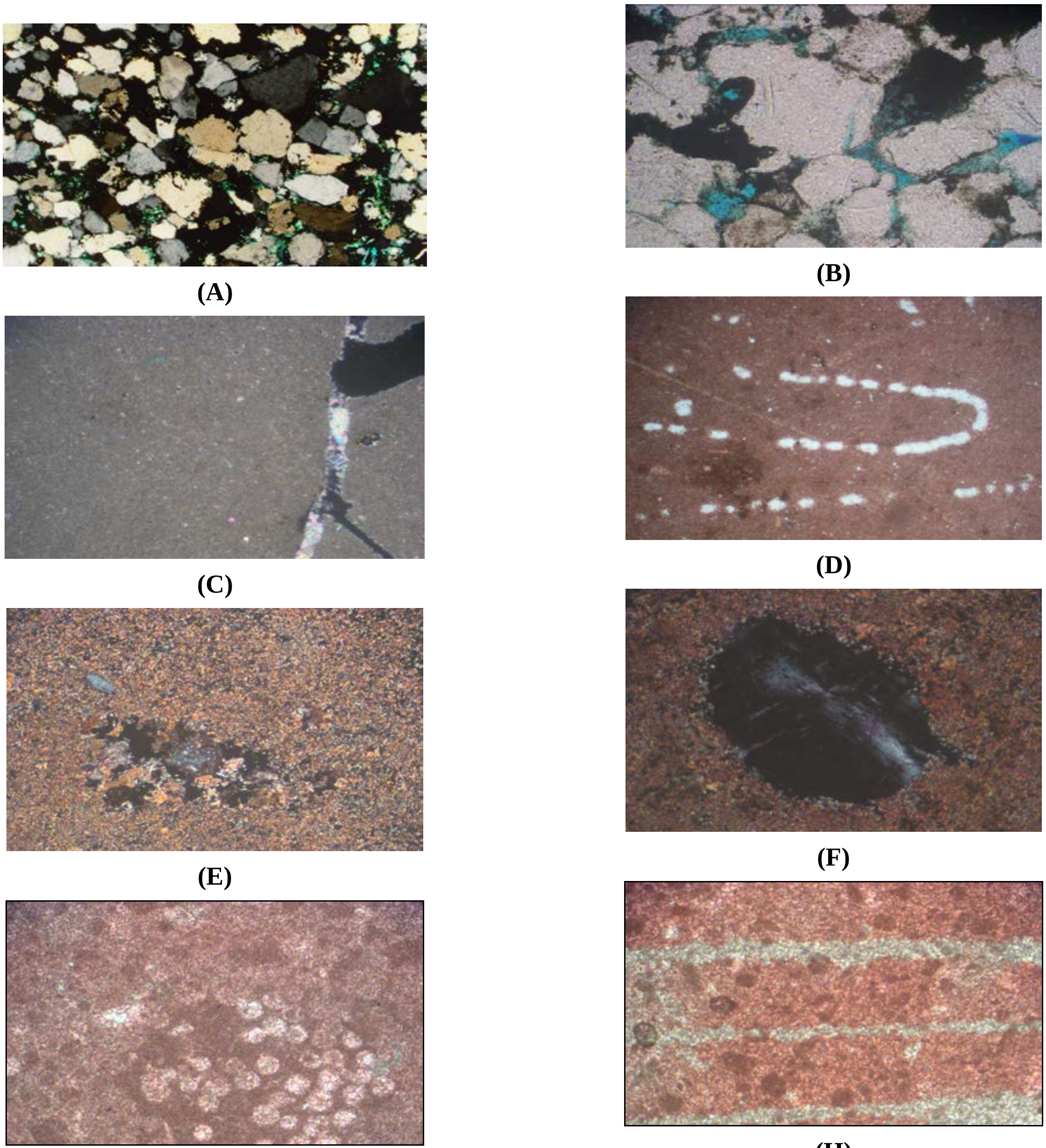


Fig. 2 Lithostratigraphic section of Gebel El Maghara Jurassic sequence, simplified after Kassab (2004).

Plate 1

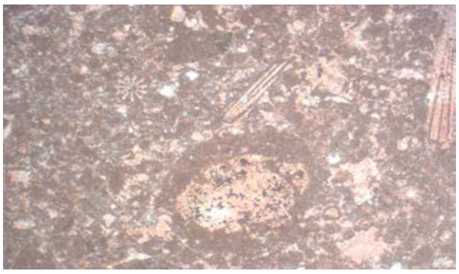


(A) **(B)** **(C)** **(D)** **(E)** **(F)** **(G)** **(H)**

Fig. A: Photomicrograph showing fine to very fine quartz grains embedded in and corroded by microsparite cement, ferruginous calcareous quartz arenite microfacies, Rajabiah Formation, C.N., X 40, Fig. B: Photomicrograph of ferruginous calcareous quartz arenite microfacies showing intergranular porosity (dyed blue) with silt-sized iron oxides filling the pore spaces, Rajabiah Formation, PPL., X 100, Fig. C: Photomicrograph showing mud matrix with a mesochannel partially filled with microsparite, PPL, X 40, mudstone microfacies, Rajabiah Formation, Fig. D: Photomicrograph showing fossil mesomoldic porosity within micrite matrix, mudstone microfacies, Rajabiah Formation, PPL., X 40,. Fig. E: Photomicrograph showing mud with mesovug partially filled with microsparite, PPL, X 40, mudstone microfacies, Bir El Maghara Formation, Fig. F: Photomicrograph showing mesovug filled by silica cement, mudstone microfacies, Bir El Maghara Formation, PPL., X 100, Fig. G: Photomicrograph showing mesomoldic foraminifera porosity filled with microsparite, mudstone microfacies, Bir El Maghara Formation, PPL., X 100, Fig. H: Photomicrograph showing mesochannels filled with dolomicrosparite, PPL., X 100, mudstone microfacies, Bir El Maghara Formation.

Plate 2

(A)



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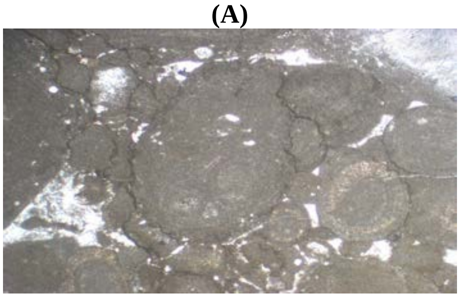
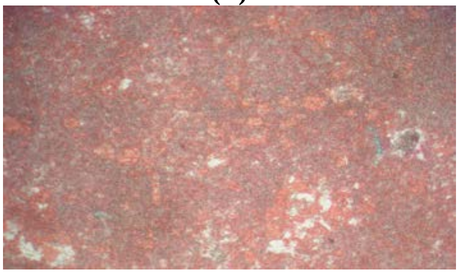


(c)



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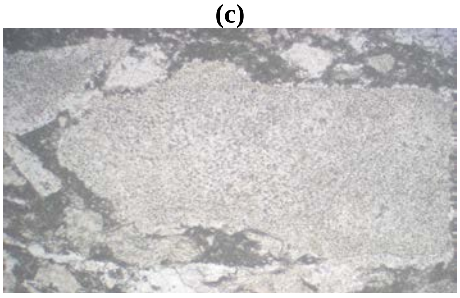
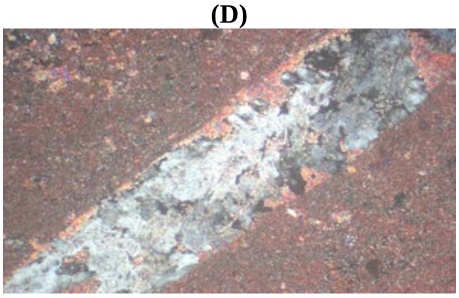


(E)



(F)

Fig. A: Photomicrograph showing some foraminifera tests and molluscan remains scattered in a micritic matrix, Foraminiferal and molluscan mudstone microfacies, Kehailia Member, Masajid Formation, C.N., X 40, Fig. B: Photomicrograph showing some foraminifera tests, molluscan remains and echinoid spines scattered in a micritic matrix, Foraminiferal and molluscan mudstone microfacies, Kehailia Member, Masajid Formation, PPL., X 40, Fig. C: Photomicrograph showing fine to medium oolites cemented together by microsparite with some tangential structure, Oolitic grainstone microfacies, Kehailia Member, Masajid Formation, PPL, X 40, Fig. D: Photomicrograph showing neomorphism indicated by a micrite matrix containing some microsparite patches, Foraminiferal and algal sparitic mudstone microfacies, Masajid Formation, PPL., X 40, Fig. E: Photomicrograph showing algae remains embedded in micrite to microsparite matrix, Foraminiferal and algal sparitic mudstone microfacies, Masajid Formation, PPL., X 40, Fig. F: Photomicrograph showing large to mesomoldic porosity filled completely by microsparite and silica cement, Foraminiferal and algal sparitic mudstone microfacies, Masajid Formation, PPL., X 40.

The pore spaces can be described as: 1) micro intercrystalline or matrix pore spaces, 2) mesofossil and test molds filled with microsparite, 3) mesovugs filled by silica cement, and 4) meso to large channels filled by sparite, microsparite and silica cement (Plate 2, Fig. F). The percentage of the total pore spaces is low and doesn't exceed 10 %.

DEPOSITIONAL ENVIRONMENTS

According to Al Far (1966), the Jurassic Rajabiah, Bir El Maghara and Masajid formations are three marine sequences alternated with other three continental formations. In the present study, the depositional environments of the marine sediments in Gebel El Maghara have been revealed from the studied facies and microfacies. Rajabiah Formation is composed at its lower part from clastic ferruginous calcareous quartz arenite microfacies, which could be considered as continuity for the depositional conditions prevailed during the deposition of the upper parts of the underlying continental Mashaba Formation.

Upwards, the Rajabiah and Bir El Maghara samples are composed of carbonate mudstone microfacies equivalent to SMF no. 23 which according to Wilson (1975) and Flügel (1982) was deposited in a shallow subtidal environment (Facies zone no. 8, restricted platform, Fig. 3).

The top of the Jurassic sequence in Gebel El Maghara, Masajid Formation gave rise to the deposition of shallow subtidal microfacies, foraminiferal and molluscan mudstone (SMF 19) and foraminiferal and algal sparitic mudstone (SMF no. 19 & 21). Some more or less deepening of the sea base occurred during the deposition of the middle parts of Masajid Formation, which could be revealed by the oolitic grainstone microfacies (SMF 16) which was deposited in Shelf lagoons to restricted platform (facies zones 7 & 8, Fig. 3).

Therefore, the Jurassic marine sediments in Gebel El Maghara have been deposited in shallow subtidal environment, Fz. 8 (restricted platform), with some sea transgression into Fz. 7 (shelf lagoon) during the deposition of the middle parts of Masajid Formation.

DIAGENETIC IMPACTS

From the petrographical point of view, diagenetic processes are important due to their effect on the composition and texture of the rocks and due to their dishancing or enhancing effects upon the pore spaces of the studied rocks. The studied samples were affected by a number of main diagenetic processes as follows:

1) Compaction and pressure solution

Compaction process is a dishancing process for the porosity and permeability of sedimentary rocks. El Maghara area is a complex structural anticline; it is a main part of the Syrian arc in north Egypt, but the carbonate content of the studied rocks reduced and diminished the tectonic impacts on the studied Jurassic marine sequence in Gebel El Maghara. The main effect could be revealed through the clastic microfacies in the lower parts of Rajabiah Formation. It is indicated by point contact, long, and frequently concave-convex contacts between the quartz grains of the ferruginous calcareous quartz arenite microfacies (Plate 1, Fig. A). It could also be indicated by fracturing of some quartz grains (Plate 1, Fig. B).

2) Cementation

It is the main dishancing effect for the porosity and permeability of the studied rocks. The most common cementing materials of the studied microfacies associations are the carbonate and silica.

Microsparite is the main shell and tests' cement (Plate 1, Fig. G; Plate 2, Figs. A & B). Sometimes drusy and blocky sparite is present filling the vugs, channels and fossil molds (Plate 1, Figs. C, D & E; Plate 2, Fig. F).

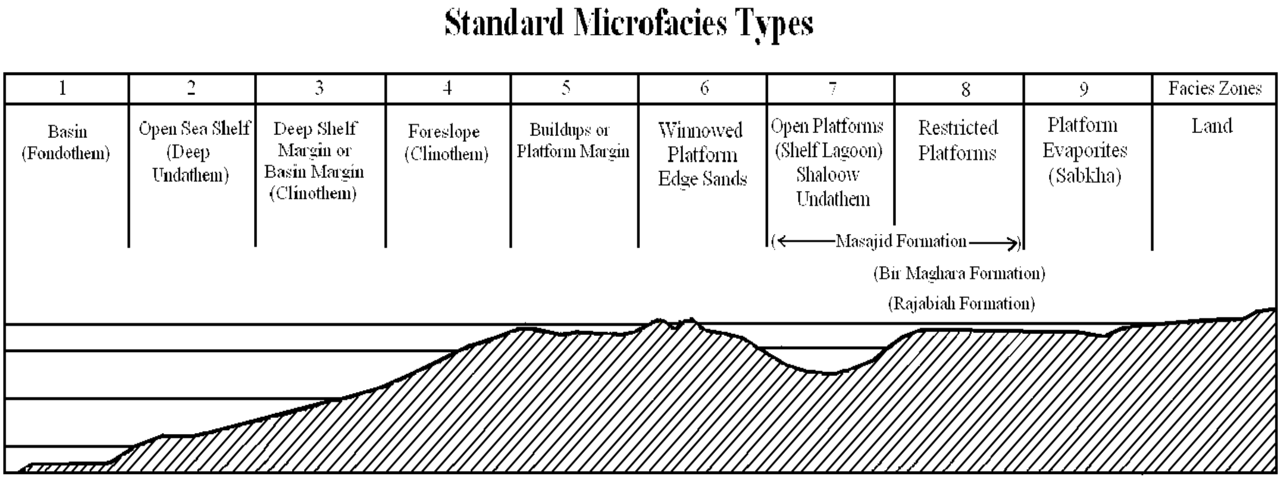


Fig. 3 A sketch showing the Standard Microfacies types (SMF) of Wilson (1975) and Flügel (1982) and the facies zones of deposition prevailed during the Jurassic in El Maghara area.

The presence of micrite as a main rock constituent and microsparite as disseminated patches within some of the carbonate microfacies associations of the studied rock samples reveal quiet conditions (Plate 2, Fig. D) that prevailed in north Sinai during the depositional and the post depositional history of the Jurassic rocks.

A second phase of cementation is represented by silica filling different sizes of channels, fractures and vugs in many samples of the studied carbonate rocks (Plate 1, Fig. F; Plate 2, Fig. F). These figures show an excellent illustration for the invasion of the groundmass by marine Si-bearing solutions through micro to mesochannels and fractures which were introduced by the tectonic activities in the area of study. Although the first phase of invasion by Ca-bearing solution seems to be the main porosity reducing factor, silica and microquartz seem to have the final diminishing impact on porosity of the present rocks (Plate 2, Fig. F), particularly in the Masajid Formation.

3) Dolomitization

Dolomitization process, is rarely encountered through the microfacies analysis of the present rocks, except for some zones in the carbonate mudstone microfacies of Bir El Maghara Formation (Plate 1, Fig. H) and the foraminiferal and algal sparitic mudstone microfacies Masajid Formation (Plate 2, Fig. D), due to later invasion by Mg-bearing solutions filing the channels and fractures.

4) Aggrading Neomorphism

It is presented in the studied samples as microsparite patches within the main dominant micrite matrix in the foraminiferal and algal sparitic mudstone microfacies of Masajid Formation, due to growth of the micrite and microspars into pseudo spar and calcite.

5) Dissolution and replacement

Dissolution is the main diagenetic process responsible for enhancing porosity and permeability of sedimentary rocks, while replacement results in an opposite effect. Dissolution of matrix and cement, crystals and grains in the present rocks increased the vug and shell moldic porosity, e.g. the mudstone microfacies (Plate 1, Figs. D & E). Dissolution of most of the molluscan shells and the foraminifera tests increased the intraparticle and moldic porosity, but later it was reduced by deposition of microsparite, e.g. foraminiferal and molluscan mudstone microfacies of Masajid Formation (Plate 2, Figs. A & B).

PETROPHYSICAL FEATURES AND BEHAVIOUR

From the present routine and special core analyses, it is achieved that the bulk density of the marine facies in Gebel El Maghara fluctuates between 2.31 and 2.53 g/cm^3 for Masajid samples, 2.42 and 2.57 g/cm^3 for Bir El Maghara samples and between 1.93 and 2.42 g/cm^3 for Rajabiah samples; whereas the porosity values lie between 0.6 and 7.2 %, for Masajid samples, 0.9 and 4.5 % for Bir El Maghara and between 3.1 and 19.2 % for Rajabiah samples. The relatively low porosity and bulk density values of most of the samples indicate the presence of some clay content (have low density values) and isolated vuggy porosity due to the diagenetic impacts. Samples of the lower parts of Rajabiah, however, are differentiated from the other samples by their lower bulk density and porosity, where the sampled sandy facies of Rajabiah are porous in contrast to the other parts of the section.

The apparent electric resistivity values of Masajid core samples at 10 kppm (R_w = 0.56 ohm.m) lie between 63 and 1728 ohm.m for Masajid samples, 52 and 619 ohm.m for Bir El Maghara samples and 8.7 and 203 ohm.m for Rajabiah samples; whereas the electric resistivity values at 50 kppm (R_w = 0.14) vary between 29 and 622 ohm.m, 31 and 273; 3 and 69 ohm.m for Masajid, Bir El Maghara and Rajabiah formations, respectively. The electric resistivity of the Rajabiah is relatively lower than the other values of the marine sediments, due to the porous horizons in its lower facies whereas Bir El Maghara shows lower values than that of Masajid which could be attributed to presence of some clay content which have good distribution in Bir El Maghara rock samples giving rise to more or less dull to dirty appearance of the hand specimens.

On the other hand, the electric tortuosity of Masajid, Bir El Maghara and Rajabiah formations vary between 2.5 and 8.3, 1.9 and 3.3, 1.7 and 3.4, respectively; whereas the mounce potential values vary between -0.6 and 1.3 millivolt, 0.4 and 1.3; 0.1 and 0.9 millivolt, respectively. The similarity in electric tortuosity values of both Bir El Maghara and Rajabiah facies could be attributed to porous horizons in Rajabiah and electrically active clay content in Bir El Maghara samples.

A total of thirty samples out of the studied samples having porosity more than 5 % were selected for conducting further permeability, irreducible water saturation and channel diameter measurements. The irreducible water saturation of the selected Masajid samples varies between 36.8 % and 57.7 %, whereas for the Rajabiah samples, varies between 9.5 % and 44.9 %, the permeability values vary between 4.4 mD and 618 mD for Rajabiah samples and 0.2 and 0.6 mD for Masajid samples, whereas the pore channel diameter between 0.11 and 1.02 µm (capillary to subcapillary channels) for Rajabiah samples and 0.02 and 0.05 µm (subcapillary channels) for Masajid samples.

In the following paragraphs, a number of petrophysical relationships are introduced to follow up the petrophysical behaviour, to examine the mutual effects between the different petrophysical parameters, to check the effect of the diagenetic history impacts and to offer a number of empirical equations of high precision which could be used to calculate one petrophysical parameter in terms of other.

1) Bulk Density - Porosity Relationship

The bulk density values have good inverse relationship with the porosity values with very high correlation coefficient of the studied samples (Fig. 4), indicating a homogeneity in pore fabric distribution for the Rajabiah and Bir El Maghara facies, and a more or less heterogeneity for Masajid samples.

The following equations could be used with a high degree of precision to calculate the porosity values in terms of bulk density.

For Rajabiah Formation

$\varnothing = -35.92\ \sigma b + 88.71$ (r = -0.99)

For Bir El Maghara Formation

$\varnothing = -24.46\ \sigma b + 63.13$ (r = -0.91)

For Masajid Formation

$\varnothing = -24.25\ \sigma b + 62.81$

2) Porosity - $F_{0.56}$ Relationship

The formation resistivity factor of the first saline saturation at 10 kppm (Rw = 0.56) is inversely proportional to the porosity values in a good relationship (Fig. 5, $r \geq -0.74$). The correlation coefficient value of log $\varnothing$ - log $F_{0.56}$ of Masajid samples is less than that of the other facies indicating less homogeneity in pore fabric distribution due to the effect of some diagenetic factors, particularly, the differential cementation and aggrading neomorphsim (Plate 2, Fig. D). Also, it could be attributed to the presence of some electric active clays sharing in the electric response of the present samples. The following equations could be used to calculate the formation resistivity factor at 10 kppm in terms of porosity value.

For Rajabiah Formation,

$\text{Log } F_{0.56} = -1.57\ \varnothing + 3.23$ (r = -0.99)

Bir El Maghara Formation,

$\text{Log } F_{0.56} = -1.51\ \varnothing + 2.91$ (r = -0.96)

For Masajid Formation,

$\text{Log } F_{0.56} = -1.01\ \varnothing + 3.23$ (r = -0.75)

On the other hand, the relatively low (m) values for the Masajid Formation with low porosity percentage indicates the presence of some matrix porosity (Plate 2, Figs. A, B, D & F), whereas similarity in (a) values is due to similarity in the mineralogical composition, mainly carbonate rocks.

3) Porosity - $F_{0.14}$ Relationship

The formation resistivity factor at the second saline saturation at 50 kppm (Rw = 0.14) is also inversely proportional to the porosity in an excellent relationship (Fig. 6, $r \geq -0.87$). The correlation coefficient of the F - $\varnothing$ relationship at 50 kppm for the Masajid Formation is relatively higher than that at 10 kppm, which ensures the presence of some electrically active clay content, became less active at 50 kppm (Nabawy and El-Hariri, 2006). The formation resistivity values are attributed to the porosity values according to the following empirical equations.

For Rajabiah Formation,

$\text{Log } F_{0.14} = -1.70\ \varnothing + 3.55$ (r = -0.98)

For Bir El Maghara Formation,

$\text{Log } F_{0.14} = -1.47\ \varnothing + 3.27$ (r = -0.96)

For Masajid Formation,

$\text{Log } F_{0.14} = -1.19\ \varnothing + 3.52$ (r = -0.87)

Also, the relatively low (m) values for the Masajid Formation with low porosity percentage indicates presence of some matrix porosity.

4) $F_{0.14}$ - $F_{0.56}$ Relationship

The formation resistivity factor of the 50 kppm full saline saturated samples was plotted against that of the 10 kppm to establish their mutual relationship and the effect of clays in both cases. An inverse relationship with good correlation coefficient was observed (Fig. 7, $r \geq 0.90$) for the different rock samples indicating the main dependence of the measured electric features on the pore space network, with relatively less dependence of the Masajid samples. The formation resistivity factors could be obtained in terms of each other according to the following equations.

For Rajabiah Formation,

$\text{Log } F_{0.14} = 1.08 \text{ Log } F_{0.56} + 0.06$ (r = 0.99)

For Bir El Maghara Formation,

$\text{Log } F_{0.14} = 0.94 \text{ Log } F_{0.56} + 0.52$ (r = 0.97)

For Masajid Formation,

$\text{Log } F_{0.14} = 0.94 \text{ Log } F_{0.56} + 0.37$ (r = 0.90)

5) Apparent Electric Resistivity - Electric Tortuosity (T) Relationship

The apparent electric resistivity values at 10 kppm were plotted against the electric tortuosity (Fig. 8) indicating a good direct proportional relationship, with the highest correlation coefficient recorded for Rajabiah samples and the lowest for Masajid, which could be attributed to the effect of clay content and the relative heterogeneity in the pore fabric and distribution for both Masajid and Bir El Maghara formations.

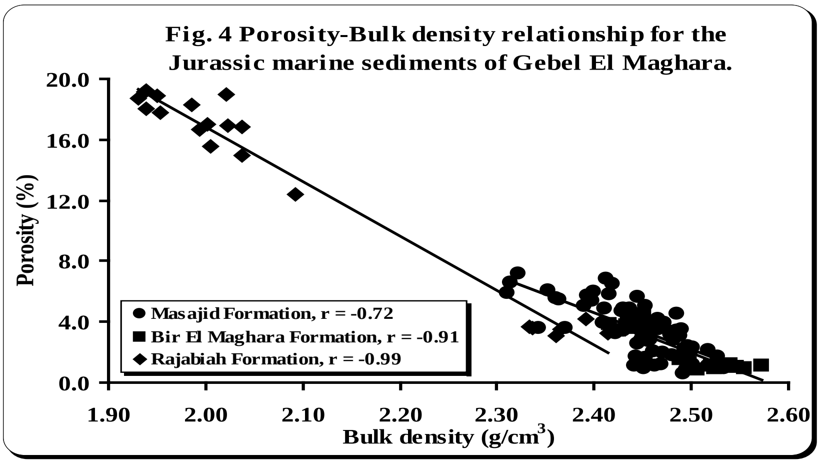


Fig. 4 Porosity-Bulk density relationship for the Jurassic marine sediments of Gebel El Maghara.
Porosity (%)
20.0
16.0
12.0
8.0
4.0
0.0
Masajid Formation, r = -0.72
Bir El Maghara Formation, r = -0.91
Rajabiah Formation, r = -0.99
1.90
2.00
2.10
2.20
2.30
2.40
2.50
2.60
Bulk density (g/cm3)

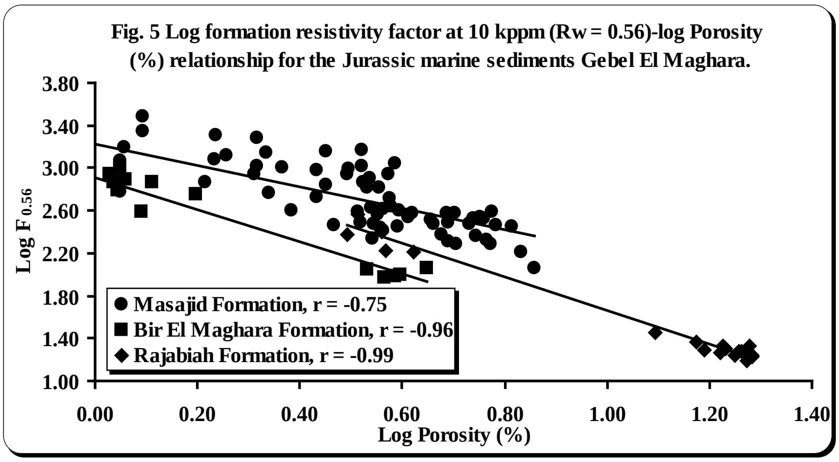


Fig. 5 Log formation resistivity factor at 10 kppm (Rw = 0.56)-log Porosity (%) relationship for the Jurassic marine sediments Gebel El Maghara.
Log F 0.56
3.80
3.40
3.00
2.60
2.20
1.80
1.40
1.00
Masajid Formation, r = -0.75
Bir El Maghara Formation, r = -0.96
Rajabiah Formation, r = -0.99
0.00
0.20
0.40
0.60
0.80
1.00
1.20
1.40
Log Porosity (%)

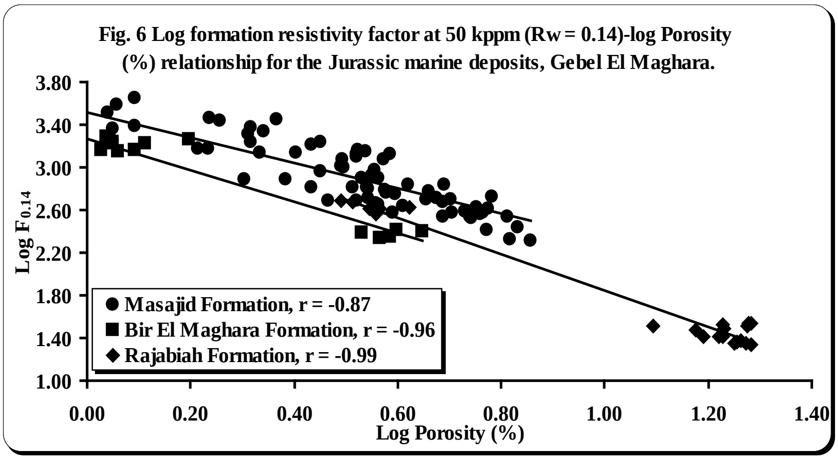


Fig. 6 Log formation resistivity factor at 50 kppm (Rw = 0.14)-log Porosity (%) relationship for the Jurassic marine deposits, Gebel El Maghara.
Log F 0.14
3.80
3.40
3.00
2.60
2.20
1.80
1.40
1.00
Masajid Formation, r = -0.87
Bir El Maghara Formation, r = -0.96
Rajabiah Formation, r = -0.99
0.00
0.20
0.40
0.60
0.80
1.00
1.20
1.40
Log Porosity (%)

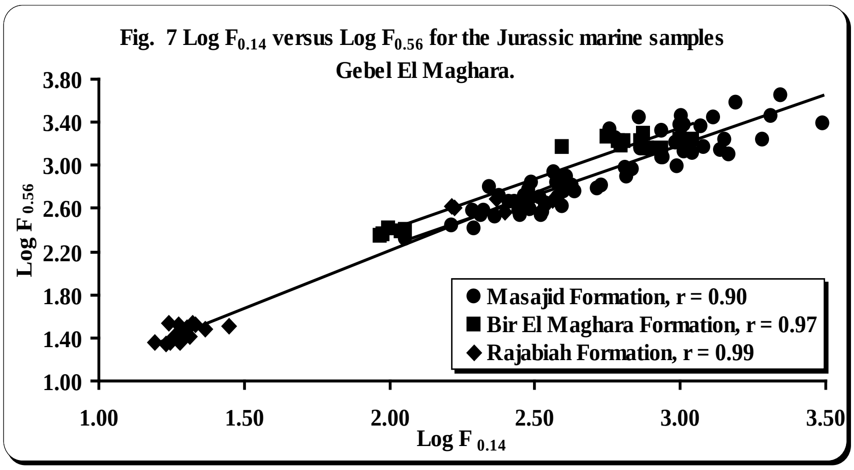


Fig. 7 Log F0.14 versus Log F0.56 for the Jurassic marine samples Gebel El Maghara.
Log F 0.56
3.80
3.40
3.00
2.60
2.20
1.80
1.40
1.00
Masajid Formation, r = 0.90
Bir El Maghara Formation, r = 0.97
Rajabiah Formation, r = 0.99
1.00
1.50
2.00
2.50
3.00
3.50
Log F 0.14

For Rajabiah Formation,

$R_{0.56}$ = 0.91 T - 0.61 (r = 0.97)

For Bir El Maghara Formation,

$R_{0.56}$ = 0.73 T - 0.47 (r = 0.89)

For Masajid Formation,

$R_{0.56}$ = 0.21 T + 1.58 (r = 0.70)

6) Mounce Potential

The mounce potential $\Delta\phi$ could be explained by generation of minor circuits acting in an opposite direction against the main current circuit passage in the pore network, where the presence of some clay content present in contact with saline water of different salinity (due to the ionic exchange) give the place of the lime-mud effect to share in and deviate the electric behaviour of the studied samples (Perkins et al., 1954).

Therefore, $\Delta\phi$ values were plotted against the sample number (Fig. 9) to detect the lime-mud effect. For the present samples, the mounce potential tracing indicates a normal electric passage for most of the studied rocks of Rajabiah and Bir El Maghara with some lime-mud effect and very low values of the mounce potential for many samples of Masajid Formation giving rise to higher electric resistivity (Fig. 8).

7) Permeability (k) – Irreducible Water Saturation (Sw_{irr}) Relationship

A total of 30 samples were selected as they have more than 5 % porosity for conducting permeability measurements. Permeability values of the studied samples (selected from the lower parts of Rajabiah Formation and different parts of Masajid Formation) are inversely proportional to the irreducible water saturation with lowest correlation coefficient for Masajid samples (Fig. 10), due to more complexity and heterogeneity of the pore throat distribution. Permeability values could be calculated in terms of Sw_{irr} according to the following equations:

For Rajabiah Formation,

Log k = -2.45 log (Sw_{irr}) + 5.16 (r = -0.92)

For Masajid Formation,

Log k = - 4.36 log (Sw_{irr}) + 6.47 (r = -0.79)

8) Permeability (k) – Porosity (∅) Relationship

Similarly, permeability values of the selected Rajabiah and Masajid samples are controlled mainly by percentage of the connected pore spaces with lower correlation coefficient for Rajabiah samples (Fig. 11), in contrast to the case of the k - Sw_{irr} due to more complexity and heterogeneity in the pore space distribution. Permeability values could be calculated in terms of porosity according to the following equations.

For Rajabiah Formation,

Log k = 7.20 log ∅ - 6.92 (r = 0. 76)

For Masajid Formation,

Log k = 5.65 log ∅ - 5.16 (r = 0. 96)

9) Permeability (k) – Pore Channel Diameter (D)

Permeability values of both Rajabiah and Masajid samples are controlled mainly the channel diameter in a direct proportional Log-Ln relationship (Fig. 12). Permeability values could be calculated in terms of the pore channel diameter according to the following equations.

For Rajabiah Formation,

Log k = 0.93 ln (D) + 2.79 (r = 0.99)

For Masajid Formation,

Log k = 30.6 ln (D) - 1.72 (r = 0.99)

GENERAL DISCUSSION & RESERVOIR ZONATION

The mineralogical composition and diagenetic history of the studied marine formations have some impacts on the petrophysical properties of their samples. The petrophysical behaviour and features of the studied rocks reveal an intergranular porosity for the lower parts of Rajabiah formation represented by the ferruginous calcareous quartz arenite microfacies, whereas characterized by matrix porosity for the rest of the sampled sequences. Impacts of diagenetic factor like cementation reduced and diminished the channel and fracture porosity and filled the fossil moldic porosity. Taking into consideration cutoff values of permeability more than 50 mD, porosity more than 10 % and irreducible water saturation less than 25 %, the whole marine sequence in the Gebel El Maghara structure has poor storage capacity properties except for the lower parts of Rajabiah Formation (Fig. 13), which are characterized by environmental conditions similar to that prevailed in the upper parts of the underlying Mashaba Formation.

Compaction due to the tectonic effects, however, was observed only for the lower parts of Rajabiah Formation (Plate 1, Figs. A & B) and has no effect on the storage capacity properties which may be due to later dissolution and leaching out by low saline solutions. Also the consequent uplift of El Maghara area has protected this area from the effect of intensive diagenetic processes like cementation, dissolution and leaching out.

However, the dishancing porosity-diagenetic impacts could be revealed from the petrographical and microfacies analyses of the studied marine samples.

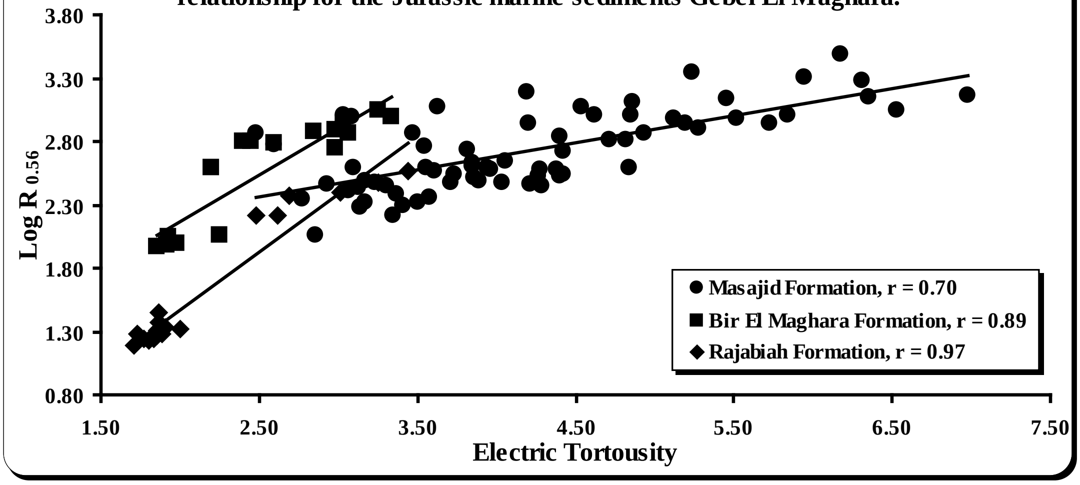


Fig. 8 Log apparent electric resistivity ($R_{0.56}$) -Electric tortuosity (T) relationship for the Jurassic marine sediments Gebel El Maghara.

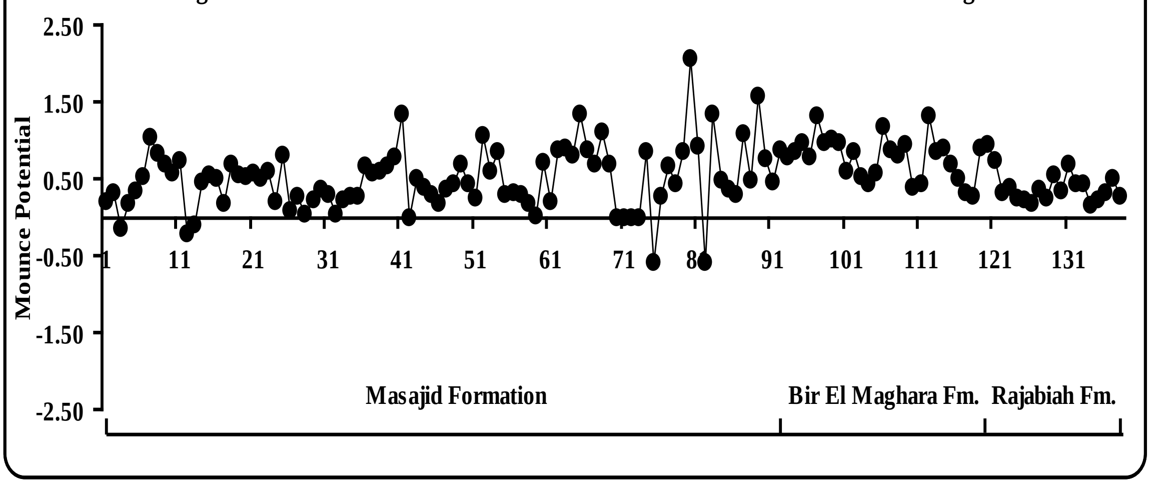


Fig. 9 Mounce Potential values of the Jurassic marine sediments in Gebel El Maghara.

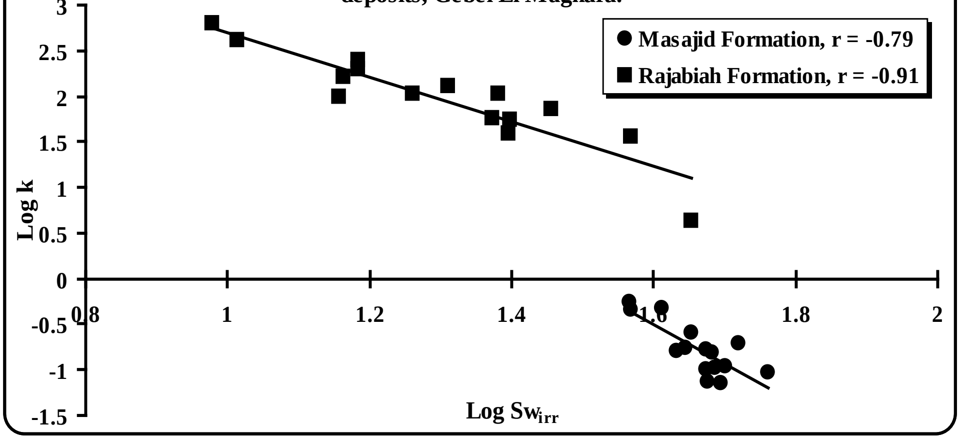


Fig. 10 Log permeability-Log Swirr relationship for the Jurassic marine deposits, Gebel El Maghara.

Fig. 11 Log permeability-Log effective porosity relationship for the Jurassic marine deposits, Gebel El Maghara.

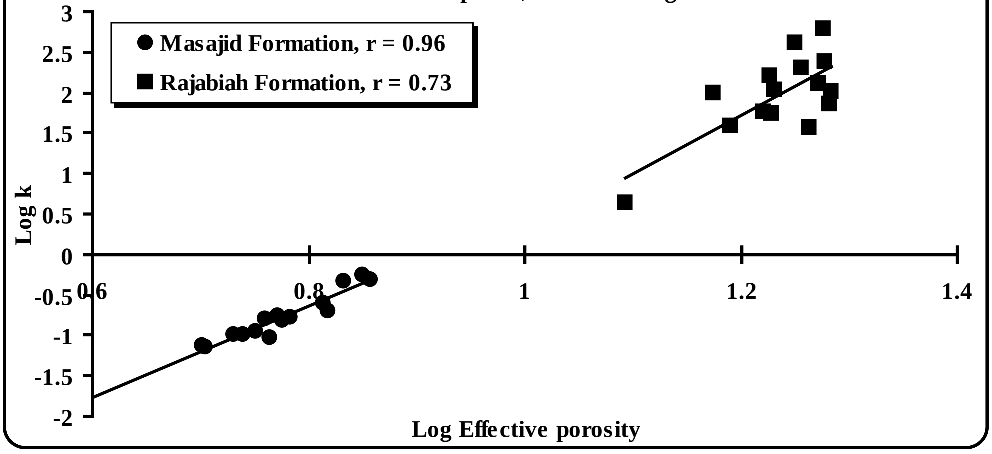
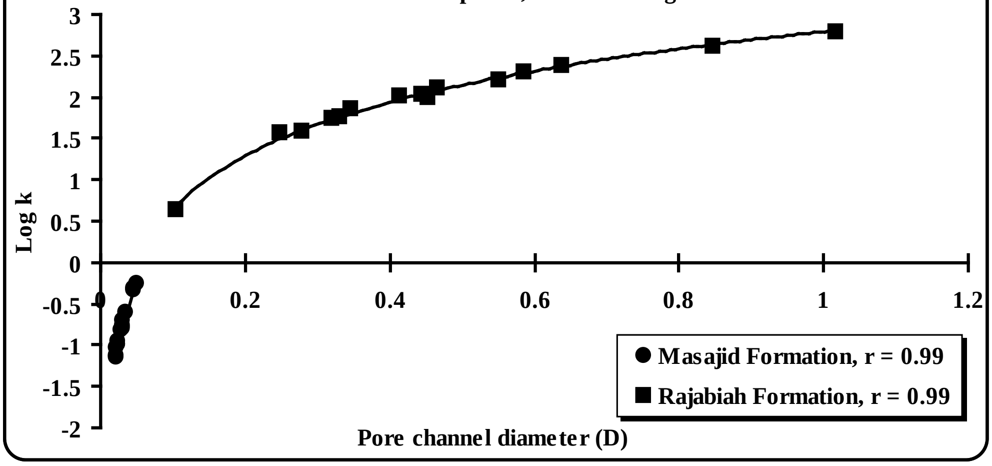


Fig. 12 Log permeability-Pore channel diameter relationship for the Jurassic marine deposits, Gebel El Maghara.



They are represented by later cementation of the channels, molds and vugs by microsparite and dolomicrosparite (Plate 1, Figs. C, E, and H). Cementation by silica, in facts, completely obliterated porosity of Masajid and Bir El Maghara formations (Plate 1, Fig. F; Plate 2, Fig. F) except for some horizons characterized by poor porosity (4-7 %).

The presence of aggrading neomorphism in an advanced stage with adequate reflux of Ca-bearing solutions may offer porous rock horizons by increasing the crystal size from the micrite into microspar and, therefore, replacing the matrix porosity by intercrystalline porosity and the subcapillary channels by capillary channels, i.e. enhancing the storage capacity properties, which are not the case of the present rocks. Aggrading neomorphism is represented only in very narrow zones in the middle parts of Masajid Formation (Plate 2, Fig. D) which was deposited mainly in a relatively open shelf conditions.

The lime-muddy nature of the present marine rocks, their low to very low storage capacity (less than 2-3 % for most samples), their hardness and the bright colour for Masajid Formation, offer a good recommendation about the use of these sequences as blocks for building purposes and as stone sheets for ornamentation purposes. It is also recommended to conduct a further scientific study for their uses in the building purposes.

On the other hand, the diagenetic history, the tectonic impacts and uplifting of the Gebel El Maghara sequences, give a prediction about the petrophysical properties and storage capacity of the other alternated continental formations, Mashaba, Shusha and Safa formations. They are expected to have good storage capacity, where the continental sequences have in general a good primary intergranular porosity, and in presence of weak diagenetic processes, it may be preserved giving rise to units with good storage capacity properties.

CONCLUSIONS

From the present microfacies and diagenetic studies, it is achieved that;

1) Rajabiah Formation is composed mainly of ferruginous calcareous quartz arenite (clastic microfacies) at its lower parts and mudstone microfacies (SMF 23) at the other parts, Bir El Maghara samples are composed also of mudstone microfacies (SMF 23), whereas Masajid samples are composed of foraminiferal and molluscan mudstone microfacies (SMF 19), oolitic grainstone microfacies (SMF 16) and foraminiferal and algal sparitic mudstone microfacies (SMF 19 & 21).

2) The 2-D description of pore spaces indicated that, they could be described as matrix porosity with few channel and vug porosity, filled later by microsparite and obliterated by silica cement. The intergranular porosity was restricted only to the lower parts of Rajabiah Formation. These rock samples were deposited in restricted platform conditions (Fz. 8) with some sea transgression during the deposition of the middle parts of Masajid Formation giving rise to deposition in shelf lagoon zone (Fz. 7).

3) The carbonate content of the studied rocks reduced the tectonic impacts in the micro scale, where the main compaction effect could be presented through the clastic microfacies in the lower parts of Rajabiah Formation. Cementation by microsparite and later by silica is the main porosity dishancing factor through most samples, whereas dissolution and leaching out is the sole porosity enhancing factor at the lower parts of the section.

4) From the petrophysical studies, the bulk density is directly proportional to the porosity values, whereas the formation resistivity factors at 10 and 50 kppm are inversely proportional to the porosity values. Permeability values are also directly proportional to the pore channel diameter and porosity, and inversely proportional to the irreducible water saturation.

5) The Electric tortuosity is directly proportional to the apparent electric resistivity, whereas tracing the mounce potential indicates a normal electric passage for most of the studied rocks with some lime-mud effect for the Masajid samples.

6) The studied rocks have poor storage capacity properties except for the lower parts of Rajabiah Formation. So, it is recommended to study the Jurassic marine rocks in Gebel El Maghara area for building and ornamentation purposes.

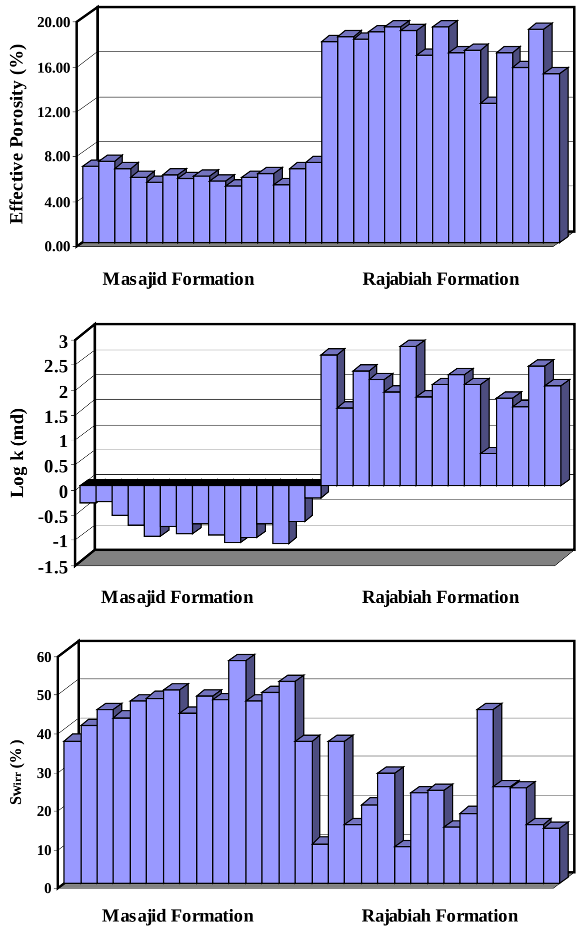


Fig. 13: Main storage capacity properties of the samples selected from Masajid Formation and the lower parts of Rajabiah Formation.

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