Egyptian Geophysical Society
EGS Journal, Vol. 13, No. 1, 153-161 (2015)

EFFECT OF THE MINERALOGICAL COMPOSITION ON THE PETROPHYSICS AND RESERVOIR ROCK QUALITY OF ABU MADI FORMATION IN BALTIM GAS FIELDS, NILE DELTA, EGYPT

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تأثير التركيب المعدني على بتروفيزيائية وجودة صخور الخزان في تكوين أبو ماضى فى حقول الغاز بلطيم، دلتا النيل، مصر

الخلاصة: خلال العقد الأخير تم حفر العديد من الآبار التى إخترقت صخور الخزان داخل تكوين أبو ماضى فى منطقه حقول بلطيم. وأظهرت بيانات الإنتاج والتسجيلات الكهربائية فى منطقه بلطيم وجود كميات معتبره من الغاز لم تستخرج بعد من خزانات هذا التكوين. يتألف تكوين أبو ماضى فى منطقه حقول بلطيم من الحجر الرملى الناتج عن الترسبات النهريه فى الوديان القطعية. مكونات هذا الترسبات فى هذا الوادى بالأساس عبارة عن حجر رملى مع مزيج من المعادن الأخرى. تتكون هذه المصفوفة من الحجر الرملى من كميات متنوعة من الكوارتز، الفلسبار والمعادن الطينية وشظايا الصخور، والتى تعرضت لتاريخ نشأة متأخرة معقدة وأثرت على خصائص المكامن الحالية. بالتالى، التغاير في خصائص البتروفيزيائية تعتبر ذات أهميه كبيرة فى قضيه جوده صخور الخزان والإنتاج. تقدم هذه الدراسة نتائج تحليل النشأة المتأخرة في إطار مقيد بالسحنات الترسيبيه يهدف إلى فهم تأثير المعادن وعمليات النشأة المتأخرة على تطور نوعية الخزان .تم جمع ثلاثين عينه صخريه إسطوانيه تنتمى لمستويات الخزان داخل تكوين أبو ماضى من ثمانية آبار لإجراء التحاليل الصخرية، ودراسة تأثير التركيب المعدني على نوعية صخور الخزان فى هذه الدراسة. وقد تم تحديد أربعة أحداث نشأة متأخرة رئيسية وقعت خلال الدفن وهى: الطلاء الطينى حول الحبوب – ضغط / ذوبان الحبوب المصفوفة؛ و تحلل الكوارتز و الفلسبار و الملاط الكلسى فى المسام المتبقية. ويعد المحتوى من معادن الطين و الملاط الكلسى من العوامل الرئيسية التي تغير نوعية الخزان فى هذه الأحجار الرملية وتتناسب كفاءه الخزان مع وجود ملاط الحديد الكلسى بينما ترتبط قيمه المسامية عكسياً مع محتوى الملاط ووجود الفلسبار خصوصاً عندما يكون متغيراً ومتحللاً حيث يؤدى إلى زيادة قيم المسامية عن طريق خلق المسامية الثانوية (المسامية الصغيرة). ويعطى توصيف المعادن و الخواص البتروفيزيائية مفاتيح مفيدة لتحديد مراحل النشأة المتأخرة أفقياً و عمودياً، و التنبؤ بتوزيع الخصائص البتروفيزيائية للخزان الجوفى.

ABSTRACT: *Upper Messinian Abu Madi Formation in Baltim Fields has been penetrated by wells targeting reservoirs levels during the last decade. Production and well log data in this area suggest that significant volumes of gas are still present in reservoirs levels of this formation.*

Upper Messinian Abu Madi Formation in Baltim Fields consists of fluvial sandstones filling incised valleys. The valley infills are made up of sandstones with a complex mineralogy. The matrix of these sandstones is made up of various amounts of quartz, feldspars, clay minerals and rock fragments. They were subjected to a complex diagenetic history and the resulting paragenesis influenced the present reservoir properties. Consequently, heterogeneities in the petrophysical properties result in significant reservoir rock quality and production issue.

This study represented the results of a diagenetic analysis, performed within a well constrained sedimentological facies that aims at understanding the impact of mineralogy and diagenesis on reservoir quality evolution.

Thirty core samples from eight wells were collected to perform a petrographic analysis, and to propose an effect of mineralogical composition on petrophysical reservoir rock quality.

Four main diagenetic events were identified that occurred during burial through petrographic analysis, namely clay coating around the grains, compaction/dissolution of matrix grains, quartz and feldspars dissolution, and carbonate cementation in the remaining pore space.

Clay minerals (in shape of ferroan chlorite) content and carbonate cementation are the main factors that control the reservoir quality of these sandstones.

The reservoir quality is influenced by the presence of ferroan calcite cementation, while high porosity value is associated with low cementation content and vice versa.

Presence of feldspars, especially when it's highly altreated and desolated, leads to increasing porosity values by creating secondary porosity (microporosity). The characterization of both mineralogy and petrophysical properties gives useful keys to locate the diagenetic phases laterally and vertically, and to predict the petrophysical properties distribution in the subsurface reservoir.

INTRODUCTION

Baltim Concession is a large exploration license located in the offshore Nile Delta, Egypt. The concession covers 430 km^2 of the central portion of the present day Nile delta cone (Figure 1).

The reservoirs of Baltim East and Baltim North fields belong to the Upper Messinian Abu Madi

Formation and are characterized by medium-coarse grained fluvio-deltaic sandstones (Dolson, 2000).

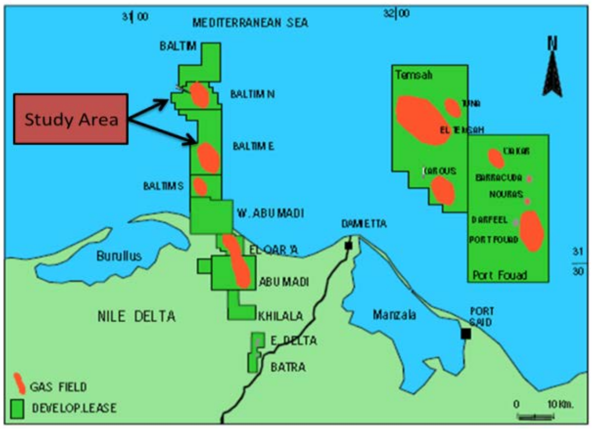

Figure (1): Location map of Baltim Fields.

Abu Madi Formation is the sedimentary infilling of a fluvial paleovalley (Kamal, 1998) developing from south to north for about 130 km and from east to west for about 30 km. Baltim North Field represents the northern portion of the Paleovalley. In this study; nine wells located in Baltim fields have been used (Figure 2).

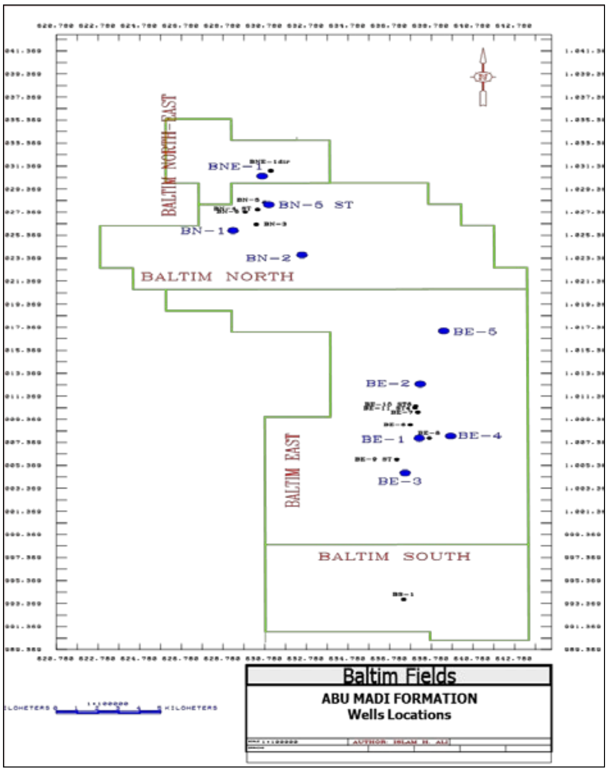

Figure (2): Studied wells in Baltim Fields.

Stratigraphic correlations between these wells allow identifying two reservoir levels within Abu Madi Formation. These levels are: Level III Main and Level III Lower (Figure 3).

In Baltim fields, only Levels III Lower & III Main are gas bearing in Abu Madi Formation (Fornaciari, 1994). The two reservoir levels are separated from each other in both Baltim East and Baltim North fields (ENI, 1999).

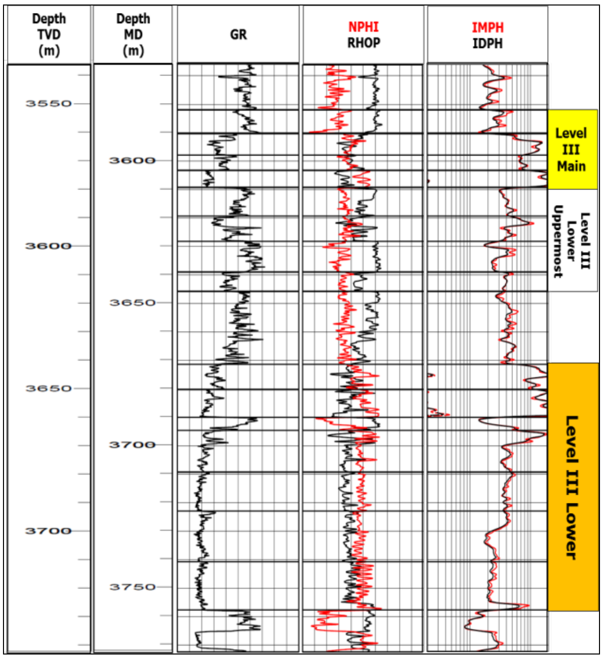

Figure (3): Reservoir subdivision of Abu Madi Formation in Baltim fields.

Sedimentological facies analysis carried out on cores drilled in Baltim East and Baltim North gas fields allowed identifying 5 Facies Group (Fonnesu,1994); related to a fluvio-deltaic depositional setting in Abu Madi Formation (Figure 4):

1- Facies-1: Pebbly sandstones (Facies 1a) to massive coarse to medium grained sandstones (Facies 1b)
2- Facies-2: Tabular trough cross bedded and parallel laminated medium sandstones with abundance of carbonaceous fragments (Facies 2a) and some granules along the laminae (Facies 2b).
3- Facies-3: Rippled fine grained sandstones due to low energy currents occurring in the channels.
4- Facies-4: Alternances of shales/silty shales and fine grained rippled sandstones.
5- Facies-5: Laminated siltstones with poor sandstone intercalations.

The samples have been classified according to the two reservoir levels (Level III Lower and Level III Main) and the sedimentological facies associations, the results have been treated and elaborated by reservoir levels.

1- **Petrographic analysis:** This analysis results from the synthesis of data obtained from different analytical approaches (Descalzi, 1988) and is aimed to the definition of the petrographic and pore network variables that influence the reservoir efficiency. The identification of such variables allows to highlight trends and to predict reservoir quality. The samples have been classified according to the reservoir level (Level III Lower and Level III Main) and the sedimentological facies associations. The results have been treated and elaborated by reservoir levels.

2- **Petrographic analysis of Level III Lower:** This level was cored and sampled in wells BE-1, BE-5, BN-1 and BNE-1, distributed along the cored wells. Figure 5 shows samples locations in BE-1 and BE-5 which have been used in the petrographic analysis of this reservoir level.

Facies		Description
Facies 1	a	Pebbly to coarse sandstone with clay chips and carbonaceous fragments.
	b	Massive coarse to medium grained sandstone.
Facies 2	a	Coarse to medium sandstone with large cross-bedding.
	b	Coarse to medium parallel sandstone with carbonaceous fragments along laminae.
Facies 3		Medium to fine sandstone with tractive current ripples.
Facies 4		Medium grained rippled and cross bedded sandstone.
		Medium sandstone and shale.
Facies 5		Laminated siltstones with sand intercalations.

Figure (4): Sedimentological Facies Group.

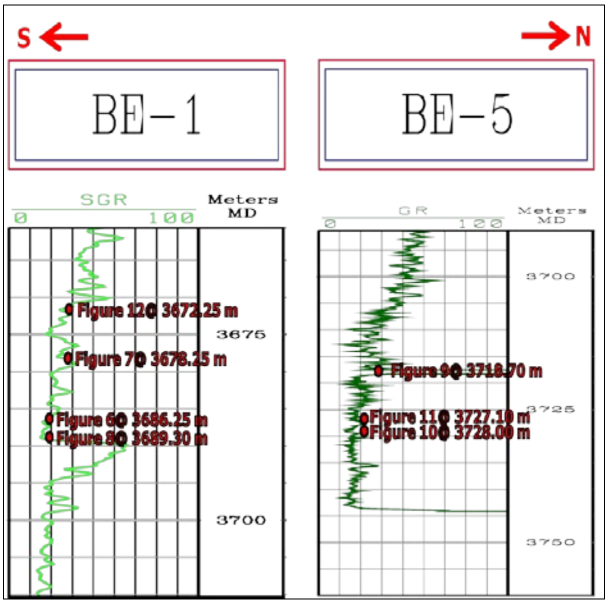

Figure (5): Samples location in BE-1 and BE-5, Level III Lower.

All sandy facies are represented; namely facies 1a, 1b, 2a, 2b and facies 3. The textural characteristics of these deposits are as the following: The mean grain size is from upper fine to upper medium, the degree of sorting is low to moderate, the degree of roundness is from very high to high, the texture is grain supported and the packing is from very low to low and the degree of coherence is moderate. Considering the relative abundance of grain, authigenic minerals and detrital matrix, the amount of the authigenic minerals ranges from 0 to 25% in all the facies while the detrital matrix is always absent. This level is characterized by the lowest percentage of authigenic minerals with respect the other levels of Abu Madi Formation (Figure 6).

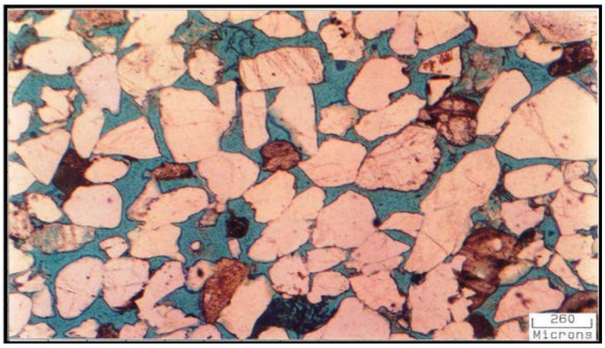

Figure (6): Abundance of Grains, Level III Lower (BE-1 well, 3686.25 m).

The detrital assemblage is dominated by mechanically and chemically stable components (i.e. quartz grains) while the mechanically stable and chemically unstable components (i.e. feldspars, micas, carbonate lithic fragments, pyroxenes, etc.) range from 15 to 30% and mechanically unstable and chemically stable to unstable components (i.e. deformable lithic fragments) range from 5 to 20%.Rock characterization summaryis a mathematical calculation of petrographic analysis results which reflect numerical analysis of reservoir rock components. Table (1) represents the rock characterization summary of Level III Lower for core of BE-1 well, where the cored interval is dominated by quartz grains (53%) and the authigenic minerals range from 10-15 %. In particular feldspars, chert and composite quartz are in moderate amount, the lithic carbonate, both spathic and micritic, are in modest percentage, while other lithic, such as intrusive, metamorphic and clastic, glaucony and biotite flakes are very rare.

As a general rule, Level III Lower is characterized by a little abundance of the mechanically stable and chemically stable components (i.e. quartz); the dissolution and alteration phenomena have slightly modified the composition chiefly affecting the mechanically stable and chemically unstable grains (Figure 7).

The most important authigenic minerals are microporous ferroan calcite, fairly present chiefly as pore lining and scarcely as pore filling and neomorphosing. Kaolinite represents the other phyllosilicate authigenesis and is very modestly distributed as neomorphosing. The quartz overgrowths are small and very rare and with partly occlusive feature. Also a modest amount of carbonate cement as occlusive plagues is recorded and in a sample coalescent occlusive carbonate reaches very high proportion (about 40%).

Table (1): Rock characterization summary for Level III Lower from core of BE-1 well.

ROCK CHARACTERIZATION SUMMARY

WELL NAME	BE-1
FORMATION	Abu Madi Formation
ZONE / INTERVAL	Level III LOWER / (3671 - 3757.5 m)
CORE INTERVAL	3665 - 3692 m
DEPTH SHIFT	(+9)

1 - PETROGRAPHIC CHARACTRISTIC :

ROCK NAME	CALCITIC SUBLITHIC ARENITE	%
DETRITAL GRAINS	QUARTZ	53.0%
	FELDSPAR	4.5%
	DETRITAL CLAYS	4.5%
	BIOCLASTS	4.2%
	LITHIC	6.8%
	OTHERS	3.0%
AUTHIGENIC MINERALS	FERROAN CALCITE	12.7%
	Qz OVERGROWTH	0.8%
	KAOLINITE	1.0%
	CHLORITE	0.7%

DETRITAL GRAINS	76%
AUTHIGENIC MINERALS	10 - 15%
POROSITY RANG	9 - 14%

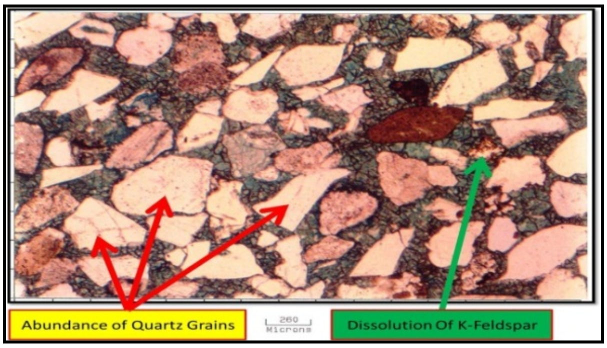

Figure (7): Dissolution of K-Feldspar, Level III Lower (BE-1 well, 3678.25 m).

The pore network is characterized by primary preserved pores, with microporosity mainly present in altered lithic grains and in ferroan chlorite and kaolinite aggregates. Secondary pores, linked to dissolution of unstable grains, are present but normally partly filled by remnants of the parent grain ("dirty" secondary pores).Facies groups in Level III Lower are variable; the largest pores and highest image analysis porosity are represented in facies 1b and facies 2b, Figure 8 and Figure 9.

Figure 10 and Figure 11 represent facies 1a and facies 2a which are showing large pores but lower porosity.

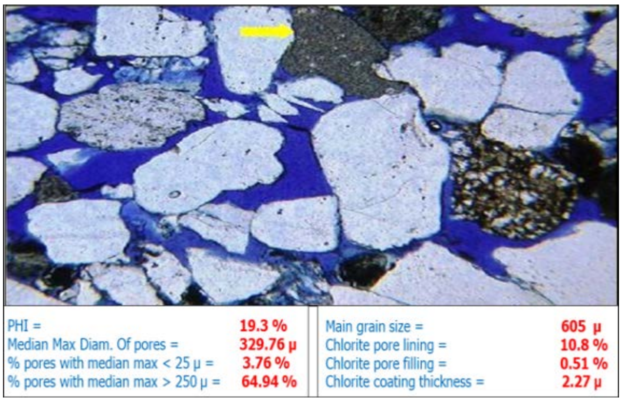

Figure (8): Facies 1b with large pores and high porosity, Level III Lower (BE-1 well, 3689.3 m): thin chlorite coating, almost unconsolidated, minor amounts of microporosity linked to the partly altered argillaceous lithic fragments (yellow arrow).

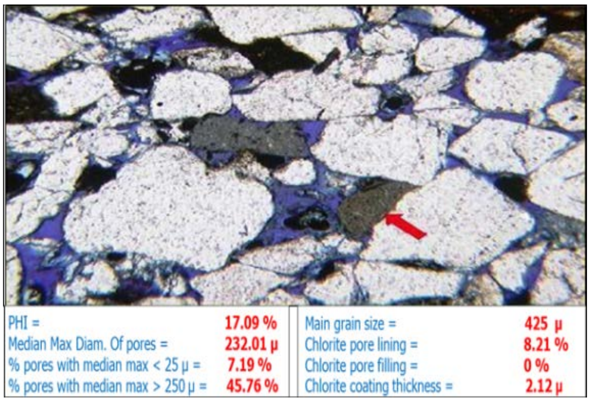

Figure (9): Facies 2b with large pores and high porosity, Level III Lower (BE-5 well, 3718.7 m): thin chlorite coating, consolidated, poorly sorted; Microporosity is moderately, micritic lithic fragments (red arrow) might contribute to microporosity.

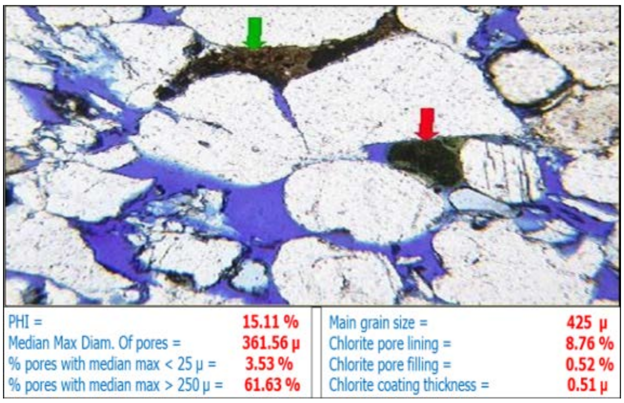

Figure (10): Facies 1a with large pores and Low porosity, Level III Lower (BE-5 well, 3728.00 m): very thin chlorite coating, mechanical compaction (squeezed argillaceous lithic fragments – green arrow), minor amounts of microporosity linked probably to altered glaucony (red arrow).

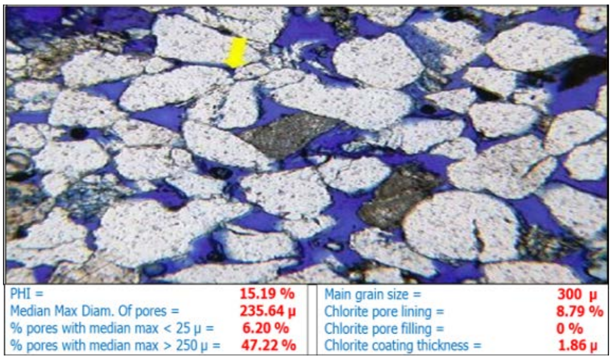

Figure (11): Facies 2a with large pores and Low porosity, Level III Lower (BE-5 well, 3727.10 m): thin chlorite coating, moderate amount of microporosity due to the lithic argillaceous fragments and to the primary reduced porosity (yellow arrow).

Whereas facies 3, Figure 12; with the smallest pores and lowest porosity represent the worst facies belong to Level III Lower.

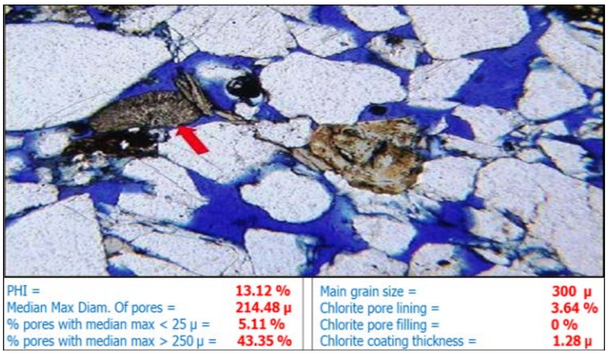

Figure (12): Facies 3 with small pores and Low porosity, Level III Lower (BE-1 well, 3672.25 m): thin chlorite coating, high amount in argillaceous lithic clasts(red arrow).

From these thin sections analysis, the pore dimension distribution shows that; the amount of micropores (< 25 micron) is always low, below 20%, apart from few samples, where it reaches around 25%.In general, the amount of microporosity increases from Facies-1 to the one of Facies-3. The ferroan chlorite coating thickness is variable, and ranges from 0.51 to 2.27 microns, and is, in many cases, relatively thin with respect to grain size.

From this detailed petrographic analysis of Level III Lower, Figure 13 represented the facies change in the two studied wells BE-1 and BE-5.

3- **Petrographic analysis of Level III Main:** Thin section samples related to Level III Main come from the cores of wells BE-1, BE-2, BE-3, BE-4, BE-5, BN-2, BN-5 (ST-1) and BNE-1. The cored sampled facies are: 1a, 1b, 2a, 2b and 3. Figure 13 represented samples locations in BN-5 ST-1, BN-2, BE-3 and BE-4 wells which have been used in this petrographic analysis of this reservoir level.

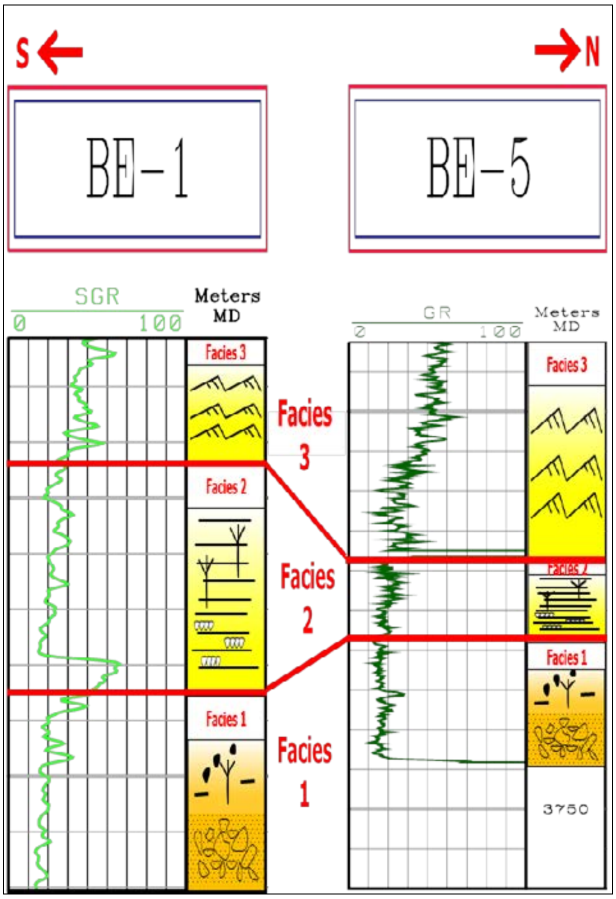

Figure (13): Facies change, Level III Lower.

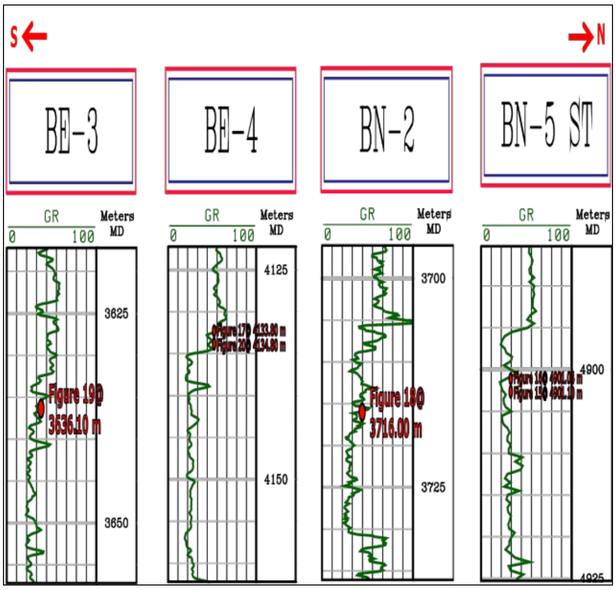

Figure (14): Samples location in BN-5 ST-1, BN-2, BE-3 and BE-4 wells; Level III Main.

From the mineralogical analysis of these thin sections the authigenic minerals amount in all the facies groups ranges from 5 to 40%. Considering the mean values, this level exhibits intermediate amounts of authigenic minerals in comparison with the other level. The mechanically stable and chemically unstable components (i.e. feldspars, micas, carbonate lithic fragments, pyroxenes, etc.) vary from 15 to 40% and of the mechanically unstable and chemically stable to unstable grains (i.e. deformable lithic fragments) from 0 to 25%.

Rock characterization summary of this Level III Main derived from core of BN-5 ST-1 well; where the rock name is: Subfeldspathic Arenite which reflects the high amount of quartz grains and the abundant amount of feldspars. The detrital grains percent reaches about 81% where the authigenic minerals percent ranges between 10-17 % (Table 2).

Table (2): Rock characterization summary for Level III Main from core of BN-5 ST-1 well.

ROCK CHARACTERIZATION SUMMARY

WELL NAME	BN-5(ST-1)
FORMATION	Abu Madi Formation
ZONE / INTERVAL	Level III Main / (4895.3 - 4925 m)
CORE INTERVAL	4898.00 - 4933.57 m
DEPTH SHIFT	(+ 6)

1 - PETROGRAPHIC CHARACTRISTIC :

ROCK NAME	SUBFELDSPATHIC ARENITE	%
DETRITAL GRAINS	QUARTZ	50%
	FELDSPAR	7%
	GLAUCONY	6%
	BIOCLASTS	3%
	LITHIC	3%
	OTHERS	12%
AUTHIGENIC MINERALS	FERROAN CALCITE	5.6%
	Qz OVERGROWTH	0.5%
	PYRITE	1.3%
	CHLORITE	1.3%
	CALCITE	1.5%
	SIDRITE AND KAOLINITE	2.0%
	DETRITAL GRAINS	81%
	AUTHIGENIC MINERALS	10 - 17%
	POROSITY RANG	2 - 9%

The unstable components are: feldspars in fair quantity; chert and composite quartz moderately present; carbonate both spathic and micritic, and argillaceous lithic fragments have modest percentages and glaucony is scarce. The other components, such as intrusive, metamorphic and clastic lithic grains, are very rare. In general; the deposits of this level have more mechanically stable and chemically unstable grains than the other level.

The dissolution and alteration phenomena acted moderately changing the original composition; as in the other level, chiefly the mechanically stable and chemically unstable grains have been involved.

The presence of feldspars promotes the presence of relatively high (SWi), especially when it's highly altreated and desolated, and leads to increasing porosity values by presence of secondary porosity (Figure 15).

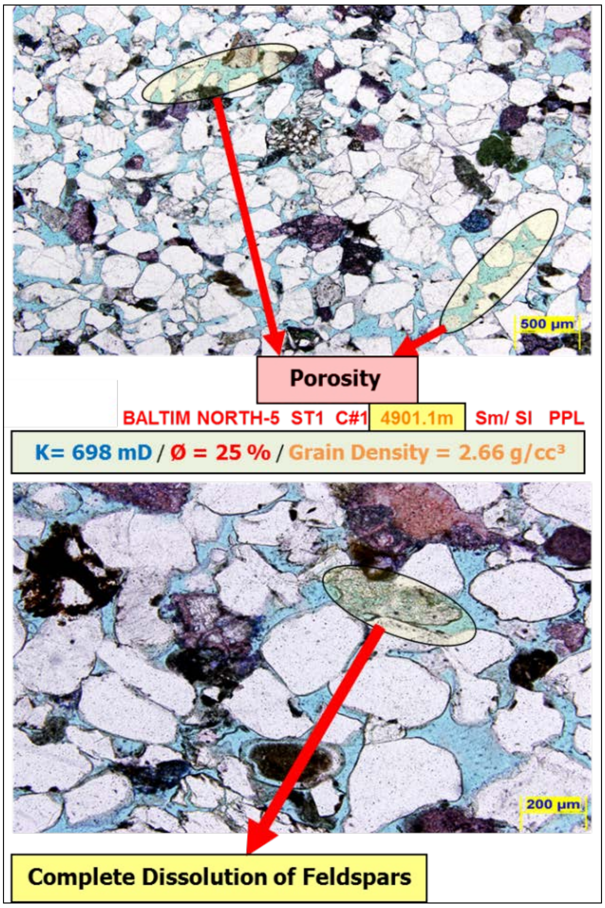

Figure (15): Photomicrograph showing the dissolution of Feldspars leads to high porosity in Level III Main (BN-5 ST-1 well, 4901.1 m).

Ferroan chlorite represents the most significant authigenic mineral, and it is present as pore lining and pore filling, the former more abundant than the latter. The neomorphosing texture is just scarcely present. The other authigenic phyllosilicate, kaolinite, is very scarce; considering the abundance of ferroan chlorite, the dominant feature is microporous. The quartz overgrowth is very rare and with partly occlusive feature; while the carbonate cement amount ranges from rare to modest with both occlusive and partly occlusive features. The distribution of porosity and pore diameter is almost continuous from very low to relatively high values. High porosity values are associated with little amount of cementation and vice versa (Figure 16).

The best facies within Level III Main are belonging to facies 1b and facies 2a, with more than 20% porosity and more than 250 microns pore diameter. Samples belonging to facies 2a, 2b and 1b are spread in the intermediate region between 10 and 20% porosity and 100 to 250 micron of pore diameter. Whereas all facies 3 samples are below 10% porosity and 100 micron pore diameter.

The best and intermediate samples are characterized by primary pores well preserved by ferroan chlorite coatings, regardless of facies (Figure 17).

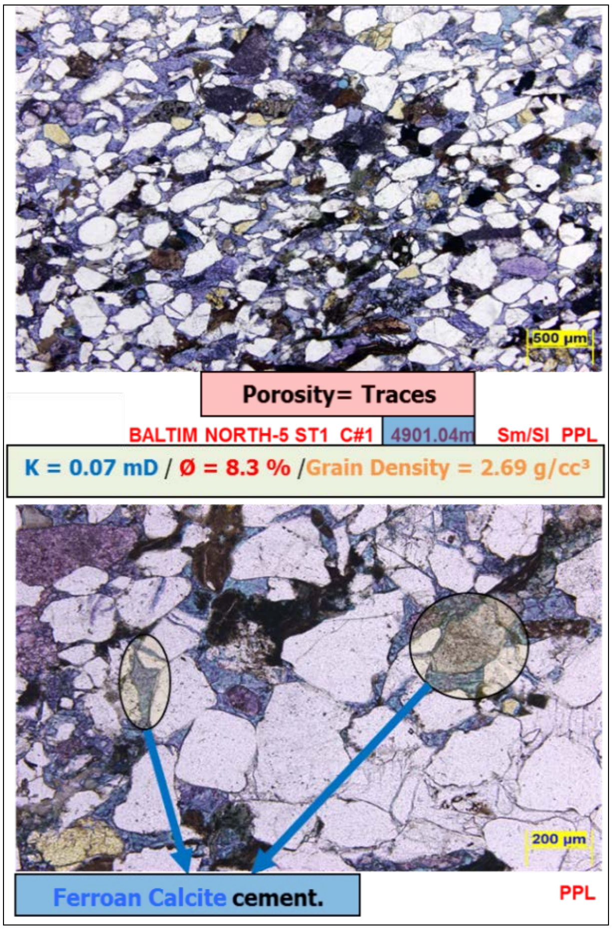

Figure (16): Presence of highly cementation amount (Ferroan Calcite), Level III Main (BN-5 ST-1 well, 4901.04 m).

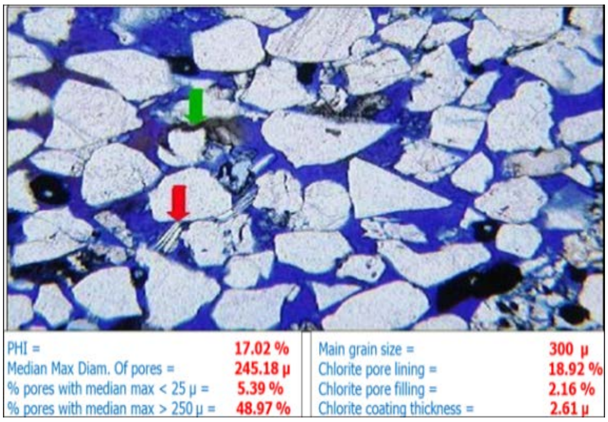

Figure (17): Primary pores well preserved by Ferroan Chlorite Coatings, facies 2b, Level III Main (BE-4 well, 4133.8 m):relatively thin chlorite coating, mechanical compaction are recorded by white mica flakes fracturing (red arrow) and by argillaceous lithic grains squeezing (green arrow).

The low pore size implies a reduction in porosity and efficiency, and an increase in the amount of microporosity; both primary and secondary (Figure 18).

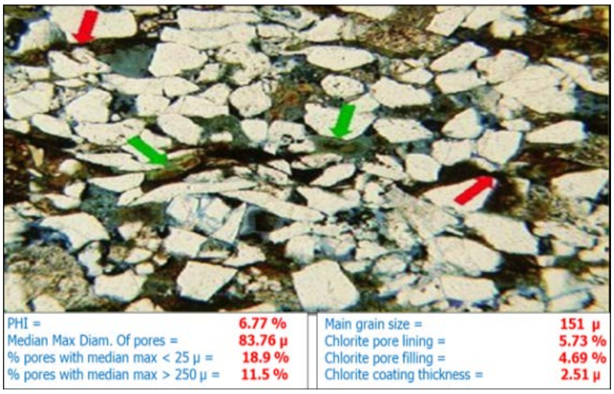

Figure (18): Increase in the amount of micro porosity, facies 2a, Level III Main (BN-2 well, 3716.00 m): relatively thin chlorite coating, abundant argillaceous lithic grains (red arrows) and glauconite (green arrows).

In the finer-grained sediments, microporosity accounts for 80% of the total, with a very low median pore size and a very limited efficiency (Figure 19).

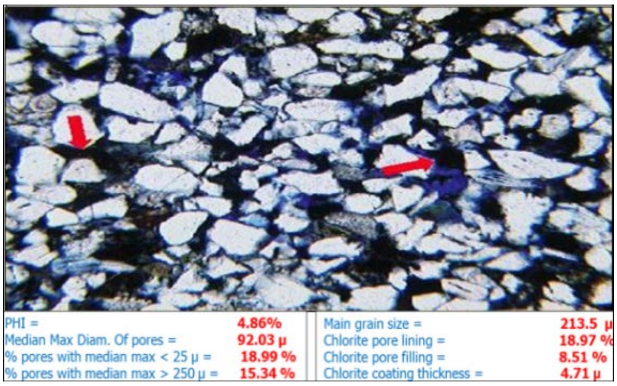

Figure (19): Facies 3, Level III Main (BE-3 well, 3636.10 m): thick chlorite coating,abundant altered clasts as dark clots (red arrows) and porosity reduced by compaction.

In the sample of facies 1a, the pore space is completely filled by a recrystallized argillaceous matrix, Figure 20; with a limited microporosity.

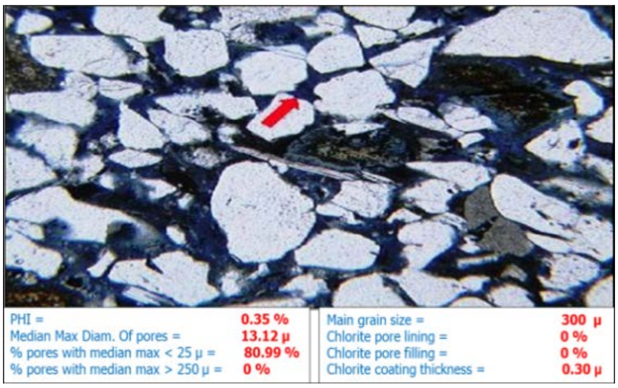

Figure (20): Facies 1a, Level III Main (BE-4 well, 4134.80 m): primary pore space is filled by a highly microporous reorganised orthomatrix, of chloritic composition (red arrows).

Petrographic analysis of thin sections samples related to Level III Main clarify that most of samples lie below 30% of microporosity (i.e. pores below 25 microns), with a strong concentration in the 30 to 10% region. The thickness of ferroan chlorite coatings is around 2.5 microns in the intermediate quality facies, rising to 3-4 microns in the fine-grained one. This implies preservation of good connectivity in the coarser-grained sediments, with a sharp decrease moving toward the finer-grained ones.

Facies change in the studied wells for Level III Main is shown in Figure 21.

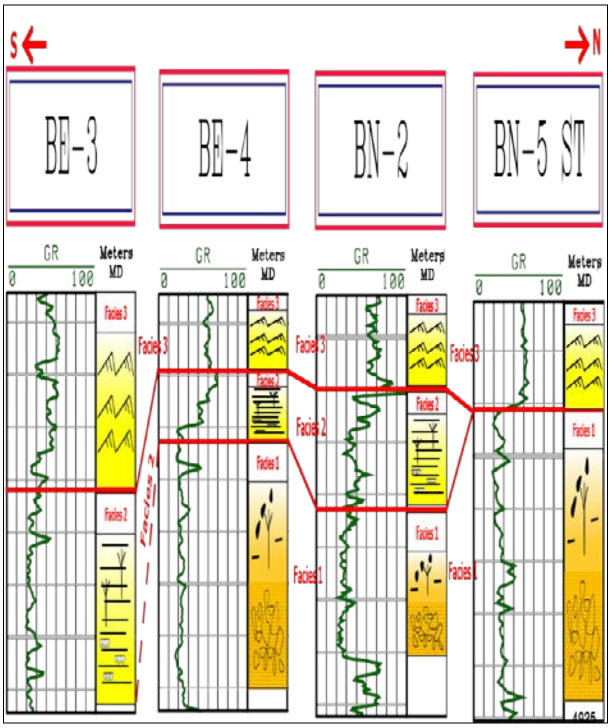

Figure (21): Facies change, Level III Main.

- **Reservoir Quality:** From petrographic analysis of these two reservoir levels within Abu Madi Formation; Level III Lower being the one with the coarsest grain size and the poorest degree of sorting, presents the lowest ferroan chlorite content (average = 12 %) and the thinnest coatings (average = 1.6 micron). Whereas Level III Main is the one with fine grained and good degree of sorting, and presents high ferroan chlorite content (average = 22%) and thicker chlorite coating more than Level III Lower (average = 2.5 micron). Rock characterization summary of both two reservoir levels (Table 1 and 2) show higher clay content in Level III Main (about 5%) than Level III Lower (about 2%).

The change in different facies within the two studied reservoir levels lead to obtain different petrophysical parameters with this change from high quality facies to worst facies (Figure 22).

As a result, the highest reservoir quality is present in Level III Lower, which is the one that presents in each facies the lowest content in total ferroan chlorite, argillaceous fragments and the thinnest ferroan chlorite coating. While Level III Main show a higher content in ferroan chlorite and thicker ferroan chlorite coatings. Ranking of facieswithin the two reservoir levels depends on porosity, Chlorite coating and micropores (Table 3):

The reservoir rock quality for both two reservoir levels (III Main and III Lower) increase towards the south (Figure 23).

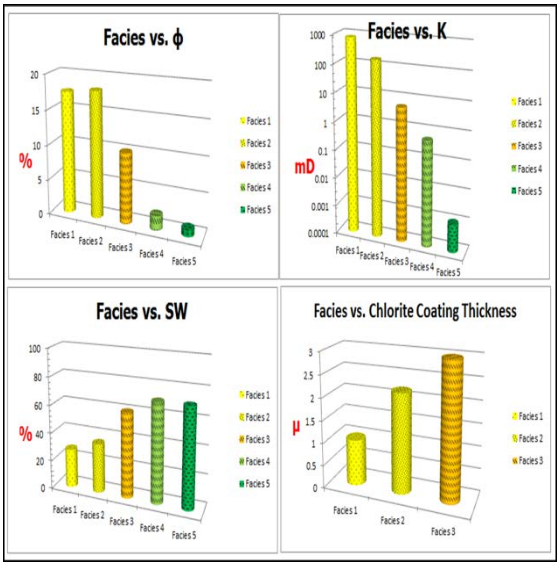

Figure (22): Facies vs. petrophysical parameters.

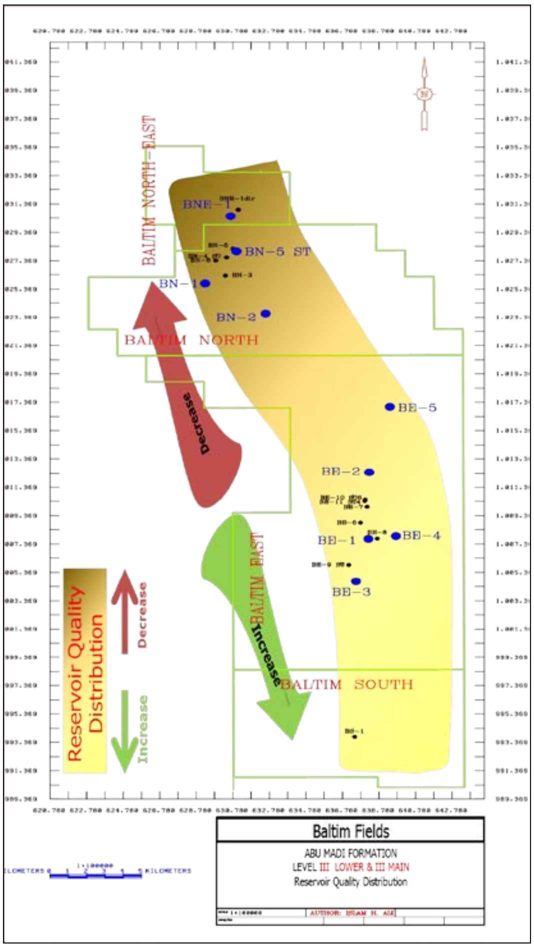

Figure (23): Reservoir quality distribution.

Table (3): Facies ranking within Level III Lower and Level III Main.

Level	Facies	Porosity (%)	Chlorite Coating (μ)	Micropores (< 25 μ)
III Lower	1a	15.11	0.51	3.53
	1b	19.3	2.27	3.76
	2a	15.19	1.86	6.2
	2b	17.09	2.12	7.19
	3	13.12	1.28	5.11
III Main	2b	17.02	2.61	5.39
	2a	6.77	2.51	18.9
	3	4.86	4.71	18.99
	1a	0.35	0.3	80.99

CONCLUSION

Reservoir rocks quality is a function of petrophysical properties which are controlled by mineralogical composition of the reservoir rocks as follows:

- Cementation material (represented by ferroan calcite) is inversely proportional to the porosity value.
- High amount of feldspar indicates the immaturity of the reservoir rocks and leads to filling of the pores hence reducing the permeability controlled by but it creates a more porosity represented by (micro porosity).
- Permeability and pore network are controlled by the amount of chlorite in a reverse direction.
- Best facies of both the two reservoir levels (Level III Lower and Level III Main) are accompanied with little abundance of cement and matrix complex.

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