 Egypt. J. Geo. **Vol. 68,** pp: 199-218 (2024)

Egyptian Journal of Geology

https://egjg.journals.ekb.eg

Rock Types and Sedimentary Microfacies of the Nubian Reservoir, Gulf of Suez, Egypt

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The present work introduce a trial to delineate the reservoir rock types (RRTs) and also determining the effect of sedimentary microfacies in the Nubian reservoir quality of the Saqqara field, southern Gulf of Suez region, Egypt. Where it is considered a way to develop and enhance the oil potentiality of this field. Therefore, petrographical investigation and evaluating petrophysical core parameters of studied samples have been utilized. The petropgraphical core investigation reveals that illite, kaolinite, pyrite and patchy dolomite are the main authigenic constituents, while the components of relatively less common is the euhedral syntaxial quartz. Furthermore, analysis of the reservoir samples by using Scanning Electron Microscope (SEM) reflecting that the dominant framework grains are detrital clays, feldspars and quartz minerals. The studied Nubian reservoirr could be subdivided into two RRTs. The best reservoir quality is represented by the rock type RRT1, which has the following characteristics; flow zone indicator (FZI) varies from tight to very good (3.2 - 10.5 µm), reservoir quality index (RQI) ranges from tight to good (0.69–1.98 µm), poor to very good porosity (7.3 -19.0 %), and horizontal permeability detected from fair to excellent (2.0 md - 2719 md). Though it is made up of quartz wackes microfacies. The reservoir rock type 2 (RRT2) characterized by tight to good FZI (0.65 - 6.10 µm), tight to good RQI (0.02 -0.86 µm), the horizontal permeability ranged from 0.0 - 570.0 md and the porosity reach to 17 %. Petrophysical reservoir parameter results indicate relatively good reservoir parameters and good thickness of oil potentiality for RRT1rather than RRT2 types. The abundance of detrital clays like patchy siderite and kaolinite minerals, is a major factor in reducing point porosity.

Keywords: Well logging analysis, core analysis, Nubian reservoir, reservoir rock types (RRT), sedimentary microfacies, southern Gulf of Suez.

1. Introduction

The Gulf of Suez is regarded as one of Egypt's most significant oil-producing regions. Where its area, length, average width, average water depth are 25,000 km², 320 km, 70 km, 77 m respectively. The tectonic setting of the Gulf of Suez that initiated during Oligocene –Miocene age is reflected many structural features such as; stratigraphic and structural traps and numerous fault blocks within the sedimentary basin. It could be differentiated into northern, central, southern intra-provinces based on structural configuration and regional dip directions. The northern and southern accommodation zones (also known as hinge zones) set these provinces apart from one another. The litho-stratigraphic sediments of the Gulf of Suez can be distinguished into three major sequences which range from the Precambrian to the Pleistocene age. The following is a description of these sequences, arranged from younger to older: There are three types of rift sequences: 1) post-rift, which includes sediments from the post-Miocene to the Holocene; 2) syn-rift (Oligocene - late Miocene age); then 3) the pre-rift, which includes sediments from the entire pre-Miocene age range, these sequences are represented by significant variation in the thickness, lithology, depositional environment and hydrocarbon potentiality (Robson, 1971; Schlumberger, 1984; Meshref, 1992; Darwish, El Araby, 1993; Alsharhan and Salah, 1994;Young et al., 2000, Bosworth and McClay, 2001; Younes, and

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Received: 08/06/2024; Accepted: 17/07/2024
DOI: 10.21608/EGJG.2024.296111.1078

Mcclay., 2002; Aziz and Gomaa, 2022, Abu-Hashish and Afify, 2022).

The sedimentary succession of the the Gulf of Suez province represented the Primary reserves of nearly 60 oil fields (million barrels -1.350 million barrels). The Saqqara oil field (target of the study) is located about 7.5 kilometers south of the Ramadan oil field offshore in the Gulf of Suez's southern section. This studied oil field was started in 2003 and is regarded as one of the Gulf of Suez's largest hydrocarbons finds (Figure 1). The normal faults closures entrapments have a significant hydrocarbon potentiality. The primary reservoir of this field confined within the Nubian sandstone Formation, consists mostly of clastics sandstone and separated into main four clastics sandstone zones (A, B, C, & D) encountering 2200 feet thickness. With the exception of zone B which composed mainly of dark shale with barren fauna. The Nubian sandstone reservoir considered the main target for most oil potentiality the Gulf of Suez basin which reflects the most significant reservoir in this region (Khalil and Mesheref, (1988); Bosworth and McClay, 2001; Nabawy and El Sharawy (2018); Galal et al., (2021).

The current study focuses mainly on three main objectives: 1) analysis of the petrophysical parameters of the studied core samples that have been selected of the Nubian reservoir; 2) analyses of the core samples petrographically beside X-ray diffraction (XRD) in order to differentiate the authigenic and detrital constituents emphasing in the permeability and porosity and sedimentary microfacies .3) dividing the reservoir section into categories of reservoir rock types (RRTs) and hydraulic flow units (HFUs) following Amaefule et.al. (1993); then 4) analyze the quality characteristics of the examined reservoir and conduct an integration study between all petrophysical parameters to evaluate the quality of the Nubian reservoir.

2. Materials and Methods

The precent study is focused primarily on analysis and examining the conventional core samples of the GS323-2A well, which covers mostly the Nubian reservoir intervals of the studied saqqara field in the Gulf of Suez, Egypt. The current study focuses mainly on three main objectives: 1) analysis of the petrophysical properties of the studied core samples that have been selected of the Nubian reservoir; 2) analyses of the core samples petrographically beside X-ray diffraction (XRD) in order to differentiate the authigenic and detrital constituents emphasing in the permeability and porosity and sedimentary microfacies . 3) Dividing the reservoir section into reservoir rock types (RRTs) and hydraulic flow units (HFUs) in accordance with Amaefule, et.al., (1993). 4) Evaluating the Nubian reservoir quality by assessing the quality parameters of the examined reservoir and carrying out an integration study between all these parameters. The depositional and petrographical textures categories of the carbonate are rocks are based mainly on Folk, (1959 & 1962) and Dunham, (1962).

The fourteen samples of side wall core (SWC) were chosen and ready for examining from the Nubian sandstone reservoir. To get rid of any remaining hydrocarbon, water, or salt residue, the samples were first cleaned using a cold extraction solvent, and then they were cleaned again using methanol and chloroform. The plugs were kept in an oven set to 60 degrees Celsius and 40% humidity after cleaning was finished. They were well dried until they reached a stable weight. After taking them out of the oven, they were placed in desiccators to cool to room temperature. After that, the entire set of samples was measured in the lab for porosity and permeability. By using Scanning Electron Microscope(SEM), fourteen core samples (SWC) were examined petrographically which involving the geometry of pores, grains sorting, grains maturing, predominant minerals contents and occluding minerals content. The automated Helium pycnometer (Ultra-Pyc. 1200.0e - down to 0.0001 g/cm3) was introduced to measure the helium porosity at room temperature and 19 pressures. Darcy law can be used to calculate permeability, which is computed using Darcy law;

$$\text{Permeability (K)} = Q\mu L / A\Delta P \qquad (1)$$

Where;

A is the cross sectional area (1CM2) ,

($\Delta P / L$) is the pressure gradient (1 atm/cm2),

μ is the fluid viscosity (one centipoises),

Q is the rate of one centimeter per square,

K is the permeability.

The Levorsen (1967), Amaefule et al., (1993), Nabawy et al. (2009), Nabawy and Barakat, (2015), ; Nabawy and Géraud, (2016), Radwan et al., (2021) classifications are the basis for calculation of the permeability anisotropy (‘λk), permeability (K),

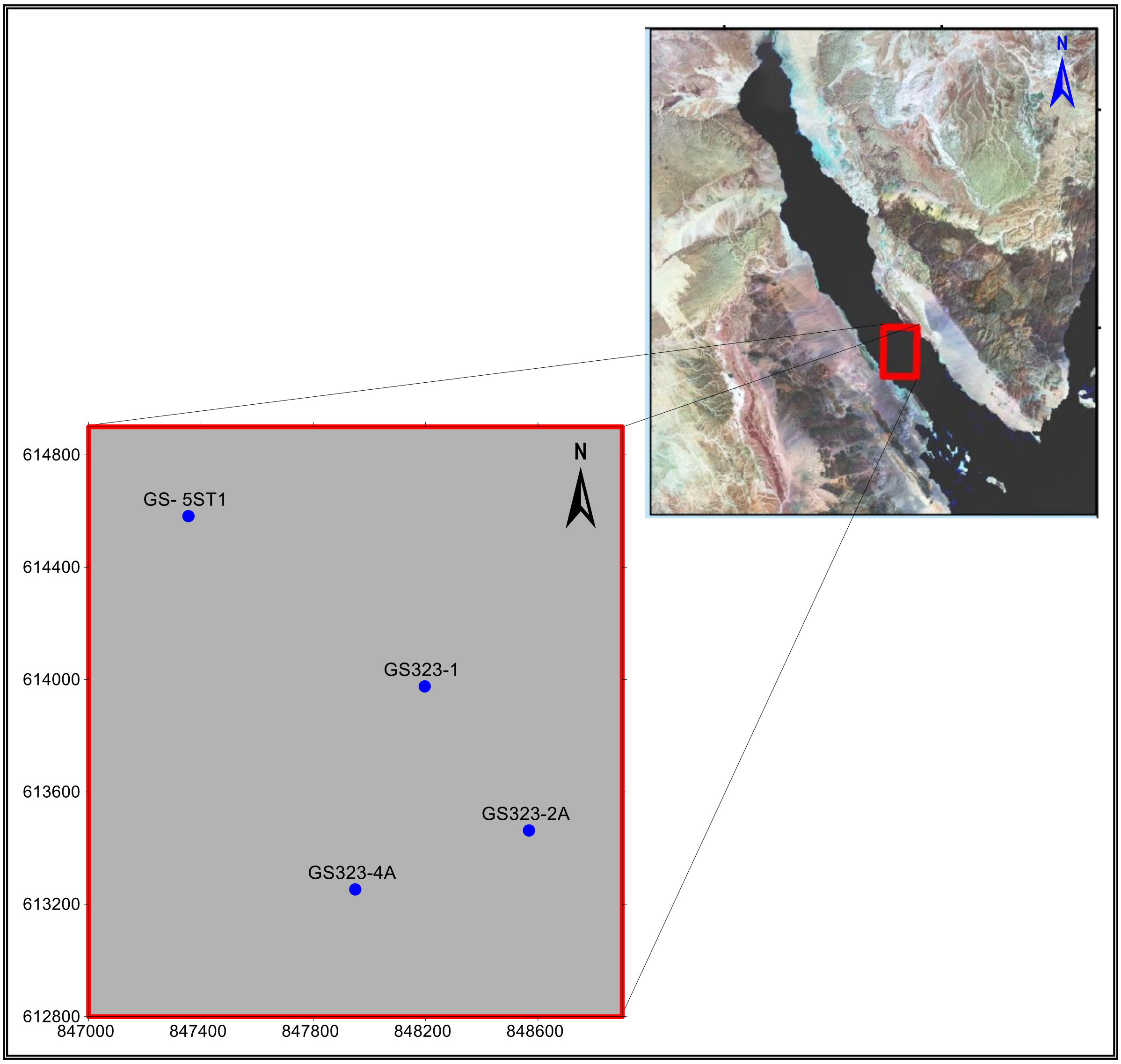


Fig. 1. Location map showing the studied wells of the Saqqara oil field, southern Gulf of Suez, Egypt.

porosity (∅He) and studied samples' ranking that including reservoir ranks, Normalized Porosity Index (NPI), Flow Zone Indicator (FZI), Reservoir Quality Index (RQI).

$$RQI = 0.0314\sqrt{\frac{k}{\emptyset}} \qquad (2)$$

$$FZI = \frac{RQI}{NPI} = \frac{0.0314\sqrt{k/\emptyset}}{\emptyset/(1.0-\emptyset)} \qquad (3)$$

$$RPI = \frac{RQI+FZI}{2.0} \qquad (4)$$

Where;
FZI: Flow Zone Indicator,
NPI: Normalized Porosity Index,
RQI: Reservoir Quality Index,
∅: porosity,
K: permeability.

The selected eleven samples of GS323-2A well have undergone X-ray diffraction (XRD) to determine the semi-quantitative compositions of the sample minerals of the reservoir under study. The measurement of the maximum intensity for each mineral are detected and this value is compared with of that of pure standard minerals intensity. The whole rock sample is divided into smaller pieces and treated by centrifugation, shaking, and ultrasound to get the particles blew than two microns from the other remaining. After calculating the weight of overall extracted clay, this clay fraction is put through additional processing and repeated measurements, which ultimately allows their relative proportions calculation and the identifying the assemblage of the clay mineral. Therefore, the results of XRD are very essential in determining the components of clay minerals related to the whole rock. Each component's peak width assessment indicates the crystallinity.

3. The litho- stratigraphic setting

The lithostratigraphic succession of the Gulf of Suez has three distinct megasequences, ranging in age from Precambrian to Recent: 1) The pre-rift sequence consists of Eocene limestones, Esna shale, thick carbonates layer of upper. Cretaceous chalk, mixed-facies interval of Nezzazat group, Nubian sandstone, pre-cambrian basement. 2) Syn-rift sequence including clastics facies of Kareem, Rudeis, Nukhul formations and non clastics facies of Zeit, South Gharib, Belayim and Abu Zenima formations. The post-rift sequence is primarily composed of sediments that are clastics and carbonate reflecting exceptional reservoir and source rocks (Darwish, (1993); Alsharhan, (2003); Ali et al., (2022); Figure 2).

The studied Nubian sandstone formation have been studied by several authors including Said (1962), E.G.P.C., (1996) Moustafa, 1997, Thorseth (2003), Alsharhan (2003), Nabawy et al. (2010), Temraz and El-naggar (2016), Nabawy and David (2016); El-Gendy et al, (2017); Nabawy et. al., (2018), Nabawy et. al. (2020), Elhossainy, 2021, Salah et al., (2023). Based on the previously mentioned authors, the studied Nubian reservoir (Paleozoic - Lower Cretaceous) is thought to be one of the most abundant potential reservoirs in these area with the gross thick exceed than 740 feet. The primary components of the Nubian Formation are composed mainly from sandstones intercalated with few carbonate and shale streaks. Its depositional condition is delineated as continental-fluviomarine to marine. It has a permeability of 70.0 – 850.0 md and a good porosity of 10 - 29 %. The thickness of net pay varies greatly from 230.2 to 700.3 ft. The Shale contents, burial depth (compaction) and the diagnostic history are the primary determinants of studied reservoir quality

4. Structural configuration

The Gulf of Suez region described as a graben rifting with a very complex structure resulting from intense tectonic activity (Oligocene - Post-Miocene). The structural configuration could be further classified into the following provinces according to the fault polarity: the southern, central, northern provinces (Figure 3). The faults orientation of the the central province are typically dips to SW direction and their strata dips to the NE direction, whereas that of the northern and southern provinces are primarily dips to NE direction and their strata dips to SW direction. Two accommodation zones (rift-transverse zones) divide these three provinces: 1) The Zaafarana accommodation zone divides the provinces in the north and center. 2) The Morgan accommodation zone divides the provinces of the south and center as shown in Figure 3. Two primary alignments heavily influence the structurally setting of the Suez rift' which are 1) the northwest-southeast oriented clysmic trend; and 2) the northeast-southwest oriented Aqba trend. The primary entrapments in the Gulf of Suez are structurally and combination types. Saqqara-1x well was the first trail for testing the normal faults closures of three way up throw in the Saqqara field which reflected an important discovery in this rift region (Said, 1962; Robson, 1971; Schlumberger, 1984; Meshref, 1992; Darwish, 1993; EGPC., 1996; Plaziat et al., 1998, Bosworth, et al., 2005, Abu-Hashish and Afify, 2022).

5. Discussion and Results

5.1. Lithofacies description

The investigation of the Nubian reservoir from ditched samples indicates that it is composed primarily from fine to medium sand grains, a small proportion of coarse-grained sands occasionally with a significantly kaolinitic cement percent (more than 30.0%). the analysis of XRD reflected that the main constituents of the studied Nubian interval are the following; 1) quartz varies from 70% to 98.3% with an average 85 %. 2) The content of clay minerals varies between 2% and 28%, with an average of 13.7%. 3) The traces of pyrite, siderite, dolomite, calcite, plagioclase with average contents of 40 %, 0.26 %, 4.9%, 0.41% and 0.31% respectively (Figure 4 & 5 and Table 1). The data indicates that the predominant constituent of clay is the kaolinite, which ranges in content from 43% to 65% with an average of 55.3%. Additionally, there is a trace content of smectite, chlorite and illite with average percent of 2.062 %, 3.38 % and 5.52 % respectively, and its average grain sizes of 2.02 µm.

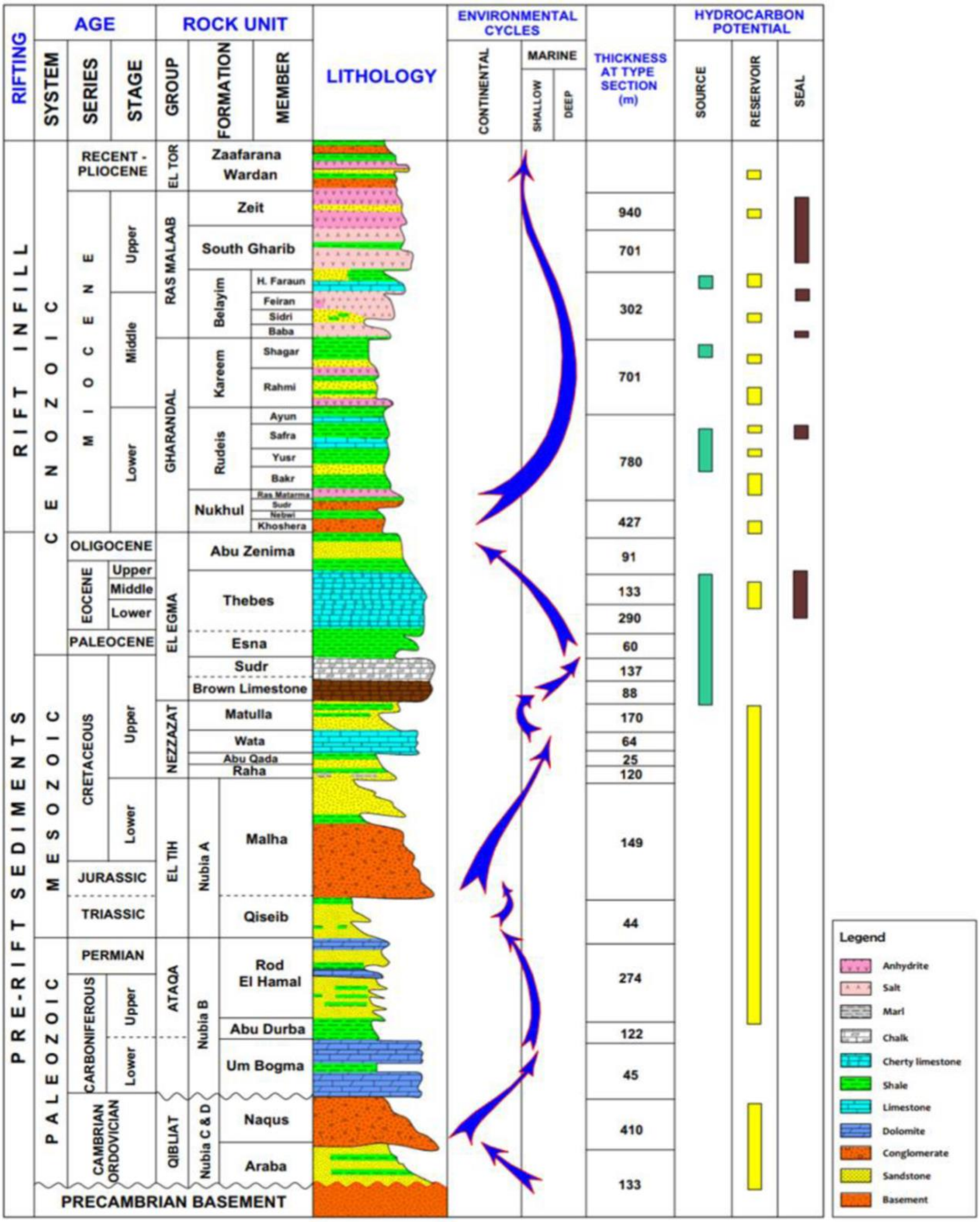


Fig. 2. Litho-stratigraphic section of the Gulf of Suez basin (modified after, Alsharhan and salah, 1995).

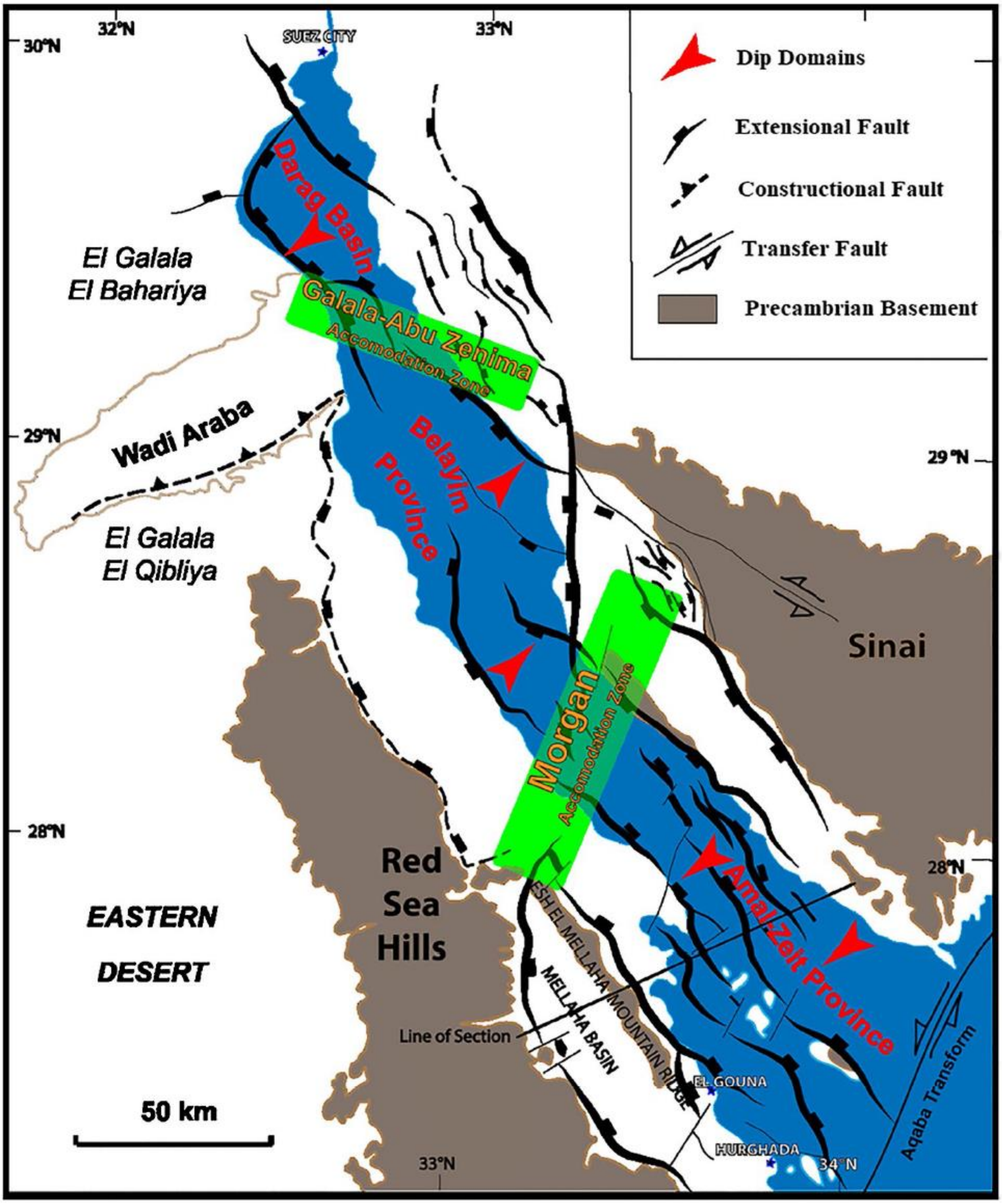
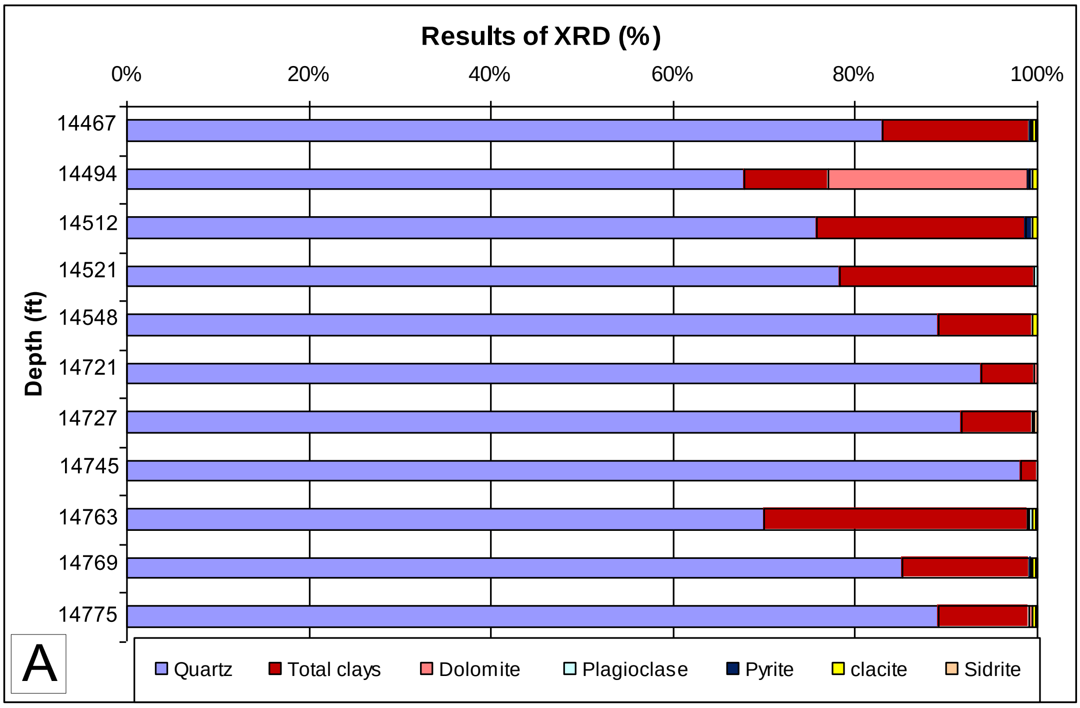


Fig. 3. The Structural setting map of the Gulf of Suez rift, Egypt (After, Bosworth, et al., 2005, Abu-Hashish and Afify, 2022).



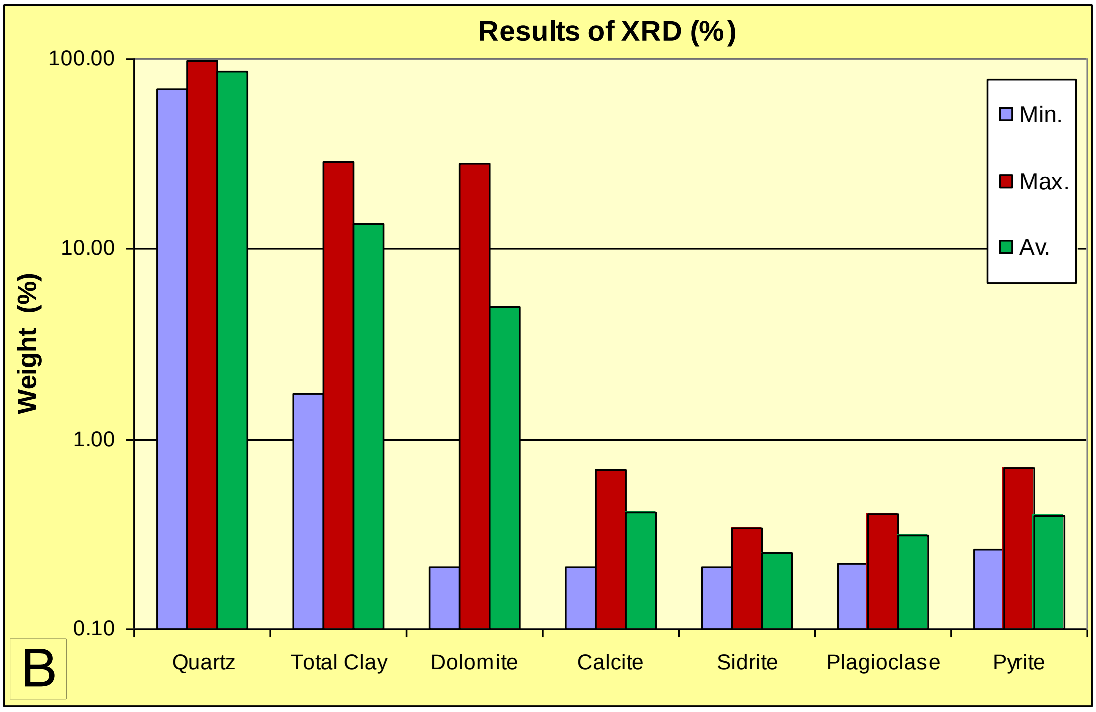
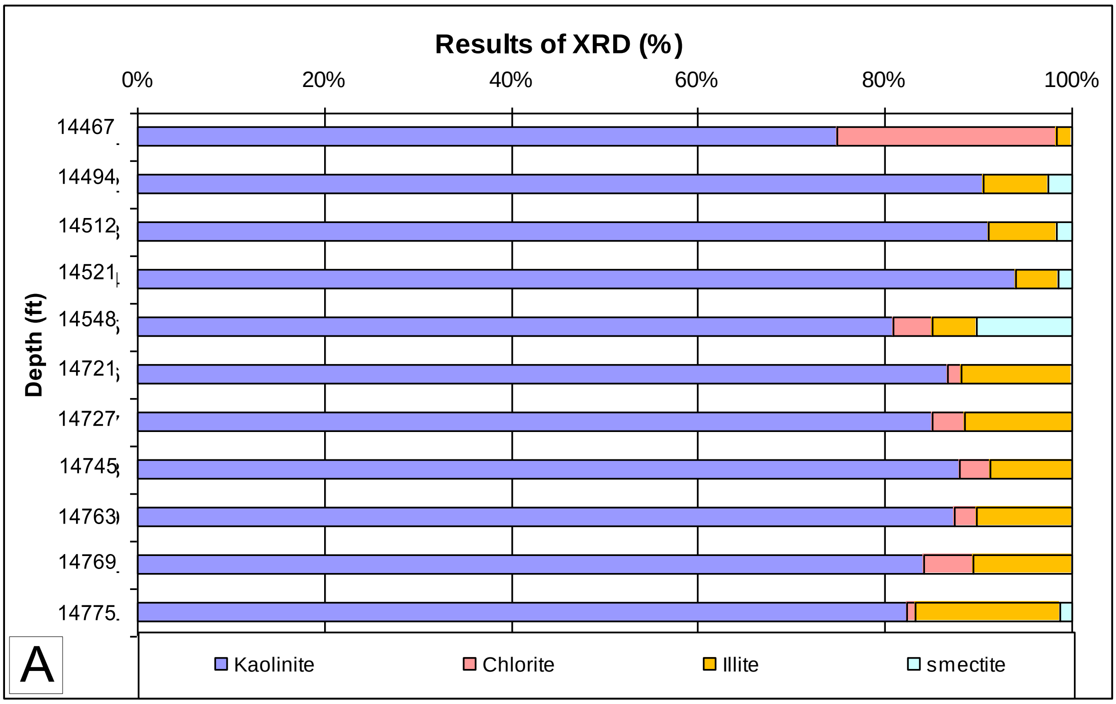


Fig. 4. The graphical presentation of XRD results for Nubian reservoir constituents, A; XRD constituents Results against depth B; XRD constituents Results with the weight percent for Nubian reservoir, Saqqara-2A well, Saqqara field, southern Gulf of Suez.



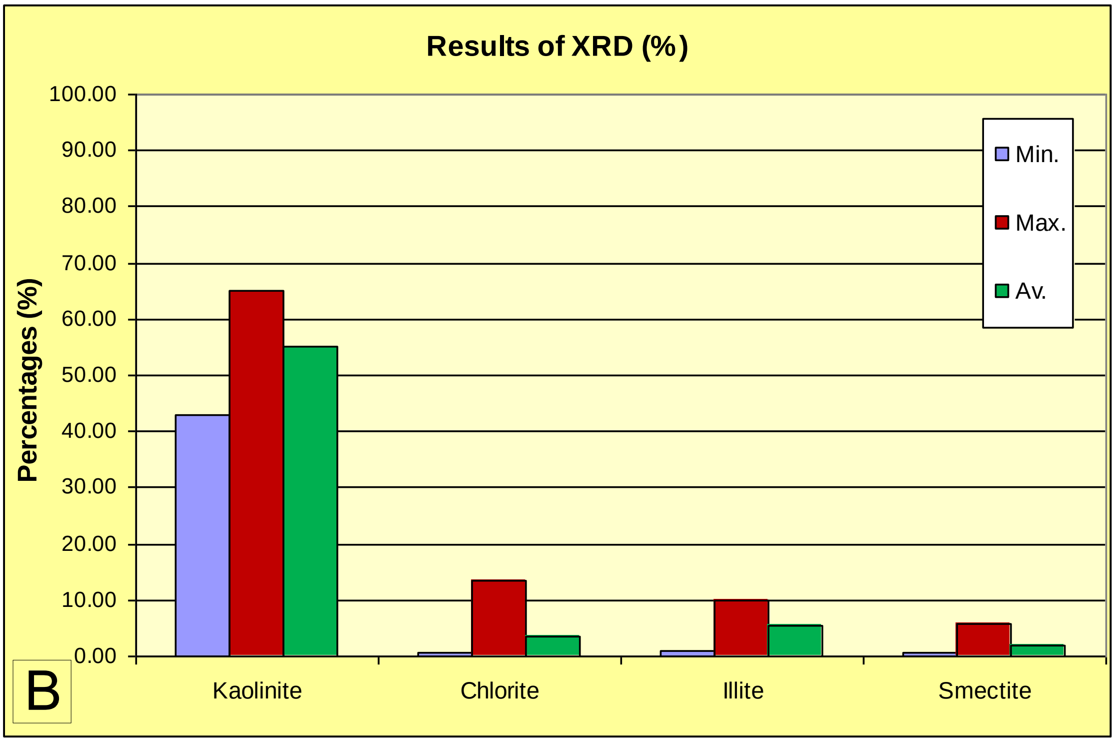


Fig. 5. The graphical presentation of XRD results for Nubian reservoir constituents, A; results of XRD for the fraction of the clay minerals only in weight percent and B; the statistical analysis of the clay minerals constituents for Nubian reservoir, GS323-2A well, Saqqara field, southern Gulf of Suez.

Table 1. The statistical analysis of the XRD results for the mineral composition of the Nubian reservoir, Saqqara oil field, southern Gulf of Suez, Egypt.

	Statistical parameters	Grain size (2µm)	Kaolinite (%)	Chlorite (%)	Illite (%)	Smectite (%)		
XRD clay components (Weight %)	Average	2.02	55.27	3.38	5.52	2.06		
	Minimum	1.20	43.09	0.60	0.91	0.79		
	Maximum	3.50	64.99	13.62	10.05	5.91		
	Statistical parameters	Total clays (%)	Pyrite (%)	Sidrite (%)	Dolomite (%)	Calcite (%)	Plagioclase (%)	Quartz (%)
XRD minerals composition (Weight %)	Average	13.68	0.40	0.25	4.91	0.41	0.31	85.53
	Minimum	1.72	0.26	0.21	0.21	0.21	0.22	69.97
	Maximum	28.99	0.71	0.34	28.00	0.69	0.40	98.28

The accessible samples from the Saqqara-1 well were also analyzed using a scanning electron microscope (SEM). The main framework grains, as observed by SEM, are quartz, feldspars, and detrital clays. Illite, kaolinite, pyrite and patchy dolomite are the primarily authigenic ingredients. The overgrowths of euhedral syn-taxial quartz minerals are rather uncommon. In general, every sample exhibits strong cementation, mostly intergranular, comparatively dense grain packing which afect on porosity development. The majority of the samples had moderate to good sorting and fine granularity. The range of point counted porosity is 0 - 34%. The primary causes of the reduction in point counted porosity are significant amounts of spatially patchy siderite and detrital clay minerals.

5.2. Microfacies analysis

There are two distinct microfacies have been detected within the Nubian Formation in the Gulf of Suez province (Alsharhan , 2003; Ali, et al., 2022, El-Gendy et. al., 2017). Based on Tucker's classification (2001), the Nubian reservoir in the study area revealed two distinct microfacies, namely quartzarenite and quartzwacke, each possessing unique petrophysical characteristics. As will be briefly covered in the following, each of them has distinct secondary components, types of cement and detrit matrix that represent their variable depositional settings and diagenetic history (Figure 6).

5.2.1. Quartz arenites facies

The majority of the quartzarenite facies is made up of more than 90% fine-grained quartz (moderately - well sorting) with a small amount of fragments remaining. The sand grains are somewhat siliceous cemented and relatively packed grains and little primary intergranular porosity. Locally enclosing illitic type of clays with tiny partially leaching framework of feldspar grains are moderately developed euhedral quartz overgrowths found in this facies. There are observed feldspar granules in the detrital framework that are highly fragments. And also traces of modest weakly crystallized illites and minor distributed pore filled detrital clay matrix (Dt cly) have been observed (Figure 6A and B).

5.2.2. Quartz wackes facies

It composed mainly from sandstone grains with matrix (more than ten pecent) and detrital feldspars with rock fragments (fewer than 10 % rock). The microscopic examination of the Quartzwackes facies revealing that quartz is fine to coarse grained that is poorly to moderately sorting, mono-and polycrystalline with slightly close packed grains. The primary intergranular porosities are uncommon

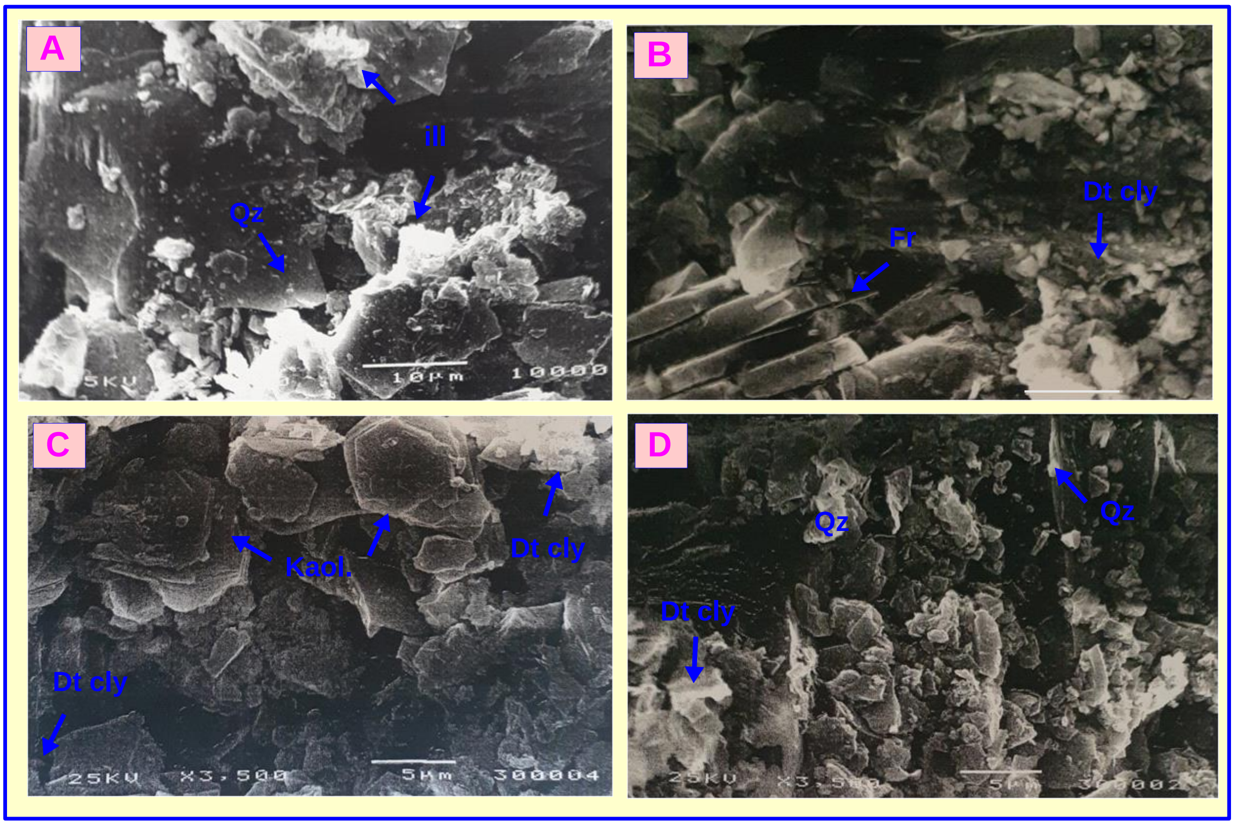


Fig. 6. Micro-Photographs of Nubian reservoir under Scanning electron microscope (SEM) showing; A and B) moderately cemented fine grains, moderate to well sorting quartz grains with relatively packing and few primary intergranular porosities, minor feldspar grains framework (Fld) with highly micro-fractured (Fr). The overgrowths euhedral quartz grains are moderately developed (Qz) with locally enclose illite minerals (ill). (C and D) well cemented, fine, moderate sorting quartz grains relatively packed grains with rarely primary intergranular porosities, leaching framework of feldspar minerals (Fld), dispersed clay matrix filled the pores, few crystallized dolomite (Do) and stacks of pseudohexagonal basal palte of kaolinite (Kaol.). a few Kaolinite minerals are replaced by the illites minerals (ill.).

indicate that the sand grains are well-cemented with small partially feldspar leaching framework and the scattered pore spaces are filled by detrital clay matrix. Kaolinite plates with considerable crystallization are accompanied by sporadic small microcrystalline dolomite rhombs. Kaolinite is locally replaced by small, weakly crystalline illites (Figure 6C and D).

5.3. Petrophysical analysis

According to the petrophysical and petrographical analysis, the studied reservoir could be splited into several hydraulic flow units (HFUs) and two rock types (RRTs). Therefore, this kind of examination is seen to be a very essential tool for assessing the specifics of the reservoir quality. Moreover, comparative study among petrophysical parameters have been constructed as briefly explained below:

5.3.1. Integration of porosity (ØHe), grain density (ρg) and bulk density (ρb).

The bulk density is primarily the product of grain density and porosity, as shown by grain density (ρg) vs. bulk density (ρb) cross-plot. For quartzarenites samples (RRT1), the bulk density confined between 2.14 - 2.45 g/cm3 which due to few detrital clay particles, cemented grains, less compacted grains and connected pore spaces. while, the quartzwackes samples (RRT2), it ranged between 2.20 - 2.61 g/cm3 due to highly microfractures and grain packing and also the occur of clay minerals contents such as illite, smectite, chlorite and kaolinite (Figure 7A & Table 2). The helium porosity versus bulk density cross-plot is very important for checking the raw data sets and their quality. High quality measurements of the petrophysical parameters are detected by the highly trustworthy relation coefficients (R2RRT1 = 0.977 - R2RRT2 = 0.995) for the two reservoir rock types under study (Figure 7B & Table 2). Consequently, using these well-established models, it is simple to compute the porosity of each type of examined rock from bulk density.

$\emptyset_{He}$ = 95.60 -35.86ρb (R^2_{RRT1} = 0.977) (Quartzarenites samples) (5)

$\emptyset_{He}$ = 95.95 -36.07ρb (R^2_{RRT2} = 0.995) (Quartzwackes samples) (6)

5.3.2. Integration of porosity ($\emptyset_{He}$) and permeability (K).

The reservoir sub-division into rock types is usually depending on the permeabilities and porosity. The spatial distribution of authigenic clay minerals and pore spaces causes the difference between horizontal and vertical permeability values. Therefore, the plotting of horizontal (Kh) and vertical (Kv) permeabilities against helium porosity (ØHe) of the diagnostic distinct rock types of the Nubian sandstone explains this in a way that shows both the predominance depositional fabric (Figure 8A). The crossplot of (Kh) permeability versus helium porosity (ØHe) exhibits a reasonable relation coefficients for both studied reservoir types (RRRT1 = 0.79 & RRRT2 = 0.77) representing primarily depositional fabric.

On the other hand, the relation coefficient constructed between vertical permeability (Kv) and helium porosity (ØHe) for samples of RRT1 and RRT2 are (R = 0.87 and R = 0.42, respectively) indicating that RRT2 samples are exposed to secondary fabric. These two crossplots represents that RRT2 samples' permeability values are lower than that ofRRT1 samples. The reason for this is that quartzarenite samples (RRT1) have relatively more effective porosity compared to quartzwackes samples (RRT2) (Figure 8B).

The well production from the entire reservoir is proposed to be a horizontally radial oriented, oriented, therefore, many authors recommended the horizontal permeability versus porosity crossplot (Nabawy and Al Azazi, 2015; Nabawy and El Sharawy, 2018). Generally, the porosity against vertical permeability cross-plots are mostly scattered and less dependable due to net overload pressure ,compaction and digenetic effect. The values of horizontal permeability (Kh) relatively higher than those of vertical permeability (Kh) could be explained by prevailing of depositional fabrics. As Table 2 illustrates, The values of average permeability for the samples under investigation are comparatively lower in the vertical orientation than they are in the horizontal orientation. The permeability-porosity relationships that have been provided allow the following models to be used in determining the (Kh) from helium porosity (ØHe):

Kh = 1E - 06 Ø.247 (RRRT1 = 0.79 for quartzarenite samples) (7)

Kh = 0.000 ØHe4.523 (RRRT2 = 0.77 for quartzwacke samples) (8)

5.3.3. Permeability Anisotropy (λk)

It defined as the ratio of horizontal to vertical permeabilities, where it considered from the essential method for estimating, verifying anisotropy of the reservoir and also reflecting the existence of the vertical fractures and fissile lamination (Nabawy & Géraud, 2016; Nabawy & David, 2016; Gendy et al, 2017). The existence of certain barrier or baffle laminas as reducing factors affect greatly in the vertical permeability. And also, natural vertical or microfractures that were produced as a result of rising overload loads beds with depth increasing have a highly effect on the vertical permeability (Kv). The plot of KV versus Kh could be utilize to distinguish between samples of secondary fabric (rocks with microsecondary fractures) and the samples of laminated rocks depositional fabrics (Figure 9). In other words, the anisotropy degree provides a precise indicator of the extent of lamination or cracking (Nabawy et al., 2018). The plot shows that for the RRT1 samples, the permeability anisotropy (λk) ranges from 0.91 to 11.14. This wide range is related to the existence of some microfractures and the extremely complex rock texture. The majority of the samples are varies greatly from isotropic ($1/1.1 \leq λk \leq 1.1$) to lamination trends ($λk \geq 5.0$), On the other hand, a small number of RRT1 and RRT2 samples closed around microfractures (Figure 9 & Table 2, Table 3).

5.3.4. The quality of the reservoir

Plotting porosity versus permeability indicates the primary contribution to the examined quality parameters of the studied reservoir. The reservoir quality index (RQI) equal net multiplication values of porosity and permeability (Amaefule et al., 1993; Nabawy & El Sharawy, 2018). Cross plot of the average permeability (Kav) against flow zone indicator (FZI) exhibits also strong relation

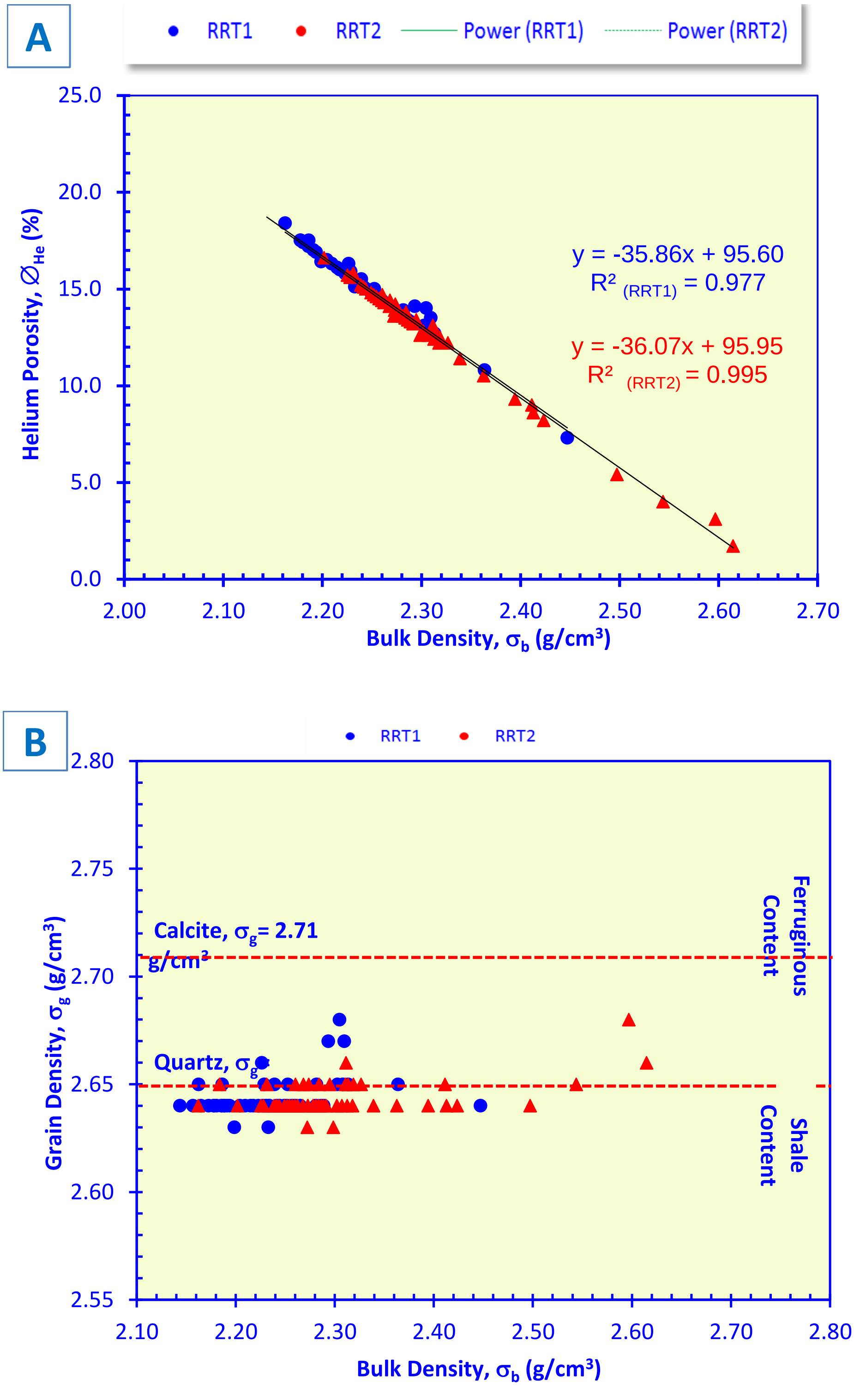


Fig. 7. A; The cross-plots of bulk density (Pb) versus helium porosity (ØHe), B; The cross-plots of bulk density (Pb) versus grain density (Pg) for discriminated two rock types (RRTs) of the Nubian reservoir, GS 323-1A well, Saqqara field.

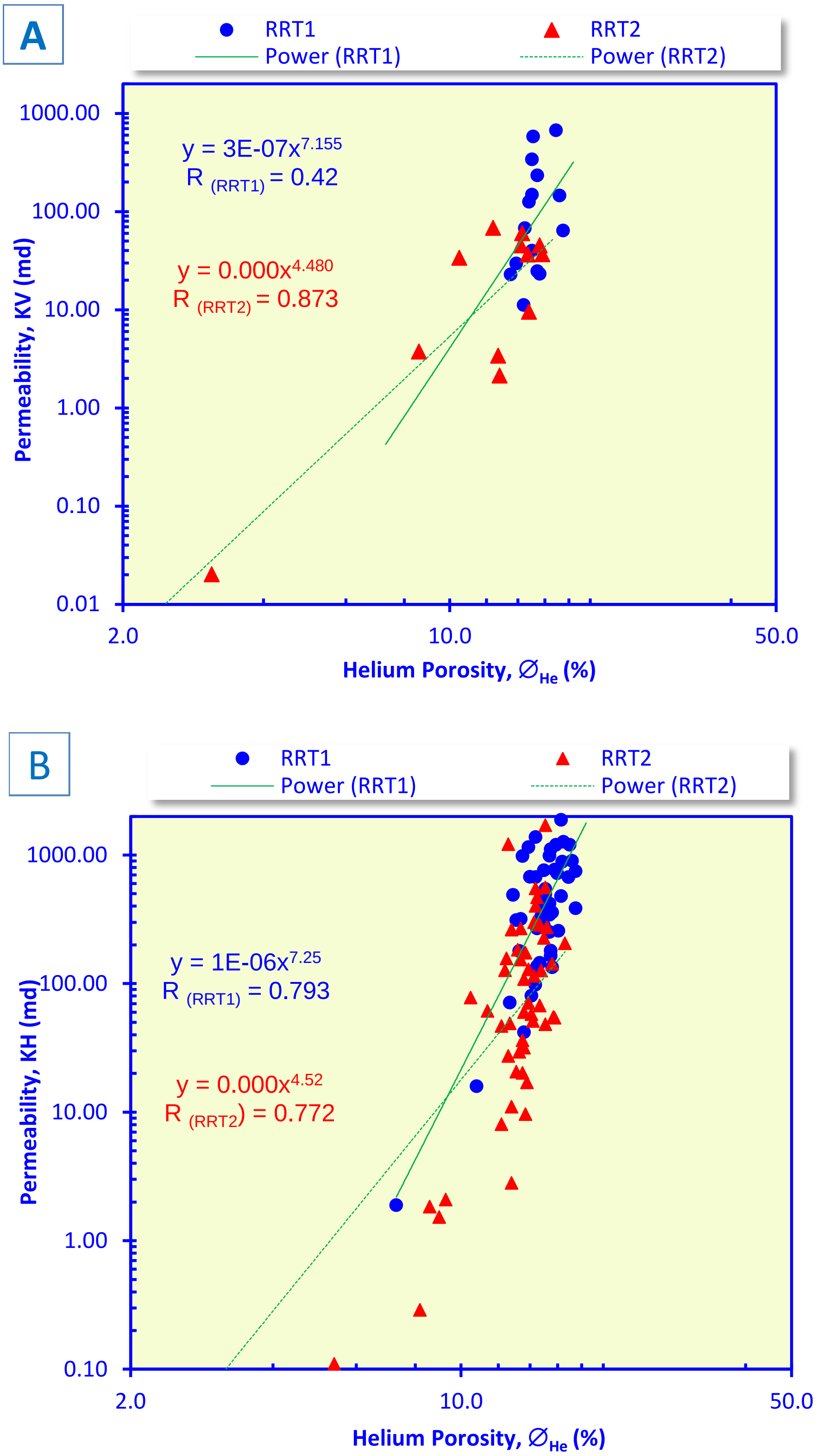


Fig. 8. A; the crossplots of helium porosity versus vertical permeability, B; the crossplots of helium porosity versus horizontal permeability for discriminated two rock types (RRTs) of the Nubian reservoir, GS 323-1A well, Saqqara field.

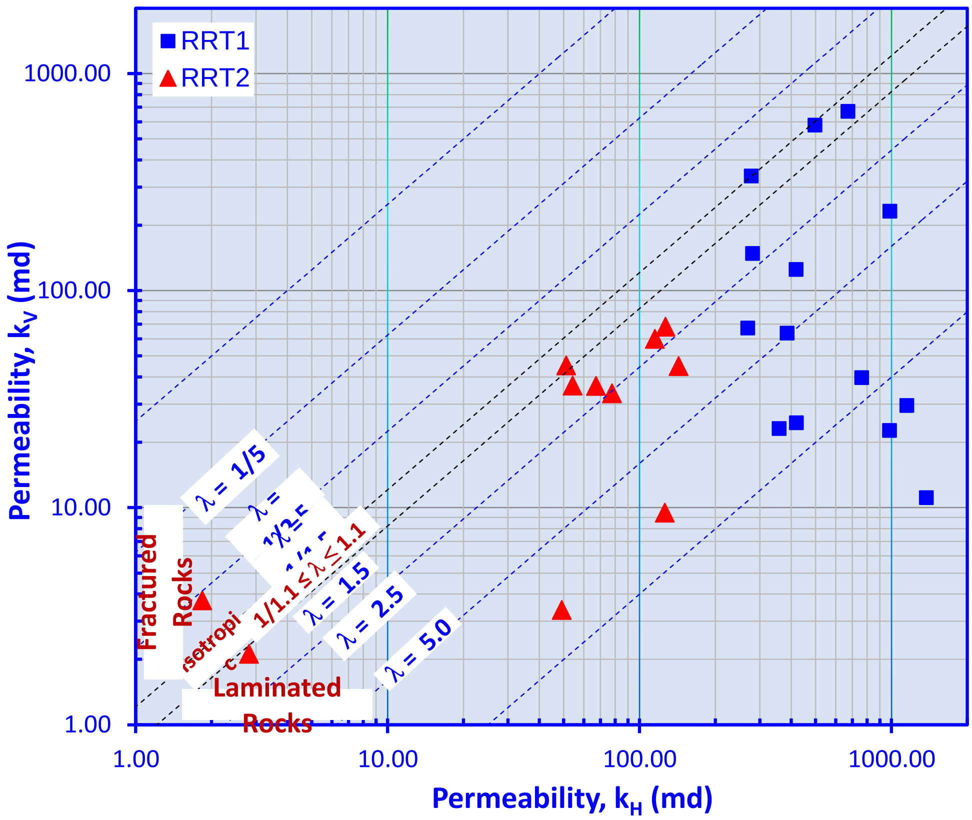


Fig. 9. the vertical permeability (KV) against Horizontal permeability (KH) for discriminated two rock types (RRTs) of the Nubian reservoir, GS 323-1A well, Saqqara field, southern Gulf of Suez, Egypt.

Table 2. The statistically analysis of the reservoir quality and petrophysical parameters of the Nubian reservoir, GS-323-1 well, Saqqara field, southern Gulf of Suez, Egypt.

RRTs		FZI	RQI	NPI	Kav	λk	KV	KH (md)	ØHe	GD	BD
		(µm)	(µm)	(µm)	(md)	-	(md)	(md)	(%)	(g/cc)	(g/cc)
RRT1	Av.	6.38	1.17	0.18	246.60	3.25	149.12	606.47	15.32	2.64	2.24
	Min.	3.21	0.69	0.08	85.76	0.91	11.10	1.89	7.30	2.63	2.14
	Max.	10.52	1.98	0.23	671.50	11.14	670.00	2719.00	18.80	2.68	2.45
RRT2	Av.	3.20	0.49	0.15	41.80	1.64	28.57	121.33	12.65	2.64	2.31
	Min.	0.66	0.02	0.02	0.01	0.70	0.02	0.01	1.70	2.63	2.20
	Max.	6.07	0.86	0.20	92.93	3.82	68.00	560.00	16.60	2.68	2.61

Where: (FZI): Flow zone indicator, (RQI): reservoir quality index, (NPI): normalized porosity index, (kav): average permeability, (λk): permeability anisotropy, (KH): Horizontal permeability, (ØHe): helium porosity, (GD): grain density, (BD): bulk density.

Table 3. The Classification and Ranks of the petrophysical properties based on (Nabawy & El Sharawy, 2018; Nabawy, et. al. 2018);

Permeability, k	Porosity, Ø	FZI	RQI	Reservoir	RPI
(md)	(%)	(µm)	(µm)	rank	rank
1.0 ≥ k	5.0 ≥ Ø	1.0 ≥ FZI	0.25 ≥ RQI	6.0	Tight
10.0 ≥ k >1.0	10.0 ≥ Ø >5.0	2.0 ≥ FZI > 1.0	0.5 ≥ RQI > 0.25	5.0	Poor
100.0 ≥ k >10.0	15.0 ≥ Ø >10.0	5.0 ≥FZI > 2.5	1.0 ≥ RQI > 0.50	4.0	Fair
1000.0 ≥ k >100.0	20.0 ≥ Ø >15.0	10.0 ≥ FZI >5.0	2.0 ≥RQI > 1.0	3.0	Good
10000.0 ≥ k >1000.0	25.0 ≥ Ø > 20.0	15.0 ≥ FZI > 10.0	5.0 ≥ RQI > 2.0	2.0	Very good
k > 10000.0	Ø >25.0	15.00 < FZI	RQI > 5.00	1.0	Excellent

Where: (k) permeability, (Ø) porosity, (RPI) reservoir potentiality index, (FZI) flow zone indicator, (RQI) reservoir quality index.

coefficients for both diagnostic RRTs samples (R2RRT1 = 0.86, R2RRT2 = 0.82) (Figure 10A). As well as, the crossplots of average permeability (Kav) versus the reservoir quality index (RQI) exhibits strong relation coefficients for both diagnostic RRTs samples (R2RRT1 = 0.99, R2RRT2 = 0.97) (Figure 10B) with clear separating points of the two distinguished RRTs. according the modification ranks of Nabawy et al., 2018. The most plotting points of (FZI) are restricted to be tight to good quality (6.1 µm ≥ FZI ≥ 0.66) for RRT2 samples, whereas it for RRT1 samples are detected to be fair to very good quality (11µm ≥ FZI ≥ 3.2). Whereas, the values of RQI for diagnostic RRT1 samples are assigned fair to high (RQI ≤ 2.0 µm), while it restricted tight to fair for RRT1 samples (RQI ≤ 0.86 µm). These results reflected a relative high grade of heterogeneity especially for the RRT2 samples as confirmed from occurrence of anisotropy grade and micro fractures (Table 2 & 3). Generally, the scattering of these samples' permeability, RQI, and FZI values reflect a broad range from tight to fair rank, further confirms the high heterogeneity grade. However, the plotting of (RQI) values versus each of FZI and NPI values considered predominant technique for detection of reservoir ranking and rock typing efficiency (Amafeule, et.al., 1993; Nabawy and Géraud, 2016). These cross-plots for the Nubian reservoir samples show two distinct samples divided into six flow units (Figure 11A).

The percent study indicates that few RRT1samples and all RRT2 samples have very low FZI and RQI values (6.10 µm ≥ FZI, 0.86 µm ≥ RQI), these reflecting that prospective reservoir are mostly confined within RRT1 samples with flow zone indicator values reviewed fair to very good (11.0 µm ≥ FZI ≥ 3.20 µm), whereas the impermeable to good reservoir samples (RRT2 samples) regarded as low reservoir quality (6.10 µm ≥ FZI ≥ 0.70 µm).The pore spaces complexity, varied grain phases and rock fabrics of the Nubian Formation may be the reason for this. Generally, RQI versus FZI crossplot indicates that the most RRT1 samples having good to very good rank, whereas the majority samples of RRT2 are belong to poor to fair rank (Figure 11B). Finally, theexamined Nubian reservoir could be diffferntiated into low reservoir quality related to quartzwacke microfacies (RRT2 samples) and another relatively high reservoir quality that related to quartzarenite microfacies (RRT1 samples).

6. Conclusions

The Nubian reservoir is composed primarily from fine to medium sand grains, a small proportion of coarse-grained sands occasionally with a significantly kaolinitic

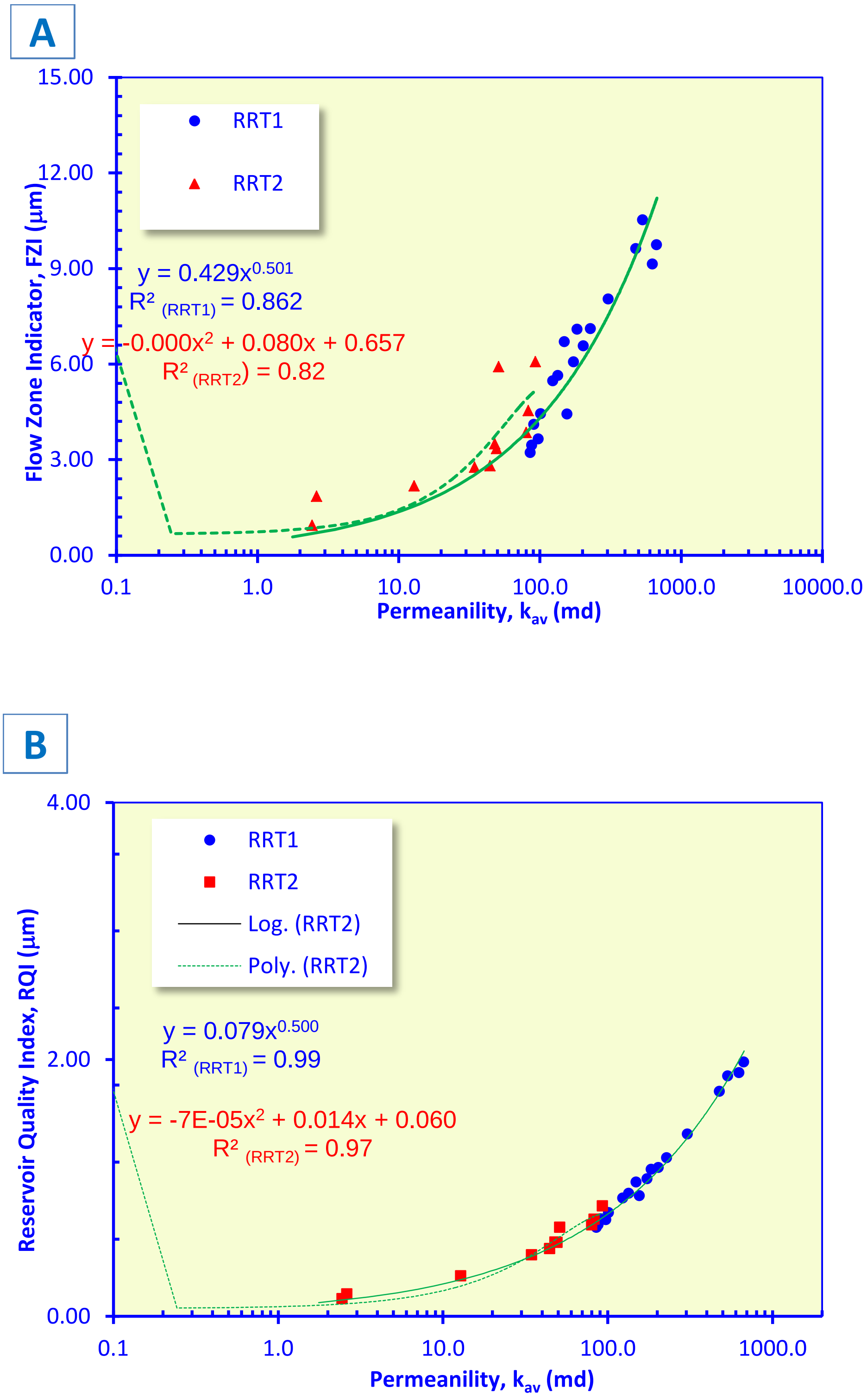
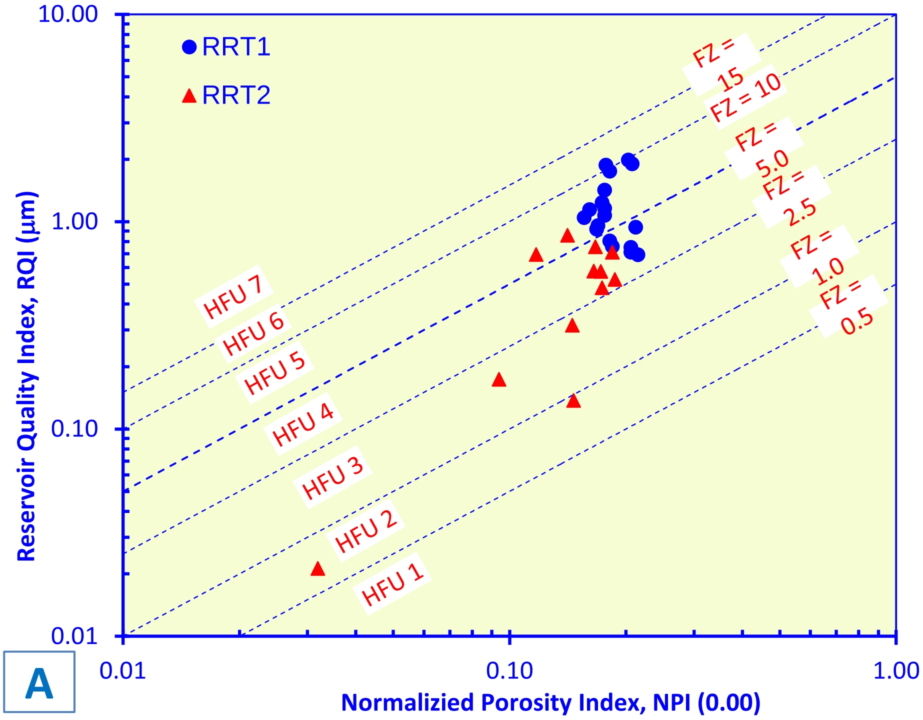


Fig. 10. A; the average permeability (Kav.) versus flow zone indicators (FZI) cross-plot, B; the average permeability (Kav.) versus the reservoir quality index (RQI) cross-plot for the discriminated two rock types (RRTs) of the Nubian reservoir, southern Gulf of Suez, Egypt.



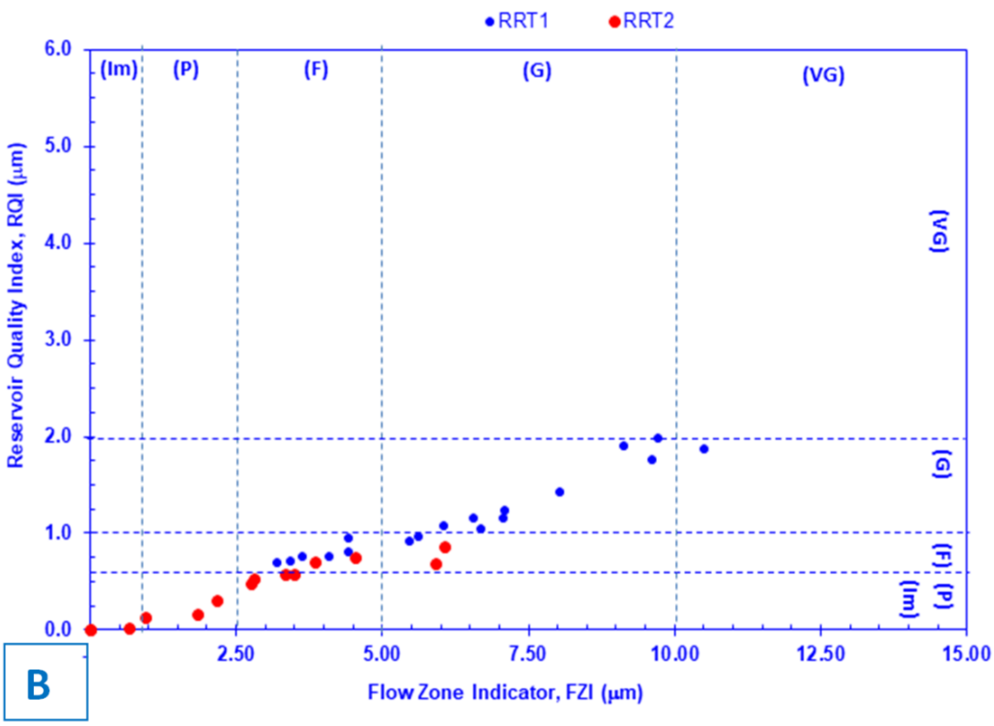


Fig. 11. A; the normalized porosity index (NPI) versus reservoir quality index (RQI) cross-plot B; flow zone indicators (FZI) versus reservoir quality index (RQI) cross-plot for the discriminated two rock types (RRTs) of the Nubian reservoir, southern Gulf of Suez, Egypt.

cement percent (more than 30%). the analysis of XRD for the studied reservoir reflected that 1) quartz varies from 70% to 98.3% with an average 85 %. 2) The content of clay minerals varies between 2% and 28%, with an average of 13.7%. 3) The traces of pyrite, siderite, dolomite, calcite, plagioclase with average contents of 40 %, 0.26 %, 4.9%, 0.41% and 0.31% respectively.The Nubian reservoir could be distinguished into two microfacies depending on petrographic analysis which are quartzarenite and quartzwacke microfacies and these consequently representing the two different rock types (RRTs) with a variable petrophysical characters. Discriminated rock type (RRT1) is relatively better in the rock quality than rock type (RRT2), where the petrophysical characters decreases from (RRT1) to (RRT2). The delineated average petrophysical parameters of rock type (RRT1) are 246.60 md, 1.17 µm, 6.38 µm, 0.18 µm, 15.32 % and 2.24 g/cc for permeabilities, RQI, FZI, NPI, porosity, bulk density respectively, whereas those for rock type (RRT2) are 41.80 md, 0.49 µm, 3.20 µm, 0.15 µm, 12.65 % and 2.31 g/cc for permeabilities, RQI, FZI, NPI, porosity, bulk density respectively. The overall results reflected that the Nubian sandstone reservoir posses a good reservoir quality especially in rock type RRT1. The abundance of patchy siderite and kaolinite are the major factor that decreasing the quality of this reservoir.

Ethics approval and consent to participate: This article does not contain any studies with human participants or animals performed by any of the authors.

Consent for publication: the Author declares their consent for publication.

Funding: There is no fund taken for this paper

Conflicts of Interest: The author declares no conflict of interest.

Contribution of Authors: author making the writing, editing and revising the MS and agree to its publication.

Acknowlegement: the author is very grateful to the Egyptian General Petroleum Corporation (EGPC) and the Petroleum Company of the Gulf of Suez (GUPCO) for their assistance and provision of these data,. I also express my sincere gratitude to the National Research Center in Egypt's geophysical science department.

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أنواع الصخور والسحنات الرسوبية الدقيقة لخزان الحجر الرملي النوبي، خليج السويس، مصر

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تقدم هذه الدراسة محاولة لتمييز خزان الحجر الرملي النوبى بخليج السويس إلى نوعين من صخور الخزان والسحنات الرسوبية الدقيقة. حيث تعتبر هذه الطريقة فعالة لتنمية الحقل موضع الدراسة. لذلك اعتمدت الدراسة بشكل أساسي على وصف ودراسة عينات الصخور ميكروسكوبيا وباستخدام نتائج القياس المعملي للمعاملات البتروفيزيقية لإنجاز هذا الهدف. قد أوضحت الدراسة المجهرية للصخور أن الخزان موضع الدراسة يتكون من معادن الااليت والكاولينيت والبيريت وقليل من الدولوميت. بينما الكوارتز المتبلر غير منتشر نسبيا فى هذا الخزان. وقد أضافت الدراسة الميكروسكوبية أيضًا أن الطين والكوارتز والفلسبار يتواجدون بشكل أساسي بين جميع حبيبات صخور الخزان المختلفة. قد تم تقسيم الخزان موضع الدراسة إلى نوعين من السحنات الرسوبية الدقيقة وصخور الخزان (RRTs) وأفضل نوع صخري للخزان هو (RRT1) لأنه يتميز بالخصائص التالية: معامل الإنسيابى (FZI) يتراوح بين (٣,٢ – ١٠,٥ µm)، ومعامل جودة الخزان (RQI) يتراوح بين (0.69–1.98 µm)، والمسامية (ØHe) تتراوح بين (7.3–19.0%)، والنفاذية تتراوح (2.0 md–2719 md). بينما النوع الثاني (RRT2) يتميز بخواص أقل جودة حيث إن قيم FZI تتراوح بين(0.65–6.10 µm)، وقيم (RQI) تتراوح بين (0.02 –0.86 µm)، والنفاذية الأفقية تتراوح بين (0.0 – 570.0 md) بينما المسامية لا تتعدى ١٧%. عمومًا النتائج تؤكد وجود خواص بتروفيزيقية جيدة خصوصًا للنوع الأول (RRT1) من الخزان وأن أهم ما يؤثر على جودة الخزان محل الدراسة هو وجود معادن الطين خصوصًا السيدريت والكاولينيت.