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IMPACT OF TEXTURAL COMPOSITIONS ON PORE THROATS AND SORTING VARIATIONS IN SANDSTONE RESERVOIR: AN IMPLICATION TO PERMEABILITY, DISPLACEMENT PRESSURE AND IRREDUCIBLE WATER SATURATION

*I. Yusuf * and E. Padmanabhan*

Department of Geoscience, Faculty of Geoscience and Petroleum Engineering, Seri Iskandar, 32610, Perak

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Abstract

This study investigate the impact of rock discrete textural variability on pore throats, and its potential implication on permeability, displacement pressure and irreducible water saturation in one hundred and thirty two (132) samples from five wells. Two dimensional (2D) digital image analyses were used to extract grain size, shapes, pore types. A geometric sedimentological scale and statistical technique were also adopted for quantification and classification of the discrete grain sizes and shapes. The scanning electron microscopy (SEM) were used to visualize grain – pore throats relationship, and also mercury injection capillary pressure (MICP) data is use to quantify pore throat types, determination of displacement pressure, irreducible water saturation and pore throat sorting. Porosity-permeability systems (POROPERM) assess permeability variations from the core plugs. Results indicate that variable grain size and shape composition plays vital role in the distribution of pore throats types in reservoir rock. Five pore throats diameters were identified and classified into micropore, mesopore and macropore throats. It also indicates that medium to coarse sub-rounded well-rounded and granules have strong influence on the amount of mesopore and macropores throats developed. Furthermore, increase in silts and clay fractions clogged and occluded pore throat resulting to abundance of micropore throats. High composition of mesopore and macropore throats in rock framework decreases irreducible water saturation and displacement pressure, but increases permeability. Whereas, increase in abundance of micropore throats, necessitate increase in displacement pressure, irreducible water saturation, thus decreases in permeability values. Pore throats sorting coefficient reveals to be an essential tool in determining degree of pore throats connectivity in reservoir sandstone. The understanding of discrete textural compositions as it influences variation in pore throats abundance and distribution will improves accurate prediction of fluid flow and its recovery in reservoirs.

Keywords: textural compositions; pore throats; pore throat sorting; mercury capillary pressure; displacement pressure; reservoir sandstone; permeability.

1. Introduction

Pore throats size in siliciclastic rocks form a continuum from the sub millimeter to the nanometer scale [1], and it also determines if a rock transmit fluids. Thus, large interconnected pore throats translates to higher permeability, [2] and this have an ultimate control on fluid flow [3-4]. In siliciclastic reservoir, it was revealed that high porosity, do no guarantee high fluid flow; permeability, [5]. Most properties of reservoir rocks are controlled by grain-pore relationships [6], and properties such as permeability, electrical conductivity and drainage capillary pressure are strongly influenced by pore throat size, [7-9]. Petroleum geologists are accustomed to characterizing reservoir rocks in terms of porosity and permeability instead of the pore throats size [1]. Reservoir rock properties such as throats size, throats sorting, pore structure and shapes continuously contributes to fluid flow [10]. Perhaps, estimation and prediction of permeability in reservoir is still a challenge, [11-12]. There is still no sufficient literature on evaluation of the discrete textural variations on pore throats abundance and distribution. However, in other to augment the extensive studies on understanding relationships between porosity and permeability, more attention is needed to understand the effect of the discrete textural compositions on pore throats distribution, which invariably have positive effect on fluid dynamic and distribution within reservoirs. It was common in research articles that, grain size and shapes are mostly used for descriptive (qualitative) evaluation, [2,13], but with negligible consideration on how certain textural component impact on pore throats abundance and distribution towards realization of more subsurface realistic model for fluid displacement.

This work attempts to investigate if specific pore throats types are peculiar to some discrete textural compositional abundance that vary geological units. Hereafter, such knowledge on pore throats distribution in relation to discrete internal variables will improve achieving subsurface more realistic model, accurate prediction of fluid flow and displacement in a way more useful to reservoir engineers, [14] during field design and development. This paper will assess, for the first time, impact of rock discrete textural variability on pore throats in one hundred and thirty two (132) specimens in five exploratory wells from five (5) selected reservoir sandstone lithofacies from the study area. The objectives will be: 1) to investigate the discrete textural composition variations 2) to determine and classify the identified pore throats and sorting 3) evaluate their potential implication on irreducible water saturation, displacement pressure and permeability measurement.

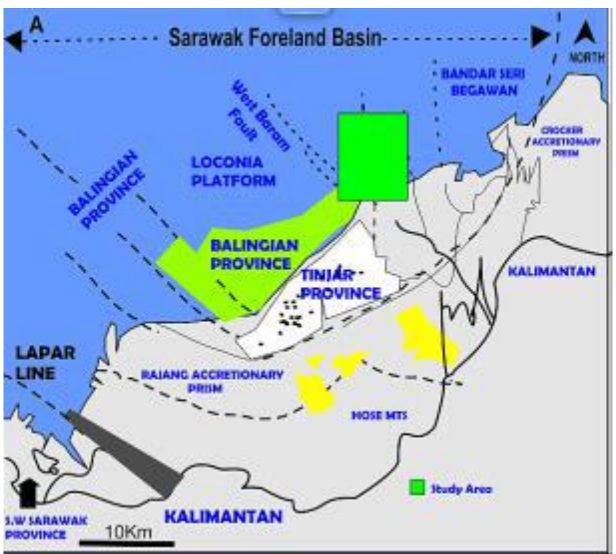

Figure 1. Location of the Sarawak basin and the study area (*Modified after [22]*)

The study area is located offshore, with hydrocarbon exploration history of more than thirty-five years (35), [15], perhaps with a present recovery rate of 30%, [16-17] from approxi-mately more than one hundred and sixty (160) exploratory wells (Figure 1). The productive reservoir units consist of an approximately 21420 m's thick stacked sequence of shallow mari-ne sands, [18] distributed in excess of 200 zones, and extensively faulted. The offshore forma-tions of the study area include coastal to coastal-fluviomarine sands deposited in a north-westward prograding delta since the Middle Miocene (from Cycle IV onwards), in which the Cycle V (Middle to Upper Miocene) to Cycle VII (Upper Pliocene) are the most developed, [18-20] Figure 2.

In the area, Cycle V (Middle to Upper Miocene) to Cycle VII (Upper Pliocene) is well developed, prograding over thick diachronous pro-delta shales which have been mapped as the Setup Shale Formation onshore. Each cycle develops in a coastal plain environment to the south dominated by deposition of sands, silts and clays, and grades northwards into holomarine neritic to bathyal environments with deposition of mainly clays, silts, minor sands and, in places turbidities, [21]. Furthermore, there is massive heterogeneity with more than twelve (12) variable sandstone lithofacies, [22] as identified from the sedimentological and stratigraphic analysis of both onshore and offshore cores varying from variable degree of textural variation, sedimentary structures and biotubations [20,22].

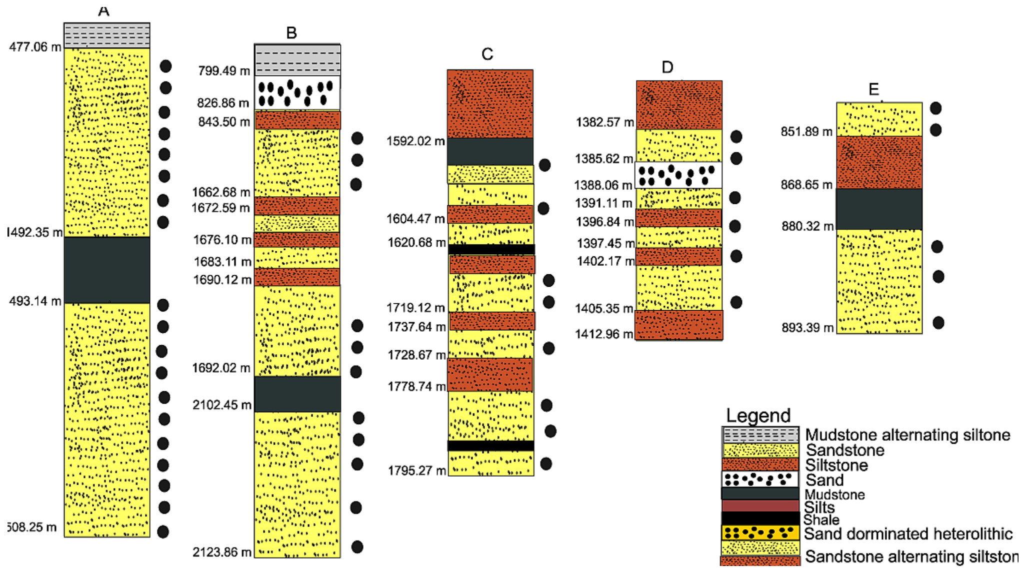

Figure 2. Lithological core logs for samples and sample points

2. Specimen description

The total of one hundred and thirty two (132) samples, twenty- five (25) 1.5”core plugs from five (5) variable facies and exploratory wells A, B, C, D and E as depicted in Figure 2 were collected from the core laboratory. The identified facies from the wells include; the coarse friable sandstone (CFRS); F1 (Fig. 3a), massive coarse sandstone (MCS), F2 (Fig. 4a), massive friable fine sandstone (MFFS), F3 (Fig. 5a), Massive fine sandstone (MFS); F4 (Fig. 6a) and massive very friable sandstone (MVFS); F5 (Fig. 7a). The F1 consist of (n = 15) samples with no visible sedimentary structure, medium to coarse grained, well sorted and friable sandstone. This texture suggested that facie were deposited in a high energy wave dominated shallow marine (near shore) environment. The well-sorted F2 consist of (n = 24) samples, it shows distinctive massive texture contrast to other sand facies. It is intercalated with laminated mudstone and biotubated silty mudstone. This texture reflects that their deposition was made in deeper water, probably at the tail end of very stormy events. The lenticular bedded ribbon sand samples; F3 comprises of (n = 36) varying from fine to very fine grained, intercalated with subordinated mudstone. They show parallel or mixture of asymmetrical and symmetrical cross laminations with no feature of biotubation as found in other lithofacies. This facie was probably deposited during less turbulent period in a wave-and storm dominated shelf, when the amount of sand reworking and transportation was greatly reduced. The shelly laminated fining upward sandstone (n = 37) samples, F4 displays distinctive internal stratification. The basal part is planar laminated, medium to coarse grained sand with interbedded thin horizon of calcareous shells fragment grading upward into light gray, low – angle parallel laminated, fine grained sand. This facie interpreted as a gutter cast, and is deposited during storm related to a relative sea level fall, when the oscillatory wave and wind forced current scour the shelf and cut deep gutter cast.

The F5 consist of (n = 20) samples, fine to very fine grained sandstone, mudstone intraclasts are common at the base of individual layers, but are scattered. More so, its displays low angle (<15%) parallel to slightly divergent stratifications and minimum biotubation.

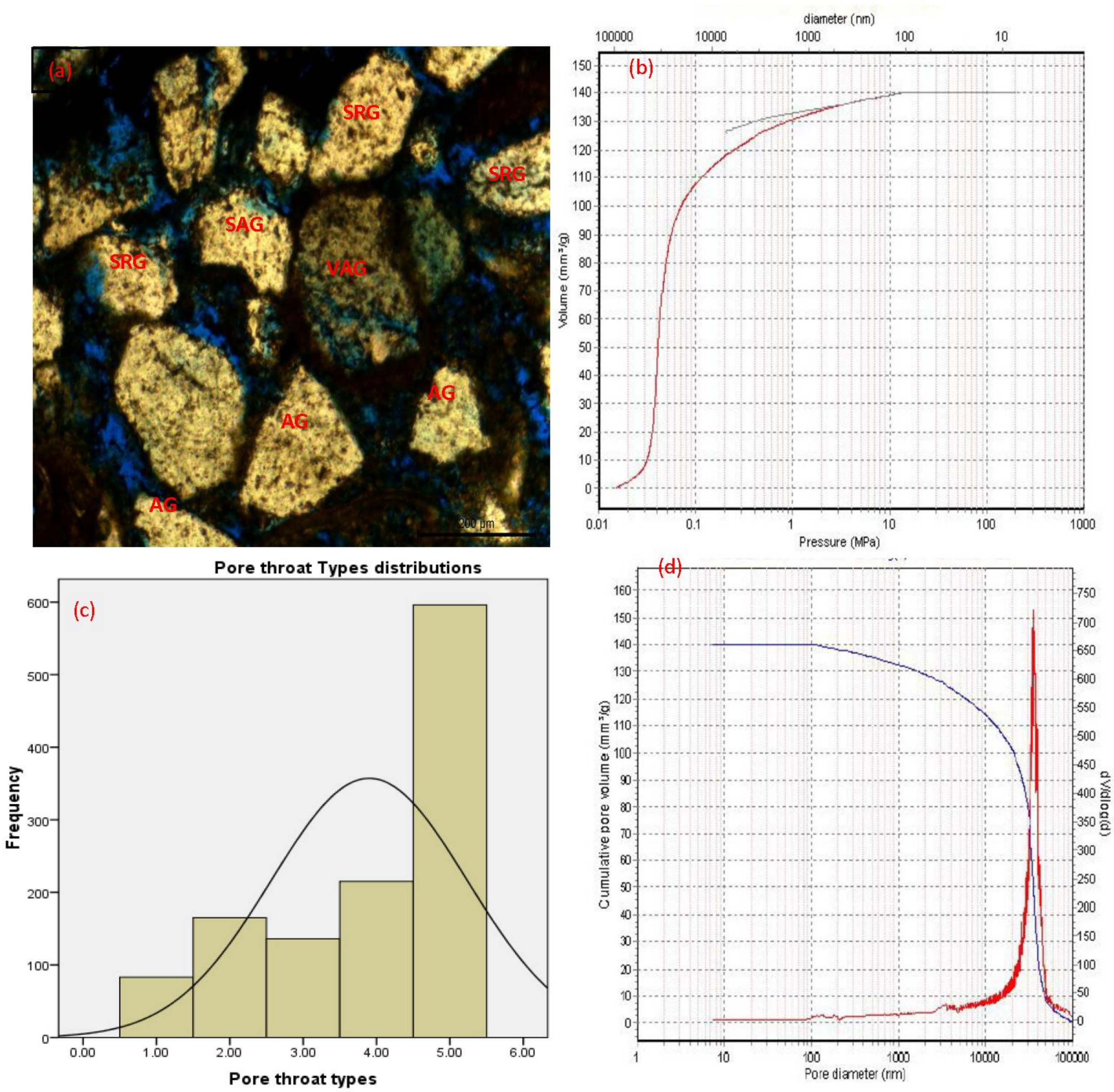

Figure 3. Pore throat sizes distribution, types and capillary pressure curves for Coarse Friable sandstone facie

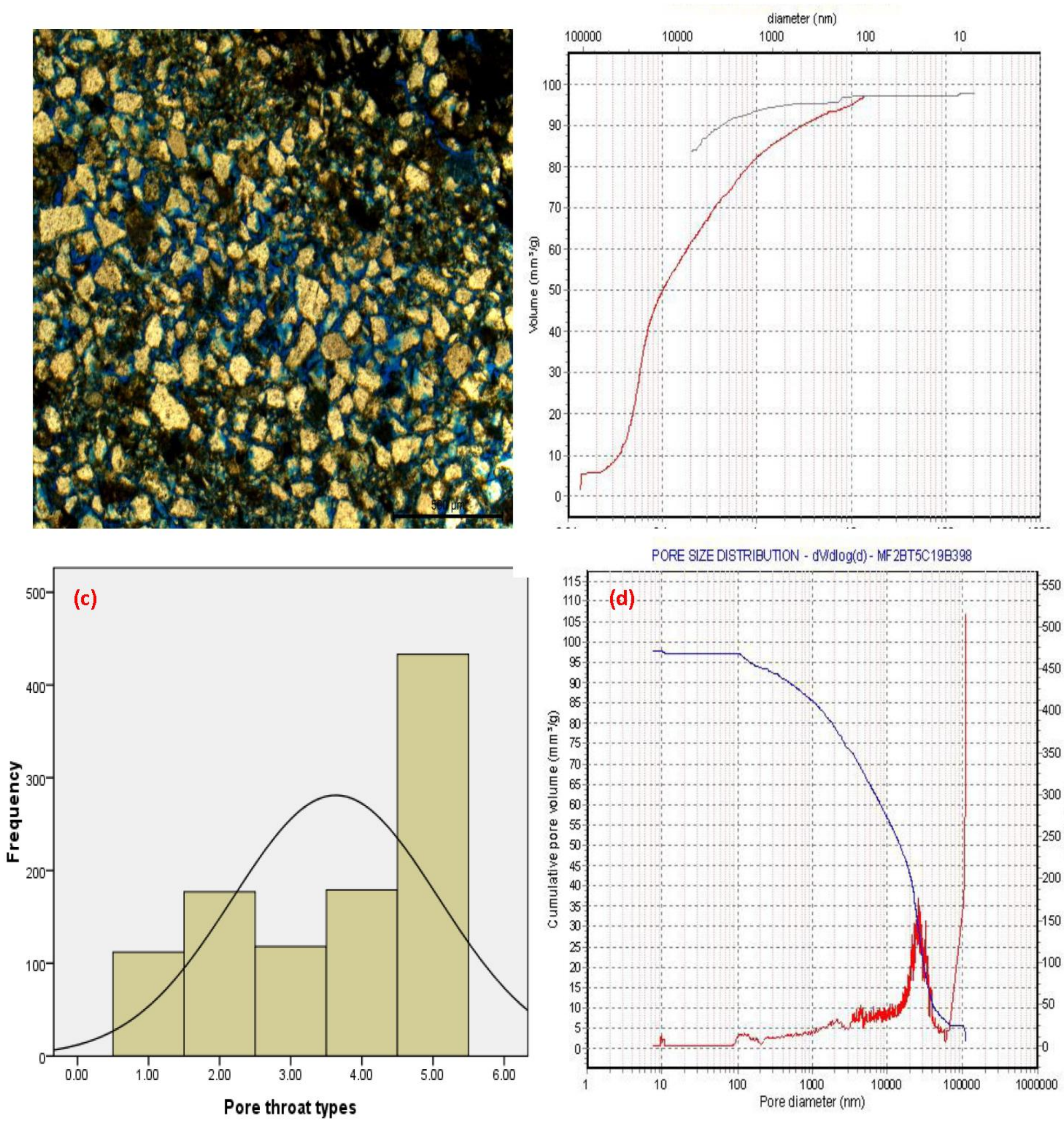

Figure 4. Pore throat sizes distribution, types and capillary pressure curves for Massive Coarse Sandstone

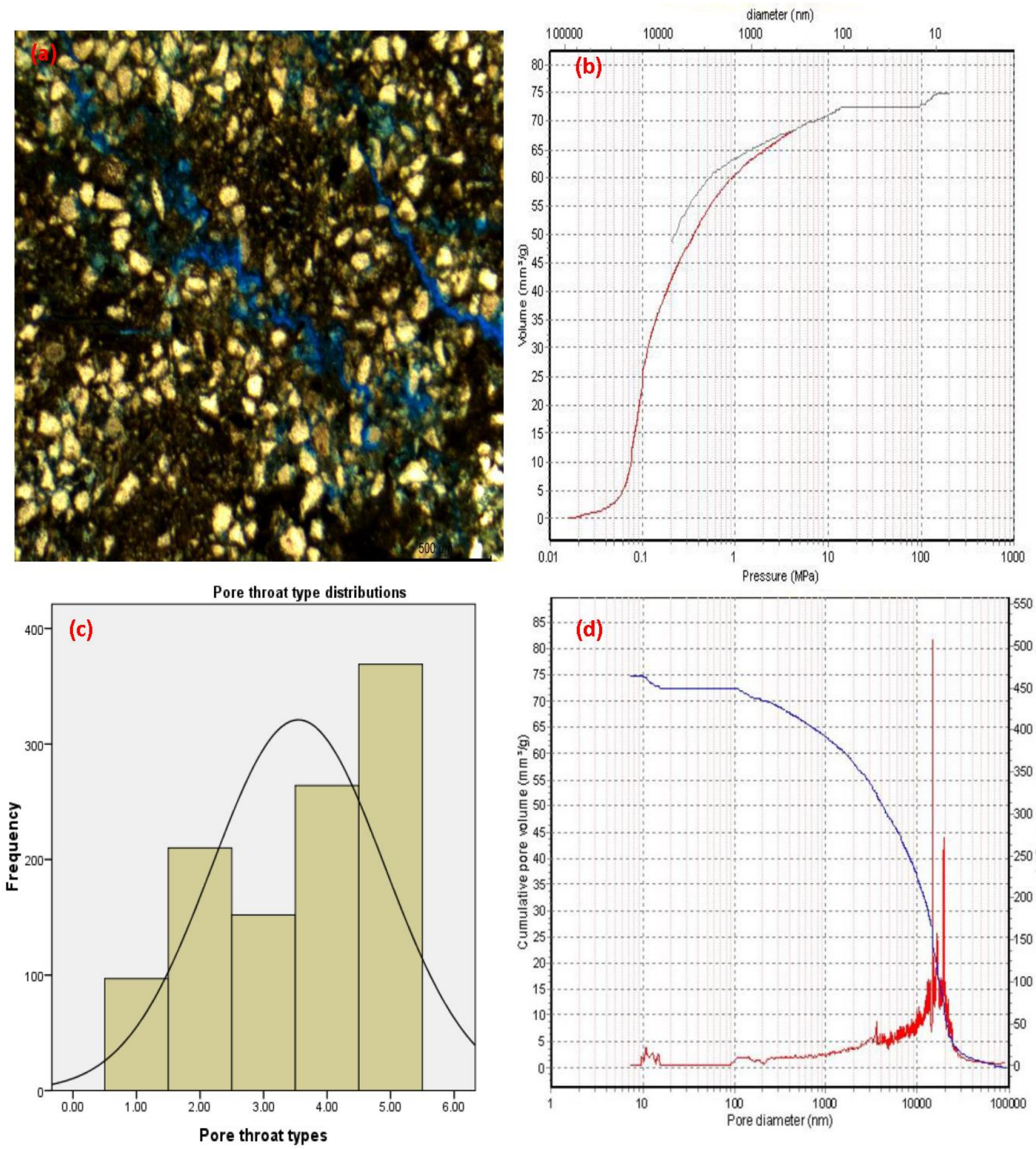

Figure 5. Pore throat sizes distribution, types and capillary pressure curves for Massive Friable Fine Sandstone

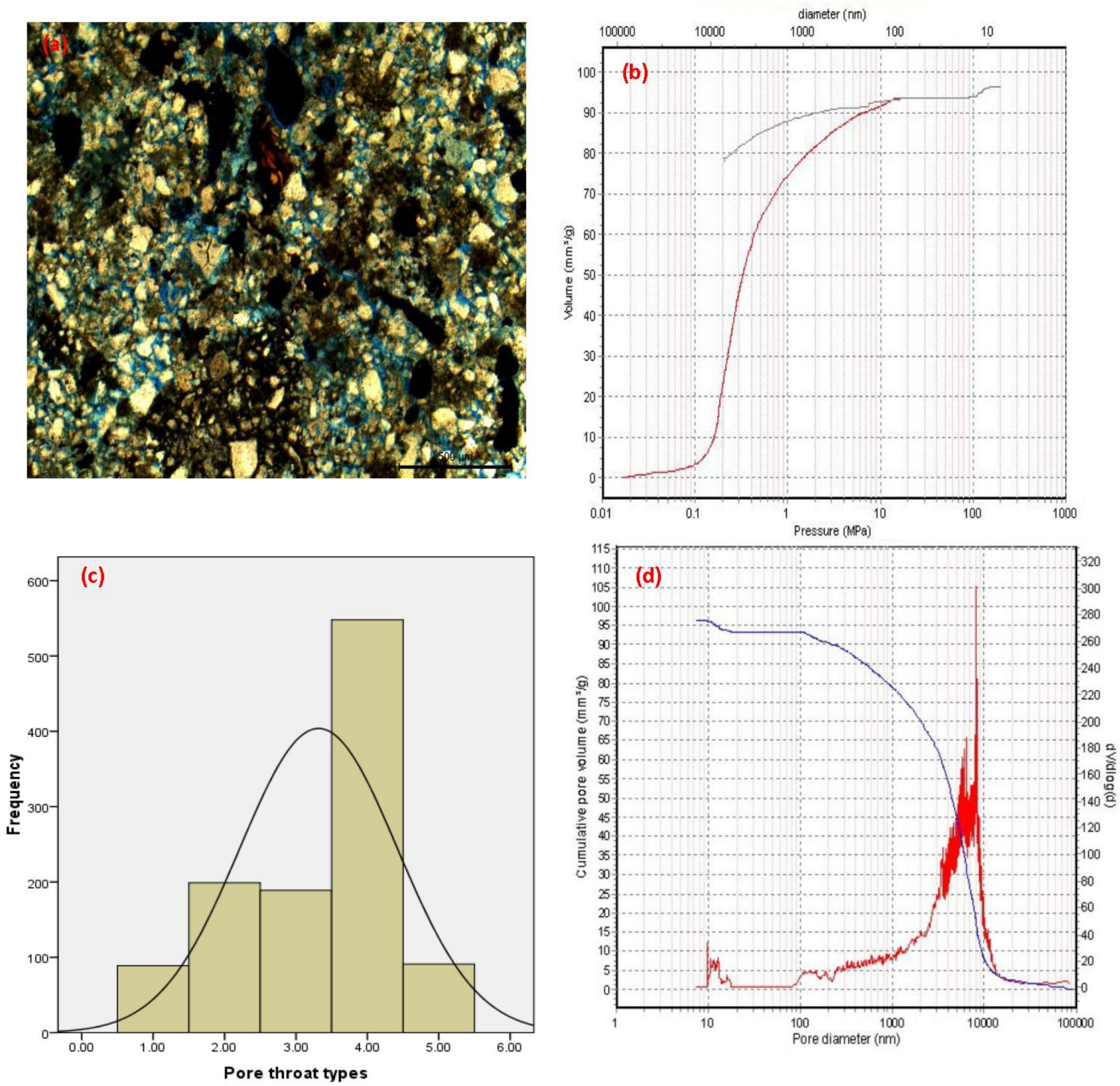

Figure 6. Pore throat sizes distribution, types and capillary pressure curves for Massive Fine Sandstone

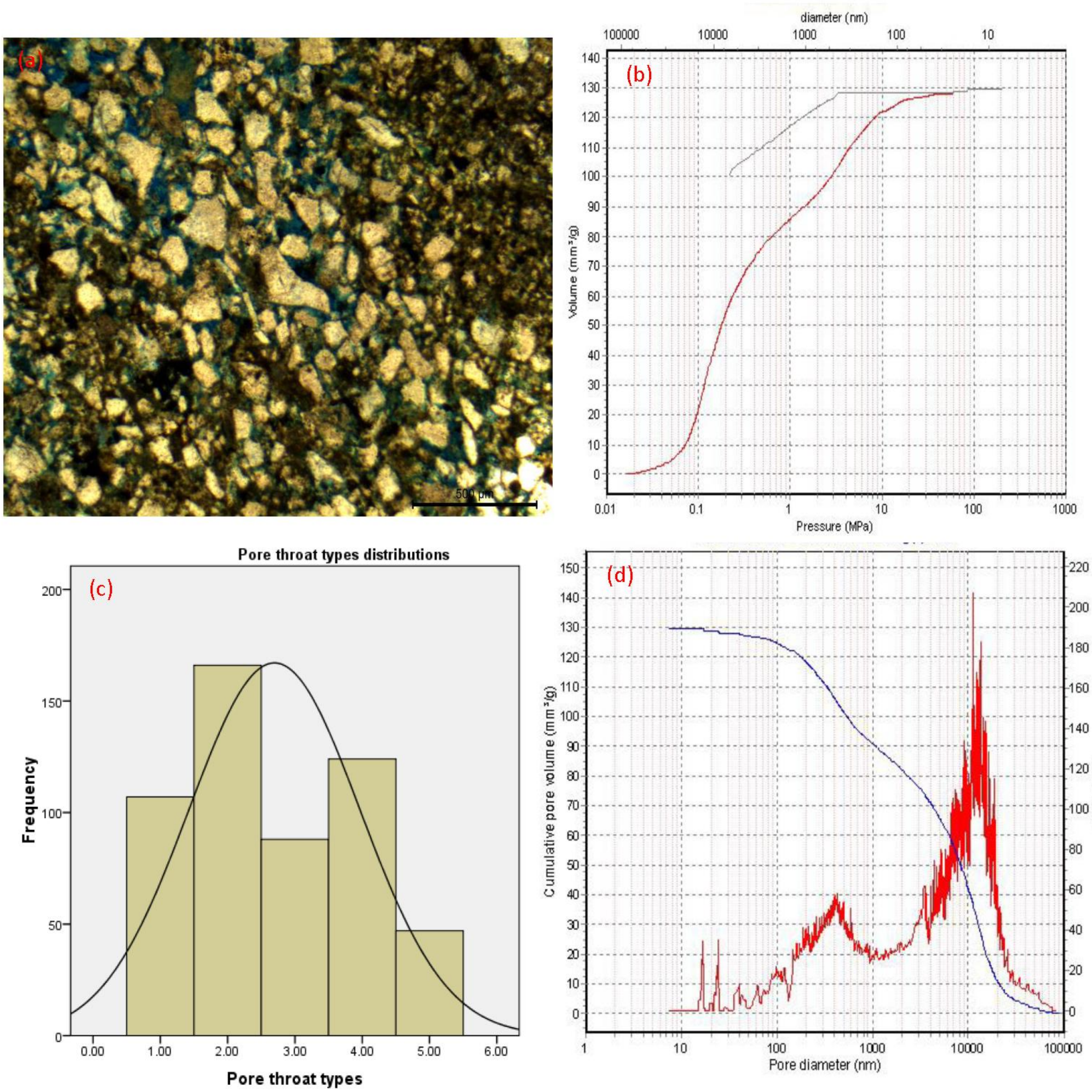

Figure 7. Pore throat sizes distribution, types and capillary pressure curves for Massive Very Friable Sandstone

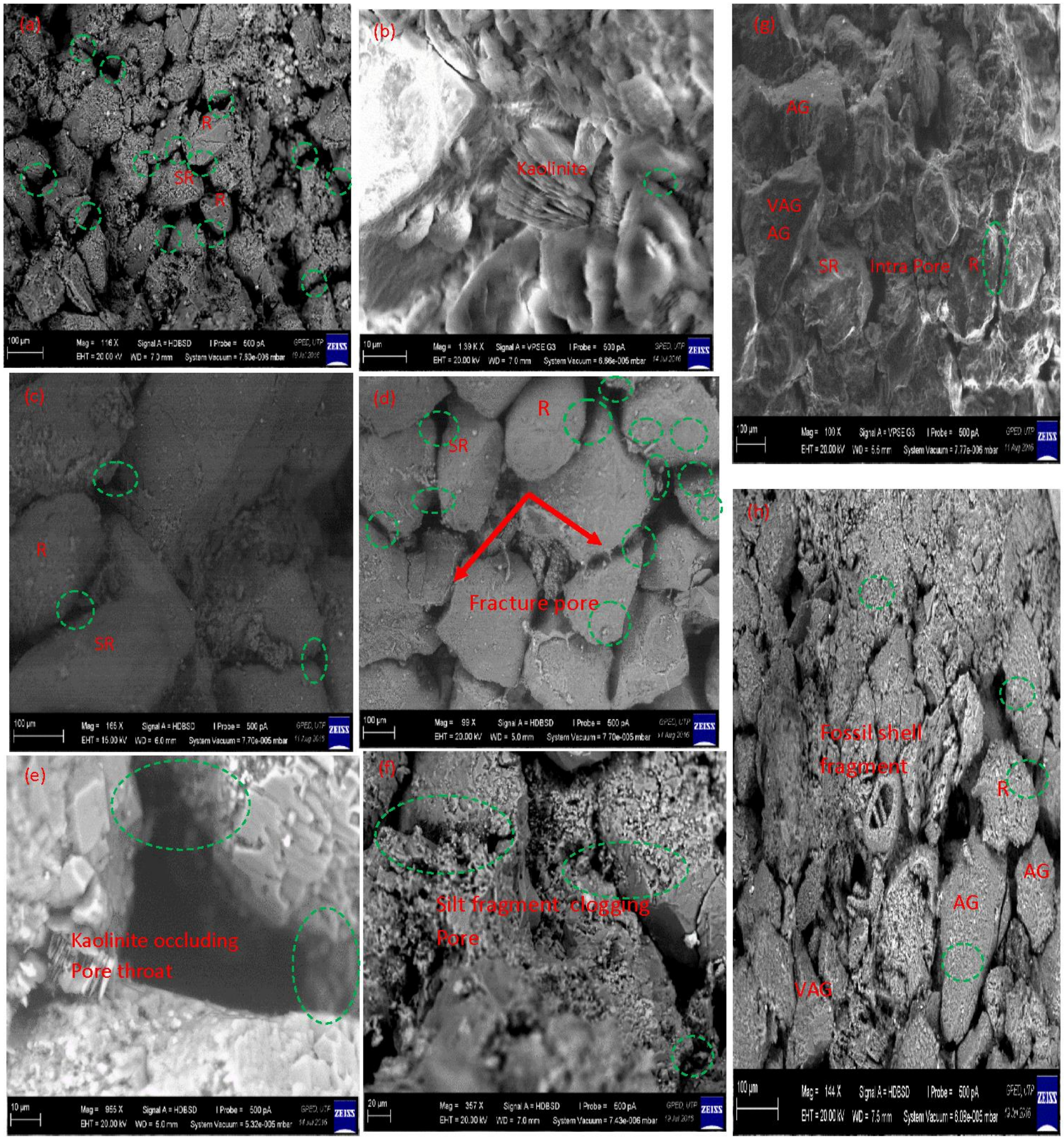

Figure 8. SEM micrographs showing variable effects on grain shapes and sizes on pore throats size variations. Also the role played by silts & pore-filling clays (kaolinite) clogging and occluding pores thereby modifying pore throats as depicted

3. Materials and methods

From five (5) reservoir sandstone lithofacies, twenty – five (25) 1.5″ core plugs and one hundred – thirty two (132) sandstone specimens within the Cycle IV/V of Middle to Upper Miocene age at variable depths were used for this study. The samples were collected from variable depths from the wells in Figure 2. The impregnated blue epoxy thin sections were made from collected specimen according to standard laboratory procedures for examination of grain-pore relationships. Digital image at 500μm magnification were uploaded into a Two-dimensional (2D) digital package, scaled and color splitted into three grey scale channels images. The obtained gray scale images were threshold, [23] to extract grain size, shapes, pore sizes and matrix information [24]. The generated quantitative datasets were evaluated for grain size and grain shape using standardized geometric sedimentological scale, [25-27]. Furthermore, mercury porosimetry equipment (MICP) Thermo Scientific PASCAL 240 Series was used for measurements and analysis of pore throats diameters, pore throat sorting (PTS) coefficient, [8,28] as in equation (1), irreducible water saturation and displacement pressure. The chips samples were initially cleaned with a Cole - Parmer Ultrasonic Cleaner, weighed in both water and air and the measurement taken by injection of mercury into the samples at high pressure.

The highest test pressure of 200MPa, at a temperature up to 25°C with mercury density of 13.534g/cm^3 was applied. The machine is programmed to automatically correct for variations in compressibility of samples.

$$PTS= \left[\frac{\text{3rd Quartile Pressure}}{\text{1st Quartile Pressure}}\right] 1/2 \qquad (1)$$

where the first and third – quartile pressures are obtained directly from the capillary curve reflecting 25% and 75% mercury saturation pressures adjusted for irreducible saturation.

The twenty – five 1.5″ representative core plugs were examine for porosity-permeability variations using an unsteady state gas permeameter and porosimeter (Coreval 30) machine in Universiti Teknologi PETRONAS. The equipment is powered within 110 -220 VAC, 60 Hz, and helium gas was injected into the core plugs at confining pressure up to 400psi and pore pressure of 250psi. The equipment measures permeability between 0.001md to 10 Darcie's and porosity up to 60%. Furthermore, permea-bility to gas test are performed by unsteady-state pressure fall-off technique. While the pore volume and porosity are evaluate through an isothermal helium expansion using expression of Boyle's and Charles' law.

4. Results and discussion

4.1. Petrography and textural compositional variations

The minimum and maximum textural compositional variations across the entire one hundred and thirty two (132) samples are given in (Table 1). The results for the variable abundance of grain sizes and shapes were quantified according to Udden [26]; Wentworth [27]; Geometric (modified) Folk and Ward [29] scales and Roundness classification by Powers [25].

In view of the results obtained, the percentage composition of matrix (M) in (n = 15) in the well to moderately poorly sorted (GST) samples are lower in composition as compared to other facies. In the well to moderate poorly sorted (WPS) samples of F5 are having the highest minimum composition, and the maximum of 46% within the well – sorted (n = 37) samples from F4. The granule composition (G) varies across the entire facies, having minimum value between null to 20% in F2; F5 and maximum value in F3 and F4. The very coarse sand (VCS) percentage compositions are at minimum in the variable facie of F3; F4; F5; F1 and F2, and however, but maximum in F3; F2; F5; F4 and F1 respectively. In F4; F3; F1; F5 and F2 coarse sand (CS) composition is minimum, but maximum in facies F3, F4, F5, F2 and F1. The medium sand (MS) is much in abundance in F3, F4, F5, F2 and F1, but minimum in F4, F3, F5, F1 and F2. In facies F1, F3, F5, F4 and F3, fine sand (FS) is at minimum variable composition, and maximum F3, F4, F5, F1 and F2.

The very fine sand (VFS) is lower in abundance in F3, F5, F1, F5 and F3, but higher in F3, F4, F2, F1, and F5. Subsequently, in all the facies, coarse silts (C-silts) are relatively lower across entire facies. But, much higher in F3 and F4 but lower in F1, F2 and F5. The medium, fine and very fine sands (MFVS) and clays (CY) are lower across the entire facies. The MFVS are higher in F3 and F4 as compared to other facies. The very angular grains (VAG) are much in an abundance in F3 and F5.

More so, the angular grains (AG) are also moderately higher in abundance in facies F3, F1, F4 and F5, but perhaps decreased in F2. The sub-angular (SAG), sub-rounded (SRG), rounded (RG and well-rounded (WRG) grains varies at different proportion across all the entire facies.

Table 1. The minimum and maximum textural compositional variations of the one hundred and thirtytwo (132) samples

Udden-Wentworth scale (Udden 1914, Wentworth 1922), Geometric (modified) Folk and Ward (1957) and Roundness classification (Powers, 1953)																		
Facies	Statistic	**GST**	**M** %	**G**	**VCS** %	**CS** %	**MS** %	**FS** %	**VFS** %	**C-Silt** %	**MFVS** Silt	**CY** %	**VAG** %	**AG** %	**SAG** %	**SRG** %	**RG** %	**WRG** %
F1	Max	WS	0.10	0.11	0.48	0.13	0.11	0.06	0.02	1.01	0.03	0.01	0.01	0.07	0.06	0.27	0.48	0.46
n = 15	Min		0.01	0.01	0.23	0.09	0.05	0.00	0.01	0.00	0.00	0.00	0.00	0.02	0.03	0.13	0.38	0.36
F2	Max	PS	0.22	0.18	0.54	0.24	0.12	0.05	0.05	0.02	0.02	0.00	0.00	0.02	0.09	0.21	0.45	0.41
n = 24	Min		0.07	0.00	0.43	0.15	0.09	0.04	0.02	0.01	0.00	0.00	0.00	0.00	0.05	0.14	0.39	0.23
F3	Max	MPW	0.39	0.38	0.62	0.33	0.14	0.48	0.19	0.30	0.06	0.01	0.09	0.16	0.25	0.23	0.54	0.27
n = 36	Min		0.08	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.01	0.07	0.13	0.16	0.13
F4	Max	PMW	0.46	0.38	0.51	0.26	0.13	0.28	0.17	0.29	0.05	0.01	0.02	0.06	0.13	0.28	0.47	0.32
n = 37	Min		0.08	0.00	0.00	0.00	0.00	0.03	0.01	0.00	0.00	0.00	0.00	0.01	0.08	0.18	0.33	0.16
F5	Max	PS	0.34	0.29	0.50	0.25	0.11	0.07	0.02	0.04	0.02	0.00	0.04	0.05	0.23	0.33	0.48	0.47
n = 20	Min		0.13	0.20	0.19	0.10	0.05	0.02	0.01	0.00	0.00	0.00	0.00	0.01	0.06	0.11	0.29	0.13

GST=*grain sorting,* ***WS***= *well sorted,* ***PS*** = *poorly sorted,* ***MPW*** = *moderately poor – well sorted,* ***PMW***= *poorly to moderately well sorted,* ***M***= *matrix,* ***G***=*granules.* ***VCS*** = *very coarse sand,* ***CS*** = *coarse sand,* ***MS*** = *medium sand, Fine sand,* ***VFS***= *Very fine sand,* ***C-silt*** = *coarse silts,* ***MFV*** = *medium, fine and very fine silts,* ***CY***= *clays,* ***VAG***= *Very angular grain,* ***AG*** = *Angular grain,* ***SAG***= *sub angular grain,* ***SAG*** = *sub angular grain,* ***RG*** = *rounded grain, WRG = well rounded grain.*

Table 2. The minimum and maximum pore types and grains orientation

Facies		**Pore information from 2D Image Analysis**					**Grain Orientation (in degree)**					
	Statistic	Micropores %	Mesopores %	InterP %	IntraP %	FracP %	0 -30^0 %	31 -60^0 %	61 - 90^0 %	91 - 120^0 %	121 - 150^0 %	151 - 180^0 %
F1	Max	0.83	0.09	0.32	0.04	0.08	0.19	0.28	0.15	0.14	0.41	0.29
	Min	0.62	0.02	0.16	0.02	0.03	0.07	0.19	0.05	0.08	0.19	0.13
F2	Max	0.97	0.05	0.25	0.06	0.11	0.17	0.31	0.19	0.15	0.25	0.19
	Min	0.95	0.03	0.19	0.03	0.00	0.10	0.18	0.05	0.06	0.17	0.13
F3	Max	0.99	0.06	0.39	0.20	0.12	0.17	0.28	0.08	0.18	0.27	0.29
	Min	0.94	0.01	0.04	0.00	0.00	0.10	0.13	0.05	0.10	0.19	0.15
F4	Max	0.99	0.07	0.29	0.14	0.13	1.00	0.32	0.12	0.20	0.31	0.25
	Min	0.93	0.01	0.06	0.00	0.02	0.08	0.00	0.00	0.00	0.00	0.00
F5	Max	0.99	0.02	0.29	0.10	0.15	0.14	30.4	0.25	0.25	0.46	0.31
	Min	0.29	0.01	0.13	0.01	0.02	0.06	0.15	0.09	0.09	0.16	0.12

InterP= *interparticle pores,* ***IntraP***= *intraparticle pores,* ***FracP*** = *fracture pores*

But however, rounded and well-rounded grains are relatively more in abundances when compared to any other textural grain shapes .However, this is an indicative of dominant similar depositional environment, whereby sediments are farther transported far away from their sources. Whereas the very angular (VAG), angular (AG) suggests sediments are deposited nearer to their source, [30]. However, the potential role played by the matrix (M) content, very coarse sand (VCS), rounded grain (RG), well-rounded (WRG), granule (G) and fine sand (FS) on pore throats are visually depicted in Figure 3(a), 8(a), (c) and (d).

4.2. Pore types and grains orientation variations

Table 2 presents the result of the 2D digitally quantified pore types and grain orientation distribution. From the table, it can be seen that, the minimum and maximum percentage of micropores, Loucks et al. [31] are higher across the entire facies, but perhaps a wide variations for mesopores distribution. The results reveal maximum abundance of mesopores in order of F1, F3 and F4. It is also noted that three (3) facies have the highest composition of sub-rounded grain (SRG) and rounded grain (RG) as shown in (Table 1) and (Figure 3a)

The maximum percentage volume of VCS, RG and WRG in these facies necessitate increase in abundance of interparticle pores (InterP) when compare to F4 and F5 as depicted in Figure 3(a), 4(a), 5(a) and 8 (a); (c) and (d). The minimum and maximum abundance of very angular (VAG), angular (AG) grains and shell fragments suggests the variable proportion of intraparticle (IntraP) pore types as shown in (Figure 6a; 7a; 8g and h)

The overburden pressure during sedimentation and burial after deposition suggest compression and compaction of available angular (AG) and very angular(VAG) grain composition probably reducing interparticle pores to intrapores spaces, [30] as depicted in Figure 8(g) and (h). The extensive tectonic events, Rijks [21] in the study area, suggests responsible for the variable volume of fracture pores (FracP) across the entire facies. As it can be seen also, the variation in pore types are moderately in abundance in order of F5, F4, F3 and F2, but lower in F1 as compared (see Figure 8d). The textural admixture also shows variable degree of grain orientations, F4 have the maximum of 0^{o}–30^{o} composition, but minimum in F5. The percentage of 31^{o}–60^{o} oriented grains is higher in F5, F4, F2, and at minimum in F1 and F1. However, it can also be seen that, grains oriented at 61^{o}-90^{o} are much in abundance in F5, F2, F1 and minimum in F3 and F4. In F5, F4 and F3 oriented grains at 91^{o}–120^{o} are more dominant, but lower in F1 and F2. More so, oriented grain greater than 120^{o} but less than 180o is abundant in F5, F1; F4 and minimum in F3 and F2.

The results indicate that in textural composition admixtures, sediments especially coarse sand (CS), coarse silts (C-silts) and medium grain sand (MS) oriented at an angle > 100^{o}, suggests to enhance the development of wider pores size (mesopores and macrospores) and possibly wider pore throats diameter (see Figure 8a and d) as indicated with dotted green circles. While those whose grains are oriented < 100^{o} suggest enhancing development of micropores. However, fine sand (FS) and very fine silts (VFS) are not affected by grain orientation, and thus is suggested to be neglected.

4.3. Pore throat size, types and distribution

From the mercury Injection capillary pressure (MICP) chart, Figure 3(d), pore throat sizes abundance and distributions in the variable textural admixture variations in the different facies are evaluated. The percentage minimum and maximum pore throat type distribution summary of the one hundred and thirty-two (132) samples from five (5) sandstone facies are given in Table 3.

4.3.1. Coarse friable sandstone (CFS); F1

The well-sorted coarse friable grained sandstone facie (Figure 3a) composes of variable quartz textural admixture as seen in Table 1 in (n=15) samples. Pore throat type distribution in percentage varies from type 1 to 5 in all the facies, Table 3. As can be seen that type 1 pore throat is the least when compared to minimal percentage values across the entire facies.

The other pore throat type composition varies also across the facies with maximum percentage distribution in Type 5 with minimum and maximum values of 30% and 50% (Figure 3c and d).

4.3.2. Massive coarse sandstone (MCS); F2

This facie comprise of moderately well-sorted quartz grained sandstones within the n = 24 members, Figure 4(a). The variable textural composition also varies across the entire facie (see Table 1) samples, as can be seen also in Table 3, Types 4 pore throat with minimum and maximum percentage values of 9% and 33% are (Figure 4c and d)predominant as when compared to coarse friable sandstone facie. However, other pore throat types vary within the facies (see Table 3.).

Table 3. Minimum and Maximum pore throat types distribution

Facies	Statistic %	Micropore throats			Meso pore throats	Macro pore throats
		Type 1 (0.001–0.01 μm), %	**Type 2** (0.101–0.1 μm) %	**Type3** (0.1001– 1 μm) %	**Type4** (0.001 – 10μm), %	**Type 5** (10,0001 – 100 μm, %
F1	**Max**	0.18	0.27	0.11	0.22	0.50
	Min	0.07	0.11	0.06	0.11	0.30
F2	**Max**	0.12	0.17	0.12	0.33	0.43
	Min	0.08	0.11	0.08	0.09	0.28
F3	**Max**	0.22	0.32	0.33	0.35	0.41
	Min	0.08	0.11	0.05	0.14	0.05
F4	**Max**	0.49	0.38	0.30	0.49	0.35
	Min	0.08	0.17	0.09	0.08	0.08
F5	**Max**	0.28	0.39	0.23	0.30	0.41
	Min	0.10	0.13	0.12	0.17	0.04

4.3.3. Massive friable fine sandstone (MFFS); F3

In the poorly to moderately well sorted (n = 36) samples sandstone facie (Figure 5a). The textural composition differs from the grain shapes, size and pore types also (Table 1 & 2), however, as can be seen in Table 4, type 2, 3 and 4 pore throat are more prominent in this facie as obtained from MICP chart (Figure 5c - d) when compare with already discussed facie above.

4.3.4 Massive fine sandstone (MFS); F4

The quartz grains within the n = 37 samples are poorly sorted (Figure 6a), and also compose of variable textural components (see Table 1& 2). The pore throat type prominent in this facie varies from type 1, 2 and 4 as obtained from MICP chart, Figure (6d - c).

4.3.5. Massive very friable sandstone (MVFS); F5

In this facie with total sample size n=20. The poorly sorted grained sandstone facie comprise of variable textural admixture (see table 1 & 2) and MICP chart (Figure 7d). Pore throat type distribution histogram (Figure 7c), the most prominent pore throat types include Type 2 and 4.

The results indicate that the percentage abundance of certain pore throat types is functions of the most predominant discrete textural composition (see Table 1). However, it also indicate that facies with high abundance of granule (G), coarse (CG) rounded (RG), sub-rounded (SRG), well-rounded grains (WRG) with certain degree of grain sorting contribute to abundance of "Type 5" pore throats which are classify as "macro-pore throats" More so, it shows that difference in percentage volume of medium rounded, sub-rounded and well-rounded grains with certain percentage of fracture pores (FracP) suggests "Type 4 "pore throats classified as "mesopore throats" (see Table 4 and appendix). The fine sand, silts and clays (Figure 8e) filling interparticle and pore spaces (see Figure 8a, c, d, e and f) by clogging and occluding pore throats (as depicted with green dotted lines in Figure 8), suggests the variable percentage distribution of the "Type 1–3" classify as "micro pore throats".

4.4. Pore throat sorting (PTS)

The capillary pressure data (Figure 3b) obtained from the well-sorted coarse grained friable sandstone facie. The first and third quartile pressures reflecting 25% and 75% mercury saturation are 0.04psi and 0.07psi. The PTS coefficient obtains is 1.75, and suggests reflecting perfect sorting [8]. In the well to moderate poorly sorted F2, the PTS obtained from (Figure 4b) capillary data is 8 from 0.05psi and 0.4psi corresponding to 25% and 75% mercury saturation pressures. The calculated value for PTS is 1.2 corresponding to first and third quartile pressures of 0.038psi and 0.048psi from (Figure 5b) in this F3 facies inferred to perfect sorting for pore throats. In F4 facie, the plateau in the capillary data in (Figure 6b) is not flattened as in F1 and F3. The first and third quartile pressures are 0.2psi and 0.63psi yielding 3.1 at the 25% and 75% mercury saturation. In the last facie, F5, the bimodal MICP data (Figure 7a) reveal also discordant in the pore throats sorting.

The obtained first and third quartile pressure vary as 0.1psi and 0.32psi (Figure 7b), thus reveal 3.2 for the pore throat sorting coefficient corresponding to no essentially sorting of pore throats distribution. The results are in agreement within acceptable range [8]. However, this evaluation also suggests pore throats connectivity in reservoir sandstone. Hence, as the PTS value decreases, the pore throats sorting and its connectivity increases and perhaps vice versa.

4.5. Pore throat types implication to irreducible water saturation, displacement pressure and permeability

4.5.1. Irreducible water saturation

The irreducible water saturation is equated to the percentage volume of water absorbed into the mineral surface [17], that pores within cannot remove it at maximum pressure. The irreducible water saturation varies across the facies in order of F1, F2, F3, F4 and F5 for 0.07 (0.93 of mercury saturation), 0.05 (0.95 of mercury saturation) and 0.03 (0.97 of mercury saturation), 0.07 (0.93 of mercury saturation) and 0.01 (0.99 of mercury saturation). However, this distribution is attributed to the variations the percentage volume of mesopore and macropore throats. Consequently, at reservoir condition, this facies transmit out more fluids due to abundance of these throats Type 4 and 5 and more so very minimal amount of water is trapped within the pores. This presented behavior hold strong potential for higher hydrocarbon recovery.

The results indicate that, as the abundance of mesopore throat and macropore throat increase, the percentage of irreducible water saturation decreases.

4.5.2. Displacement pressure

The F3, F1, and F2 have the lowest displacement pressure of 0.038psi, 0.04psi and 0.05psi psi. The abundance and distribution of mesopores and macropore throats (Type 4 and 5) in these facies necessitate ease entry of mercury into the samples. Consequently, at reservoir condition it will require lower displacement pressures to move hydrocarbons into the facies.

The predominant (Type 1 & 3) pore throats in F4 and F5 facies require higher displacement pressures up to 0.2psi and 0.1psi to move hydrocarbons into the samples in the facies.

4.5.3. Permeability variations

In F1, the higher composition of very coarse rounded, well-rounded and granule grains (see Table 1) necessitate the abundance of interparticle mesopores, and perhaps this suggest high composition of Type 4 & 5 pore throats. However, fine sand, very fine sand, clays, medium, fine and very fine silt are lower in abundance, and that necessitate the decrease in abundance of micropores, and thus Type 1, 2 & 3 pore throats when compared to other facies. This variable admixture suggest to reflect perfect pore throat sorting of 1.75 [8] responsible for the low capillary and displacement pressures. The pore throats sorting (PTS) obtain explain the potential high permeability measurement from the core plugs in this facie (see Figure 9)

The moderately poor sorted F2 constitutes very coarse rounded, well rounded, and very angular grains sand. However, it also contains moderately high matrix and granule content as compare to F1. This compositional variation also suggests the moderate high distribution of microporosity and decrease in mesopore (see Table 1 & 2), and therefore varying the abundance Type 2 & 4. This variable abundance admixture suggests contribution towards obtaining PTS value of 8, that essentially reflecting no sorting, [8] in the pore throats distribution. The textural composition discrepancies and poor pore throat sorting resulting in very low permeability measurement in this facie (see Figure 9).

In the moderately poor to well sorted facie F3, it comprise of the highest abundant of granule, very coarse and coarse sand, coarse silts sub-rounded and rounded grains than it matrix composition (see Table 1&2). This variable admixture suggests responsible for the existing abundance of interparticle mesopores and micropores as compare to all other sandstone facies.

These pore type distributions suggests to enhance high abundance of mesopore and macropore throats types, perhaps also to be responsible for the decrease in irreducible water saturation and displacement pressure. However, the obtained perfect pore throat sorting of 1.2, suggest to necessitate the moderate high permeability measurement from the core plugs (see Figure 9).

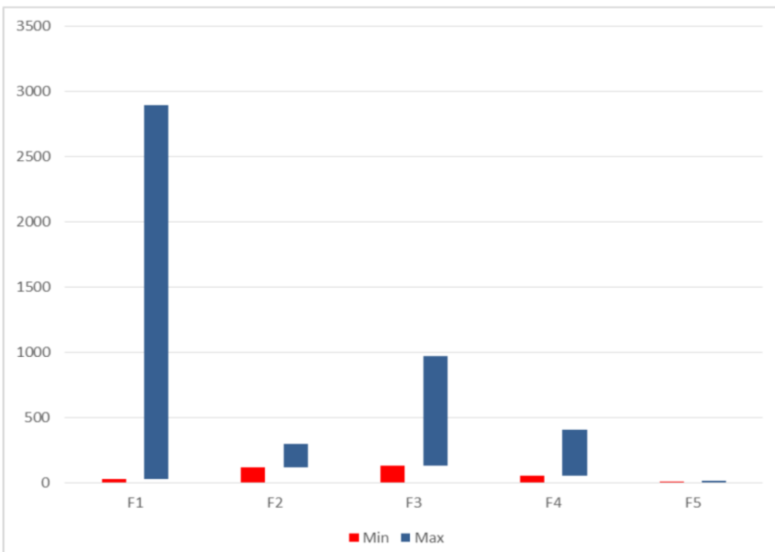

Figure 9. Showing permeability variations

The moderate abundance of Type 4 pore throats in this facie; F4, and decrease in irreducible water saturation suggests be attributed to the variable abundance admixtures of the medium coarse, sub-rounded, rounded, well-rounded grains and embedded variable sizes of shell fragments (see Figure 8h) in this facie. However, the increasing volume of matrix (M), also suggests the high abundance of micropores (see Table 1 & 2) and micropore throats. More so, this variation necessitates the slight relatively increase in displacement pressure.

Consequently, the uneven distribution in pore types, suggests responsible for poor throat sorting coefficient of 3.2 rating it as essentially no sorting, and perhaps suggests be responsible the decrease in the permeability measurement (see Figure 9).

The poorly sorted (F5) sandstone facie contains abundance of Type 1 & 2 pore throats, which are suggests resulted from spatial distribution and abundance of matrix (M) compositions (see Table 1 & 2) as shown in Figure 7(a). These variations, also suggest necessitating decrease in abundance of mesopore, and the increase in micropores in this facie.

The prominent abundance of the micropore throat types, suggest the slight increase in the displacement pressure, but the mesopore throat types suggests to necessitate for decrease in irreducible water saturation in this facie. This variability in pore throat type necessitated pore throat sorting value of 3.2, ranking this facie samples essentially no sorting in pore throats distribution, and this however, clarifies the very low permeability measurements in this facie.

The results indicate that, pore throat sorting (PTS) and the effective abundance of mesopore, macropore and micropore throats in reservoir sandstone suggests determine pore throat connectivity, and the variability in irreducible water saturation, displacement pressure, permeability measurement.

5. Conclusions

This study was devoted to assess the impact of the discrete textural compositions on pore throat diameters/type and sorting variations in reservoir sandstone, to evaluate its potential implication on displacement pressure, irreducible water saturation and permeability. The results of discrete textural compositional variations indicates that certain percentage abundance of the medium, coarse, very coarse, granule, fine sand, very fine, silt and clays, sub-round, rounded and well-rounded grains contribute to determining the abundant pore sizes, pore throat types and pore throat sorting. The percentage composition of medium to coarse sub-rounded well-rounded and granules have strong influence on the amount of mesopore and macropores sizes developed, due to proxy to circular shape effect over the other grain shapes such as angular and very angular grains. More so, sorting with grain orientation result indicate that grain oriented at angles > 100° favor abundance of more mesopore and macropores, while grains oriented < 100° facilitate abundance micropore sizes.

However, all this reveals to contribute to determine the predominant pore throats diameter and percentage composition. The identified five (5) pore throats types were classified as micropore throats, mesopore throats and macropore throats according to their diameters as measured from mercury injection capillary pressure data (MICP). The pore throat sorting coefficient values, shows that decrease in the value, translate to perfect pore throat sorting, and its increase towards maximum of 5 and above implies to be essentially no sorting in the pore throats. More so, as the percentage abundance of mesopore and macropore throats increases, the irreducible water saturation and displacement pressure decreases, but thus permeability increases. Whereas, increase in percentage of micropore throats, necessitate increase in displacement pressure, irreducible water saturation and decrease in permeability values. The composition distribution of mesopore and macropore throats are most facilitated by the discrete composition of medium to coarse sub-rounded, well-rounded grains and porous fossil shell fragments, while matrix contents, clogged and occluded pores enhances development of micropore throats. Thus, this resulting to decrease in permeability measurement. Pore throats sorting coefficient reveals to be an essential assessment for determining the degree of throats connectivity in reservoir sandstone.

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To whom correspondence should be addressed: Dr. I. Yusuf, Department of Geoscience, Faculty of Geoscience and Petroleum Engineering, Seri Iskandar, 32610, Perak, Malaysia