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Are Natural Fractures in Sandstone Reservoir: Water Wet – Mixed Wet – Or Oil Wet?

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ABSTRACT

This study accurately measures the wettability contact angle of native Kuwaiti sandstone reservoir that hosts mixed pore size distributions in both the tight sandstone matrix as well as the natural fracture (NF) embedded in it. Also, this study, effectively, investigates the geometrical size and shape of natural available voids whether matrix voids or NF voids captured in the rock 2D image frame system. Correspondingly, this study is, successfully, measure tight matrix, NF Pore wall, and NF pore opening wettability performance and recovery efficiency contributions inside the sandstone reservoir. A model pore/ grain contact angle wettability is generated. Therefore, this study thrives to enhance new physics that will advance reservoir characterization and production improvement through modeled and measured wettability contact angle.

The prepared fresh tight sandstone rock sample in the form of rock fragment is imaged and characterized for porosity, permeability, and wettability contact angle in 2D format utilizing SEM-BSE imaging techniques. The generated images will be quantified using pre-defined logic for wettability contact angle measurement. The data generated will be used to estimate the wettability distribution. Each image captured will be investigated for a magnification of X51 (1 mm Scale). This magnification scale will ensure measurement of all possible pore/ grain petrophysical porosity & permeability features, as well as wettability contact angle of 3 region representations for the tight matrix, the natural fracture pore wall, and the inside fracture void.

From measured data and computed logics, the majority portions of natural pore voids and pore-walls are medium-water-wet; however, some fracture-pore-walls show mixed and strongly oil wetting preference. The main factors in the understanding the fracture wettability are pore size distribution and pore morphology that suggests the wettability affinity likelihood. This study shows 3 natural pore regions: tight matrix, natural fracture pore wall, and inside the natural void space. These regions are necessary to characterize wettability behavior for oil production and crude oil reservoir recovery schemes, especially in EOR schemes such as water production and/ or water injection operations. Also, the fracture-to-matrix ratio shows some new interesting features characterizations.

Keywords: Natural fracture (NF) wettability preference; Natural fracture reservoir wettability assessment; Pore counting method; 2D image technology; Big Data

INTRODUCTION

Geological genesis constant actions that cause the breakage of rocks and the occurrence of continuous fractures are usually very complicated phenomenon especially in tight sandstone reservoirs. The presence of any complicated opening such as a fracture in sandstone reservoir's grain matrix gives evidence that the reservoir is tight in nature compared with the surrounding matrix. Also, this rock opening is considered as an unconventional pore system if compared with an overall unconventional matrix porosity and permeability of any total reservoir pore/ fracture void system.

Fluid/ rock relationship when fracture is available in the overall rock matrix will be crucially affected and force several fluid mobility changes due to wettability nonconformities in the behavior of the rock and fluid affinity preference. Natural fractures (NF) can also create significant permeability anisotropy, which in turn can influence the reservoir hydrocarbon production throughput in a mechanism called permeability pore enlargement.

Characterization of naturally fractured reservoirs has usually focused primarily on fractured rock petrophysical properties and morphology, such as fracture porosity and fracture permeability, fracture orientation, fracture morphology: length and width, fracture spacing, and fracture density (Al-Bazzaz, et. al. 2009). However, this study NF characterization focuses mainly on another important petrophysical property, which is characterization of wettability distribution through wettability contact angle measurements. Wettability contact angle measurement will be considered in three zones: within the tight matrix pore/ grain boundaries, within the natural fracture wall captured inside a tight sandstone rock matrix, and inside the NF void space. Also, these wettability contact angle measurements are determined using unconventional laboratory deterministic equipment spread over 2-Dimension (2D) Scattered Electron Microscopy (SEM) with Backscattered Electron (BSE) digital imaging format. These 2D-SEM-BSE images will calculate the wettability contact angle distributions, porosity distribution, and average permeability at the fracture and at its surrounding tight sandstone matrix for a tight sandstone case study Kuwaiti reservoir.

Commercial quantities of untapped hydrocarbons reservoirs will demand this approach of rock characteristics where conventional porosity and conventional permeability properties limit the expansion of sustainable crude oil production (Al-Dousari et. al., 2021). Global world (NF) reservoirs will require wettability innovative characterizations, especially (NF) reservoir contact angle measurements. The (NF) contact angle wettability contribution will assist the understanding of increasing crude oil production. Historically, understanding (NF) reservoir rock wettability, porosity and permeability parameters is considered complicated characterization. Now, (NF) wettability characterization is further considered greatly important for crude storage and fluids flow through the fractured rock, especially for early production. Early production new knowledge requires further investigation and description of wettability alterations starting from fluids transfer at the reservoir pore/ grain matrix into the wall of the natural fracture surface and to the inside of the fracture void space passing to the wellbore sand face all the way to surface production facilities. Incorporating wettability properties can help advanced stages of production.

As a result, natural fracture reservoir wettability assessment is considered as critical weighted parameter suggested for petrophysics, reservoir engineers, and geologists in order for unbiased solutions and planning of reservoir recovery schemes throughout the lifetime of reservoir development: exploration, early production, and continuous development. In addition, evaluation of the wettability for newly discovered induced fractured reservoirs, the discovery of tight unconventional shales, or as tight porosity/ permeability fractured sandstone (Agada and Geiger, 2014). Furthermore, hydrocarbon characteristics especially heavy oil production needs more investigation in terms of wettability of natural fracture reservoir (Algharaib et. al., 2019). This study will be focused on static digital wettability measurements. The unconventional static digital wettability used for this study is the measurement of the wetting of a fracture solid surface wall by an adjacent hydrocarbon liquid at rest, and it is usually represented by the static big data contact angle captured and processed (Almudhhi et. al. 2021). The angles investigated are located where the solid/ liquid interacts usually inside a rigorous pore void, or at the boundary intersection between the solid surface (pore walls) and the measured liquid film in 2D format. In abstract, Al-Bazzaz et al, 2019, showed that conventional testing of wettability will yield ambiguous, inaccurate, and meagre contact angle quantity values because conventional contact angles are often estimated by an empirical formula; or estimated from insubordinate, vulnerable, and nonrealistic assumptions using over-simplistic data of ideal reservoir rocks conditions. This inadequate efficiency or lack of wettability measurement, exclusively in natural fractured reservoir (NFR), suppress the potential zones and always depreciate the role of natural fractured (NF) from wettability standpoint due to lack of natural fracture wettability measurements (Solar et al. 2020).

In this microscopic scale pore level study, wettability characterization is measured using digital approach to determine the contact angle of pore shape and pore geometry boundaries as well as on fracture walls inside reservoir rocks. For pore geometry manifestation of wettability contact angles, a morphological technique of 2-D image capturing is suggested. However, the proposed technique is inclined to calculate porosity and permeability using 2-D images from the described shape pores of NF and their surrounding pore matrix. This manifestation is carried out by capturing the static image of (NF); then using high precision point-counting logic to scan the matrix pore and NF contact areas, such contact areas parameters are available in natural fracture features (Al-Bazzaz et. al. 2007).

This study utilizes thousands fracture/ matrix pore area measurements as well as thousands of measured fracture/ matrix contact angle as the criterion parameter for all analysis. Complex morphological natural fractures as well as tight matrix pore features measurements are honored based on actual pore area and actual pore contact angle representations (Tutuncu et al. 2018). This will yield huge wettability contact angle data that needs to be analyzed to find relations about matrix pores as well as natural fracture fluid flow contributions that enable optimizing hydrocarbon recovery and cost through time reductions (Al-Bazzaz et.al. 2007). The availability of large amounts of data helps in developing models and observes wettability patterns.

Statement of the Problem, Justification and Objective

The natural fracture (NF) wettability assessment of tight petroleum reservoir rock in general and towards tight sandstone in particular, and its effect on various aspect of hydrocarbon recovery in petroleum reservoirs is considered emerging research topic in the last decade due to the importance of the economics of remaining oil recovery. Although researchers have studied many natural fractures in sandstone reservoirs, the (NF) total affinity wettability preference yet remains to be discovered. Are (NF's) in this sandstone reservoir: water wet – mixed wet – or oil wet? Does the complex NF features actually control the wettability in this tight reservoirs? Correspondingly, this study main objective is to advance wettability contact angle characterizations into pore level (micrometer and nanometer) scales to investigate the size and shape of captured natural fracture pore/ surface wettability behavior available within captured matrix pore voids inside fresh sandstone reservoir rock sample and their wettability performance. And, subsequently, this study will enhance the understanding of the total reservoir production limits & efficiencies through the natural fracture wettability distribution. This study will focus the wettability attributes of the natural fracture contribution inside a Kuwaiti tight sandstone reservoir. All characterizations will utilize pore counting method and big data associated with 2-D digital imaging technique. In addition, porosity and permeability will be considered and measured by this technology.

Natural fractures Background & Summary

Reservoir rock and fluids properties are the backbone of most activities in exploration and production. Therefore, relaying on close-captured contact angles measurement of wettability properties is very essential and one rational method is using proven experimental digital measurement (Al-Bazzaz, et. al. 2018) (Albazzaz, et. al 2019) (Almudhhi, et. al. 2021). There are many digital styles to group the measured contact angles data. The digital measurement technique uses grouping equally spanned angles. The rationales for this method use the following practice: first, the concept of wettability is a distribution of big data, so thousands of measured data angles can be grouped for averaging and modeling purposes. Second, the Software technology limitation is maximized at 10 colored classes (clusters) only. This technique permits working with less than 10 colored clusters (less colored calculations); however, this technique cannot use/ classify more than 10 classes (10 colors). Third, the contact angles can be equally spanned between 0° to 360° degrees over 10 clusters for each cluster is 36° degrees. Another technique can use fixed colored clusters, such as contact angles fixed at 0°, 30, or 60° and so forth. But fixed contact angles limits only 10 selections and this type of selections to study larger pore/ grain features. Fourth, 10 colored clusters can be studied differently on the basis of how often they can occur or repeat themselves. Many hidden factors such as angle number, area, perimeter, elongation and circularity can be better represented in a colored cluster format, for each and every boundary angle is studied separately. Therefore, clustered big data are easily modeled for trend or pattern recognitions. Finally, grouping/ Clustering can produce new knowledge.

Reservoir rock samples are accomplished, as part of formation evaluation process, there is principally two types of core tests: Routine Core Analysis (RCA) or Special Core analysis. RCA generally provides measurements of porosity, permeability, grain density, fluid saturations and lithology of the core sample. Special core analysis mostly refers to SCAL tests that are displacement experiments in the rock samples to determined capillary pressure wettability, and some other parameters like capillary pressure. In addition, petrographic and thin section analysis, (SEM) microscopy and (CT) Scanning are applied to achieve better picture of the sample into pore level (Figure 1). 2D-SEM-BSE will be used to determine rock properties such as wettability contact angles, porosity and permeability by capturing an image from a thin section scale X51 (mm scale) of rock sample, then scan the captured image using image analysis software that has the ability to accurately measure several morphological parameters of pore and grain spaces as stated by Almudhhi et al (2021) pore Area including width and length, Pore Elongations, Pore Roundness, etc. Each feature will be shown and discussed in the result tables.

In Kuwait, tight sandstones are classified as naturally fractured reservoirs, or have been identified as being natural fracture-controlled reservoirs. Efficient management of these complex reservoirs requires the application of unconventional approaches (Sharifigaliuk et.al. 2021)

Figure 1. The SEM–BSE Captured Sandstone Reservoir Rock Image

Procedure and Scope of Work

The sandstone rock sample used in this research is prepared in the form of rock fragments. This rock fragment has fresh pores/ grain/ NF captured state inside represented fresh core plug. The analyses considered is on the fresh uncontaminated face. so that it will be imaged and categorized for porosity, permeability, and wettability contact angle in 2D format applying SEM-BSE imaging techniques. The produced images will be counted using pre-defined logic for wettability contact angle measurement. Data output will be used to approximate classification of wettability in the matrix adjacent to the NF, the wall of the fracture and inside the fracture. Each image is captured, then it will be investigated for wettability contact angle at a magnification of X51 (millimeter scale) to ensure all matric, NF wall and cavity spaces, confirming pore/ grain boundary region size, shape is captured. Also, capturing the number of big data representations for the natural fracture (NF) will endorse models to examine the NF and tight matrix relationships.

This study is divided into three phases. In phase I, image capturing, which includes emphasizing all possible wettability regions adjacent, inside and surface wall of the NF to understand the architecture performance of the fractured reservoir. In phase II, the static contact angle big data measurement is collected from 2D-SEM-BSE through sets of experiments. These data sets are analyzed to create a NF wettability model that will represent the tight sandstone reservoir. The last phase, Phase III involves the interpretation and discussion of the data collected in phase II, using the model developed in phase II and the resulting recommendations and conclusions.

The trim ends of the collected sample have been grinded and smoothed to create an organized thin section, to get clear and pure appearance of the captured image. This step is very significant to reach the optimum and accurate results by collected the required data which will be used to investigating the discussed rock properties. After Grinding and cleaning the collected sample, the rock fragment sample is inserted into SEM-Captured images and a 2-D image is being captured then scanned (Figure 1). An image with obvious NF pore/grain produced by SEM is shown in Figure 2.

Using a software, ten subcategory classes is generated with equally spaced width where each one is assigned a different color as shown in Figure 3 (Al-Bazzaz et.al. 2018, 2019) and (Almudhhi et.al. 2001).

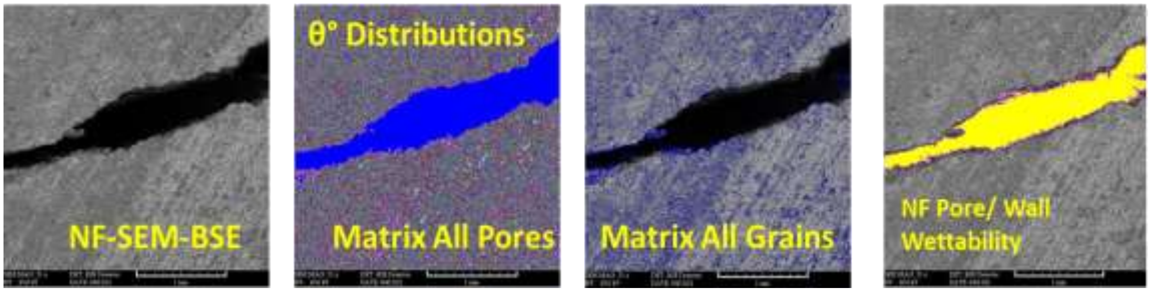
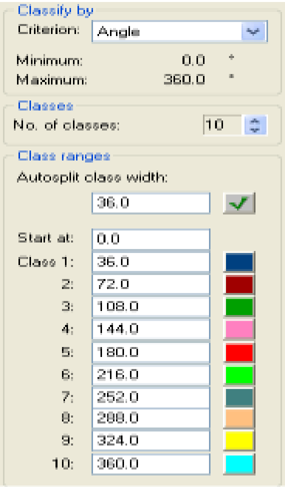


Figure 2. SEM-BSE captured image for the Kuwaiti Tight Sandstone Reservoir showing All Available Pore Contact Angle Measurements for 3 Regions: Tight Pore/ Grain Matrix, Natural Fracture (NF), and Natural Fracture (NF) Cavity Pore Wall



Criterion: Angle

Minimum: 0.0 °
Maximum: 360.0 °

No. of classes: 10

Autosplit class width: 36.0

Start at: 0.0

Class 1:	36.0	🟦
2:	72.0	🟥
3:	108.0	🟩
4:	144.0	🟪
5:	180.0	🟥
6:	216.0	🟩
7:	252.0	🟦
8:	288.0	🟧
9:	324.0	🟨
10:	360.0	🟦

Figure 3. Wettability Contact Angle Classification Color Key Identification

Analysis and Characterization

The rock sample shown in Figure 2 is imaged with a magnification of millimeter scale at X51 scale and then characterized for pore and grain space features, serious of count number, pore/ grain area (μm^2), and pore/ grain wettability contact angle (θ°) available in the SEM-captured Image. These pore space count-number will be referred to as object number. Each pore space has unique different size and shape. Also, each pore area will be measured in (μm^2) and different classes will be generated and arranged base on Angle magnitude. So, in this study the three regions (matrix, NF wall, and inside NF) will be appeared and separately measure the rock wettability: rock matrix wettability adjacent to the NF pore void wettability (Figure 4). Natural fracture pore walls wettability (Figure 5) and inside natural fracture pore void wettability (Figure 6).

Several classes will appear based on each pore morphological features which are being counted and characterized separately and then modeled by linking the overall influence or the most frequent appearances which effect on the selected region.

RESULTS

As discussed, 10 automatic-angle-base different class appeared based on the pore/ grain morphological features, in this study the classification was done based on measurement of the grain surfaces surrounding each pore void and reported as class mean contact angle. Three distinguishable regions have been investigated and measured based on the rock porosity/ permeability properties for each distinct domain. The three regions are: The tight matrix adjacent to the NF, the NF pore wall, and the inside of the NF void space. Each region has different contact angle wettability distribution, of which will be discussed in detail. Considering ten automatic classes of contact angles, the 360° angles are classified, based on Al-Bazzaz et. al. (2019) classifications as shown in Figure 3.

Wettability Preference: Effect of Natural Fracture Wettability Analysis

The backscattered image at 51X magnification (Figure 2) is showing all possible pore/ grain surface contact angle measurement captured, then 2D-image processed, then optimized contact angle distribution is manifested for all 3 regions in order to recognize the nature of wettability preference at these regions. This 2D technology has the ability of capturing the mirror effect (0°-180°) (180°-360°). In this model, 20,778 contact angle are measured in the region #1 (tight matrix adjacent to the NF), 368 contact angle measured in region #2 (NF pore wall), and 444 contact angle are measured in region #3 (inside the NF), yielding 21,590 total measured static surface/ pore angle, including some contact angles that was difficult to account in the conventional models.

Region #1: Rock Matrix Wettability Adjust to the Fracture Pore Void Wettability

In the tight matrix adjacent to the NF region, 9 out of 10 classes have been appeared based on the pore angle, each class will have different morphological properties such as object count number, pore area, pore perimeter, pore length and width and their subsequent aspect ratio, pore elongation and roundness, pore equivalent diameter, and pore/ grain contact angle wettability (Table 1). All classes captured provide big data mean average measurement of the contact angle and porosity/ permeability (Figure 4 and Table 1 Table 2).

Class 1 has the largest number of contact angles (19,571) that show a mean contact angle of 28.9°. This result indicates that this tight and nanopores size of class 1 available in the tight matrix is SWW wettability preference. Also this result is presented for pore/ grain scale area of 50.9 μm^2.

Classes 2 through 9 are all show of SOW with the exception of class 8 shows MWW. The mean contact angle for classes 2 through 9 are: 172.8°, 180.4°, 196.4°, 175.8°, 177.9°, 197.2°, 51.2°, and 206.1° respectfully. Classes 2 through 9 mean areas are: 248 μm^2, 414 μm^2, 547 μm^2, 694 μm^2, 843 μm^2, 992 μm^2, 1113 μm^2, 1265 μm^2 respectfully.

In Figure 4 & Table 1 X51 rock matrix adjacent to the fracture results are reporting the wettability in micrometer scale and counted 20,778 pores with pore area range (50.93-1,265.34 μm^2). As well as the contact angle range θ° (28.99- 206.13). this results according to Al-Bazzaz et.al classification (Table 1) suggests that the wettability for the rock matrix adjust of the fracture are not fixed and there is a wettability distribution within the rock matrix as shown in Table 1. The porosity is reported at 24.8% and permeability at 131.6 mD (Table 4).

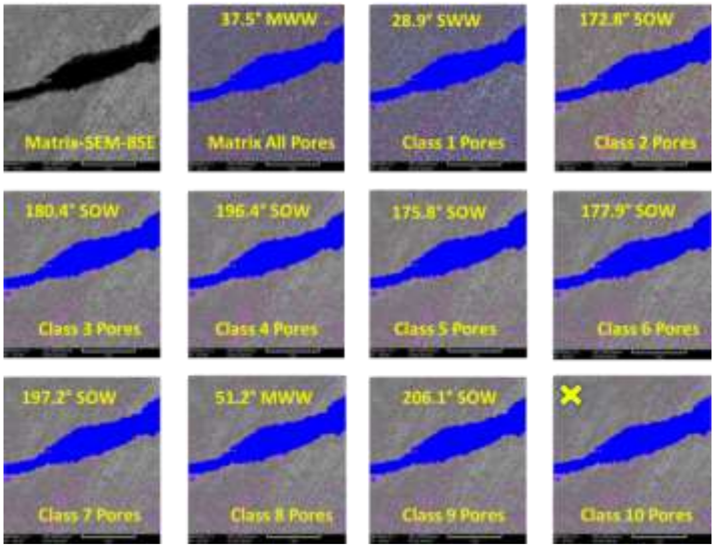


Figure 4. Rock Matrix pores classes Adjacent to the Fracture Pore Void Wettability Contact Angle Distribution

Table 1. Pore Counting Method: All pore classes of rock matrix adjust of the fracture at 51X Magnification.

	Mean Data from SEM												Calculated	
Class No	**Objects #**	**Area [um2]**	**Perimeter [um]**	**Length [um]**	**Width [um]**	**Roundness**	**Aspect Ratio**	**Elongation**	**Lgn.Prin. Long [um]**	**Lgn.Prin. Short [um]**	**Equiv. diameter [um]**	**Angle [°]**	**Frequncy %**	**Wettability**
Class 1	19571 / 20778	50.933	5.283	8.174	6.39	1	1.259	0.65	2.036	0.488	7.766	**28.999**	94.19%	SWW
Class 2	913 / 20778	248.024	54.118	26.444	15.924	1.107	1.74	2.34	13.699	6.676	17.699	**172.868**	4.39%	SOW
Class 3	174 / 20778	414.605	88.208	36.368	22.347	1.54	1.692	2.246	18.881	9.603	22.953	**180.437**	0.84%	SOW
Class 4	72 / 20778	546.909	113.911	44.336	25.735	1.931	1.779	2.46	23.041	11.05	26.373	**196.362**	0.35%	SOW
Class 5	30 / 20778	693.969	141.231	48.57	30.674	2.355	1.643	2.055	25.114	13.556	29.712	**175.797**	0.14%	SOW
Class 6	8 / 20778	843.561	177.776	58.679	36.923	3.033	1.645	2.203	30.858	15.83	32.766	**177.939**	0.04%	SOW
Class 7	5 / 20778	992.028	188.963	59.174	38.889	2.87	1.579	1.82	30.041	17.353	35.533	**197.199**	0.02%	SOW
Class 8	2 / 20778	1113.5	230.189	72.625	46.013	3.818	1.632	2.489	38.069	18.252	37.653	**51.159**	0.01%	MWW
Class 9	2 / 20778	1265.341	249.317	82.448	36.012	3.909	2.406	3.748	47.405	15.419	40.137	**206.134**	0.01%	SOW
Class 10	0 / 20778	---	---	---	---	---	---	---	---	---	---	**---**	---	---

Table 2. Summary 2D-Image Technology Big Data Model for the Tight Matrix Region

Tight Matrix Calculations	
Pore Area (μm^2)	66.00
Number of Pores	20,778
Grain Area (μm^2)	200.47
Number of Grains	51
Total Area (μm^2)	266.47
Ø (%)	24.768%
k (mD)	131.56

Region #2: Natural Fracture Pore Wall Wettability

In this region, only one class has been appeared in the fracture pore wall as shown in (Figure 5) and (Table 3) with 368 pore wall quartz mineral surfaces and the area measurements are spanned over around 74.6 μm^2, and wettability contact angle measured at θ°=33.5 which is considered as MWW based on Al-Bazzaz et.al classification, as shown in Figure 5. The porosity is reported at 50% and permeability at 1,411 mD (Table 4).

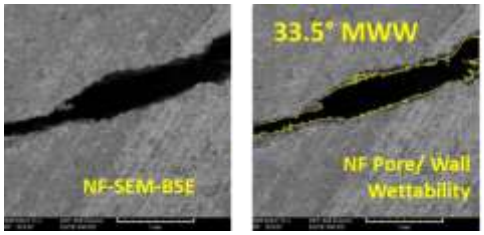
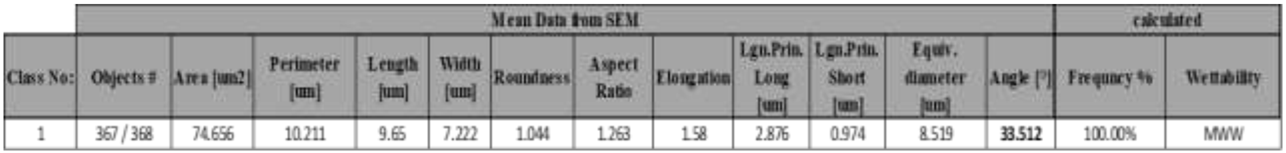


Figure 5. Natural fracture (NF) pore wall classes wettability contact angle distribution

Table 3. Pore Counting Method: All pore classes of Natural Fracture Pore Wall Wettability at 51X Magnification



	Mean Data from SEM												calculated	
Class No:	Objects #	Area [um2]	Perimeter [um]	Length [um]	Width [um]	Roundness	Aspect Ratio	Elongation	Lgn.Prin. Long [um]	Lgn.Prin. Short [um]	Equiv. diameter [um]	Angle [°]	Frequncy %	Wettability
1	367 / 368	74.656	10.211	9.65	7.222	1.044	1.263	1.58	2.876	0.974	8.519	**33.512**	100.00%	MWW

Table 4. Summary 2D-Image Technology Big Data Model for the NF Pore Wall Surface Region

NF Pore Wall Surface Calculations	
Pore Area (µm^2)	74.65
Number of Pores	368
Grain Area (µm^2)	73
Number of Grains	20,895
Total Area (µm^2)	147.65
Ø (%)	50.6%
k (md)	1,411

Region #3: Inside Natural Fracture Pore Void Wettability.

In this region Table 3 and Figure 6 and Table 5, at X51 magnification, Natural Fracture Pore Void results are reporting the wettability in micrometer scale and counted 444 pores and pore area range (221.8-47,745.5 µm^2). As well as the contact angle range θ° (41°- 354°). this results suggests that the wettability within the fracture is not fixed and there is a varied wettability distribution due to fluid interactions with each other as well as with the NF pore wall. The overall wettability preference inside the NF is 26.7° indicating a SWW type. The porosity is reported at 97% and permeability at 116,819 mD (Table 6).

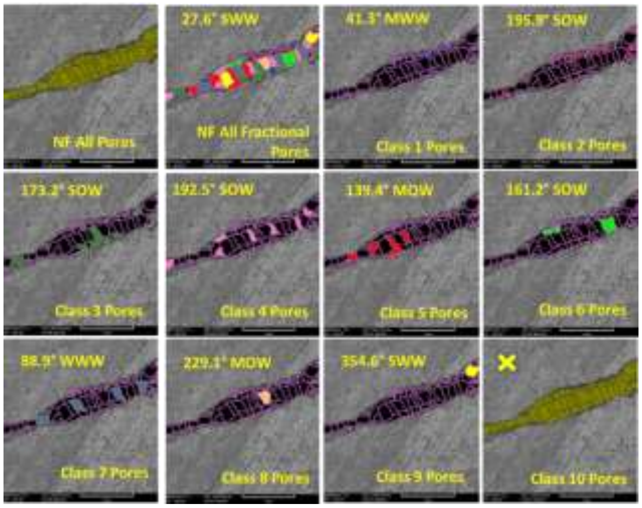


Figure 6. Inside Natural fracture (NF) pore wall as well as fluid-fluid classes wettability contact angle distribution

Table 5. Pore Counting Method: All pore classes of Natural Fracture Pore Void Wettability at 51X Magnification.

	Mean Data from SEM											Calculated	
Class No:	Objects #	Area [um2]	Perimeter [um]	Length [um]	Width [um]	Roundness	Aspect Ratio	Elongation	Lgn.Prin. Long [um]	Lgn.Prin. Short [um]	Equiv. diameter [um]	Angle [°]	Frequncy %	Wettability
1	399 / 444	221.821	23.224	14.173	9.418	1.098	1.327	1.59	5.196	1.987	10.983	**41.286**	89.86%	MWW
2	11 / 444	8542.971	501.395	152.135	104.137	2.437	1.523	1.581	72.271	45.306	104.007	**195.878**	2.48%	SOW
3	12 / 444	15085.681	656.795	219.214	127.02	2.348	1.853	2.142	105.239	55.15	138.441	**173.204**	2.70%	SOW
4	7 / 444	21354.142	777.664	267.577	151.537	2.277	1.851	2.257	126.871	64.418	164.825	**192.557**	1.58%	SOW
5	5 / 444	26096.4	873.507	286.774	150.965	2.362	1.959	2.733	146.531	64.531	182.204	**139.426**	1.13%	MOW
6	3 / 444	32021.572	1119.859	326.847	159.367	3.348	2.055	2.974	172.7	69.955	201.912	**161.178**	0.68%	SOW
7	4 / 444	36635.85	975.878	334.728	202.025	2.082	1.698	1.937	152.618	85.093	215.937	**88.873**	0.90%	WOW
8	1 / 444	44776.213	898.103	317.439	216.223	1.433	1.468	1.015	144.724	106.614	238.769	**229.113**	0.23%	MOW
9	1 / 444	47745.547	1046.556	298.427	272.578	1.826	1.095	0.597	138.661	115.851	246.559	**354.635**	0.23%	SWW
10	0 / 444	---	---	---	---	---	---	---	---	---	---	**---**	---	---

Table 6. Summary 2D-Image Technology Big Data Model for the Inside NF Region

Inside Fracture Calculations	
Pore Area (μm^2)	2,204.05
Number of pores	444
grain Area (μm^2)	73
Number of Grains	20,895
total Area	2,277.05
ϕ (%)	0.97
k (md)	116,818

DISCUSSIONS FROM OBSERVATION

The general classification of each region by X51 magnification has a unique wettability distribution, which was variable within the physical nature of these pores. Where the smallest pore shows strong to medium water wet and the largest pore area are swinging between strong oil wet to mixed oil/ water wet.

As per Figure 7, the contact angle vs. class number of the tight matrix adjacent to the fracture has been plotted for each class the bubble size. The size of the bubble represents the area of the class that represents the wettability preference (Table 4). Class 1 in this Figure has smallest pore area-size and its SWW that representing the majority pore counts, but it has the least matrix pore area contribution unlike the rest of classes, which they fall in SOW wettability preference with considerably larger pore area-size and to a lesser degree less number of pores compared to the nanopores; therefore, these pores have the dominate contribution even though they show less mineral surface exposed to this technique. Henceforth, tight matrix pores adjacent to the NF are totally affecting the wettability in a strong-oil-wet SOW manner, see Table 7. Average contact angel found as 37.5 ° which is MWW due to the larger amount of nanopores counts at SWW at θ = 28.9°. However the relatively larger pores area observed to contribute largely to the matrix as a strong-oil-wet SOW. Class 1 nanopores will give the tight signiture to the this porosity/ permeability system, and the larger pores will give the slow oil mobility from the matrix towards the NF. According to Al-bazzaz et.al. (2018 & 2019) the matrix recovery will prefer an unconventional EOR treatment at high temperature >300 °C for an optimized sweep or to lesser extent smart water with 100 < Temp.< 300 °C. Otherwise, any less aggressive EOR treatment will yield low EOR recovery factors.

On the other hand, Figure 8 shows only one class, class 1, and this class represents the entire second region of the pore wall of the NF. The entire pore walls of the NF observed to be MWW wettability preference at 33.5°. Figure 5 shows that the Natural Fracture (NF) pore wall occupies one large pore void that constructs the NF wettability distribution for the 368 rough and rugged quartz mineral surfaces. Since class1 is the only contribution in this region, the NF pore wall is observed to be medium-water-wet MWW (Table 7) that optimizes secondary water flood recovery mechanism inside and only inside the NF, but matrix pores adjacent to the NF will show slow recovery process and wettability alteration towards SWW will be critical.

Table 7. Al-Bazzaz et.al (2019) Unconventional 2D Classification of Contact Angle Wettability Preference

Wettability Symbol	**Wettability Preference Strength**	**Al-Bazzaz's Wettability Classification system (2018-2019)**	**Contact Angle (θ°)**	**Type of Suggested Optimized Recovery**
SWW	Strong-Water-Wet	**1**	0° - 30°	Primary
MWW	Medium-Water-Wet	**2**	30° - 60°	Secondary Water flooding
WWW	Weak-Water-Wet	**3**	60° - 90°	Low Salinity water flooding
WOW	Weak-Oil-Wet	**4**	90° - 120°	Chemical flooding with Low Heat
MOW	Medium-Oil-Wet	**5**	120° - 150°	Smart Water with 100< Heat < 300 °C
SOW	Strong-Oil-Wet	**6**	150° - 180°	Unconventional Treatment at High Temp. >300 °C
SOW	Strong-Oil-Wet	**7**	180° - 210°	Unconventional Treatment at High Temp. >300 °C
MOW	Medium-Oil-Wet	**8**	210° - 240°	Smart Water with 100< Heat < 300 °C
WOW	Weak-Oil-Wet	**9**	240° - 270°	Chemical flooding with Low Heat
WWW	Weak-Water-Wet	**10**	270° - 300°	Low Salinity water flooding
MWW	Medium-Water-Wet	**11**	300° - 330°	Secondary Water flooding
SWW	Strong-Water-Wet	12	330° - 360°	Primary

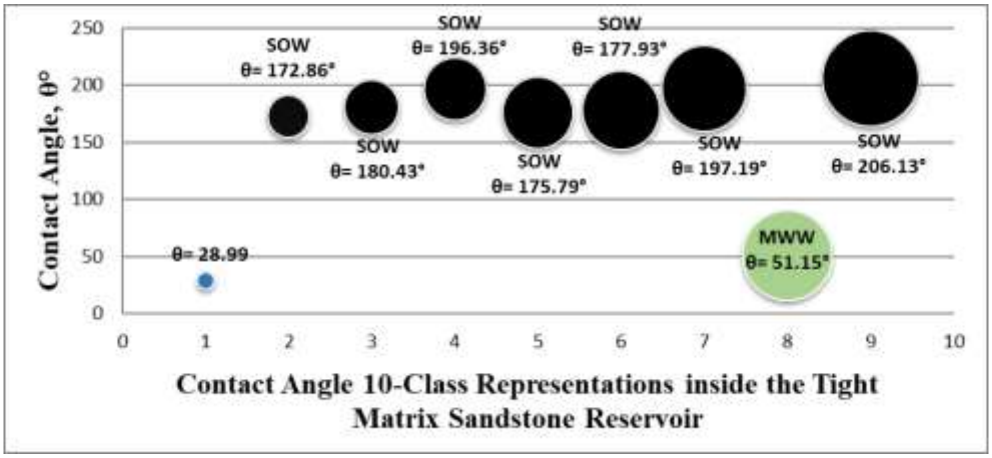


Figure 7. Contact Angle Vs Class Number for Region -1 (Tight Matrix Wettability Adjacent to the Fracture Pore Void Wettability)

Figure 8. Contact Angle Vs Class Number for Region-2

The last region studied is the inside region of the NF is shown in Figure 9. This region is most complicated because it is divided into two portions, the fluid-mineral boundary interaction, and the fluid-fluid interactions (mainly oil & water) interfacial tension interactions. This region based on Table 7, shows that SWW to MWW wettability preferences are at the boundary between the quartz mineral surface and the fluids. The mixed wettability preferences of WWW and MOW are between the water wetness and the oil wetness. These regions follow the mineral fluid boundaries in order and they pursue the largest wettability areas inside the NF. The Totally SOW resembling the crude oil is at the center of the fracture indicating that the most center region is an easy crude oil flow region. Inside the NF recovery falls under all spectrum of recoveries, primary, secondary water injections.

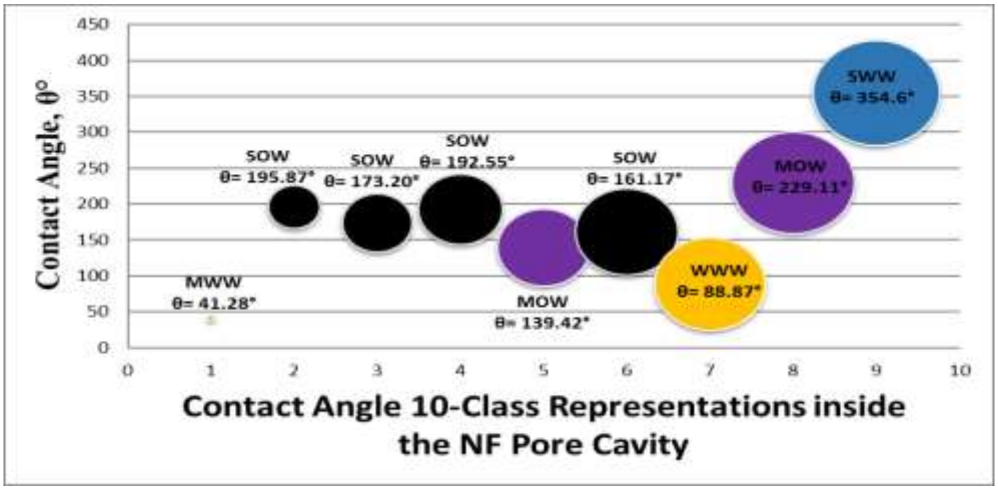


Figure 9. Contact Angle Vs Class Number for Region-3.

CONCLUSIONS AND RECOMMENDATIONS

Natural fracture (NF) wettability is a complex phenomenon that needs to be characterized in detail privileged inside a fresh tight Kuwaiti sandstone Kuwaiti reservoir discrete pore level. Static pore counting method of 2D-SEM-BSE technology that utilizes measurement of thousands of pores, grains and their boundary areas, and subsequent refracted SEM-BSE contact angles as the criterion parameter for all analysis which helps in developing models and observes wettability patterns in three distinct regions under the microscope: the tight sandstone matrix, the NF pore wall pore void, and the inside of the NF.

Thousands of pores are successfully captured in 2D-image format for a tight fractured sandstone sample. The majority of these pores are in region 1: rock matrix wettability adjacent to the natural fracture (NF) pore void wettability. These pores have the least area ensuring its matrix tightness but has SOW wettability preference with exception of class 1 pores, it behaves as SWW. The overall matrix wettability behaves as MWW because the average values were found as 66 um2, 37.5 ° respectively which is MWW. Region-1 has been categorized to 10 different classes, of which each class has different pore area and wettability contact angle. Big data demonstrated a wettability distribution within the matrix, but the most pore counted and least contributed is class1, and.

Region 2 is the NF pore wall wettability, and there are several hundreds of region 2 pores has been captured, categorized, and then measured. From observation, only one class is confirmed for analyses, and the pore area was 74.6 um^2 and wettability contact angle 33.5 ° respectively this is also MWW wettability preference.

Finally, region 3, inside the NF pore void wettability, is captured and analyzed. Region-3 has been categorized to 10 different classes each class has different pore area and wettability contact angle, and there is a wettability distribution within the NF and fluids, and distribution between fluid-fluid (mainly oil and water). The most contributed mineral fluid class is class1 at $\theta = 29°$ SWW, class 7 $\theta = 88.8°$ WWW, and class 9 at $\theta = 354.6°$ SWW, over average area values were found as 2,204 um^2 at an average total $\theta = 54.4°$ which is MWW.

From observation, are natural fractures (NF) in sandstone reservoirs: water wet, mixed wet, or oil wet? The answer is total wettability distribution is captured, processed and modeled and it is SOW at the matrix, MWW at the fracture wall and SOW inside the NF pore. The distribution has showed alternating from SWW at the tight matrix towards MWW at the fracture. Further studies are required to evaluate porosity, permeability & relative permeability within each fracture region and compare the results.

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