INTEGRATION OF MULTI-SCALE TECHNIQUES TO EVALUATE RESERVOIR WETTABILITY FOR CARBONATE RESERVOIRS IN MIDDLE EAST

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ABSTRACT

This work is to evaluate reservoir wettability and its effects on oil recovery from carbonate reservoirs in the Middle East, by integrating multi-scale laboratory techniques. We employed contact angle measurement, Amott-Harvey (AH) index and USBM method to evaluate the rock wettability. NMR wettability indices were also used to quantify rock wettability.

Contact angles of oil droplets on aged calcite plates under reservoir conditions have proved that the live crude oil was able to render the calcite surface towards oil-wet. The AH index and USBM method implied that some reservoir cores as received were water-wet. After core cleaning and wettability restoration, we found that the wettability of reservoir cores has become neutral wet to slightly oil-wet; and the degree of oil wetness varies on the rocks from the different petrophysical groups. We quantified the NMR wettability index using Fleury and Deflandre (2003) model and Chen and Hirasaki (2006) model. Correlations show that both NMR indices generally agree with the AH and USBM index, suggesting that quantitative information of reservoir rock wettability can be gained from NMR measurements. The advantage of NMR wettability indices is to gain an in-depth understanding of the evolution of multi-phase saturation and pore-scale trapping of residual phases. The effects of rock wettability on the residual oil saturation (ROS) after forced water imbibition process were also investigated.

The reservoir wettability determination in multiple-scales, show consistent trends in reservoir characteristics, and show slightly variations in different rock types. The integration of the techniques offers an in-depth understanding of the reservoir properties for potential investigations in further field development using IOR/EOR techniques.

INTRODUCTION

Carbonate reservoirs account for approximately half of the world hydrocarbon reserves. Majority of these are located in Middle East and North America. Many carbonate reservoirs tend to be highly heterogeneous or highly fractured, and oil-wet, in which capillary force opposes imbibition of water into the matrix.

Wettability is a very important concept in oil recovery processes and has a strong influence on distribution, location and flow of multiple phases during hydrocarbon production. Wettability also significantly affects capillary pressure, relative permeability and residual oil saturation [1-4]. A fully understanding of reservoir wettability significantly improves reservoir modeling and the development of an IOR/EOR process [5, 7]. Many methods have been developed for the determination of wettability, as listed in Table 1. Anderson W.G. has reviewed the advantages and limitations of all three industry-standard quantitative methods in use today: contact angle, Amott-Harvey (AH) index and U.S. Bureau of Mines (USBM) method [6].

The AH index, which measures the spontaneous displacement potential of water and oil, varies from +1 from strongly water-wet rocks to -1 for stongly oil-wet rocks. The USBM index is quntified by comparing the amount of work required to displace each of the fluids by the other. It is generally accepted that values below -0.3 are considered preferentially oil-wet, whereas values greater than 0.3 are considered preferentially water-wet. Values between -0.3 nd 0.3 are either mixed-wet (inhomogeneous wettability) or intermediate wet (lacking a strong wetting preference).

As a fast-evolving method for wettability measurement, nuclear magnetic resonance (NMR) is a technique that has been proved to be very sensitive to rock-fluid interface. NMR surface relaxation dictates that the fluid in contact with the mineral surface has a relaxation time shorter than its bulk value. For a system of intermediate wettability, both water and oil molecules will have access to the pore surface and the relaxation time depends on the amount of wetted surface and strength of the interactions. Therefore, NMR can be considered as a quantitative method for wettability index determination.

The reservoirs of interest are two thin and heterogeneous reservoirs, reservoir A and B, within a Lower Cretaceous producing field (Barremian age) in Middle East. They are separated from the overlaying Upper reservoir by a dense layer of 45 ft (average thickness). A very thin layer of around 5 ft separates reservoir A from reservoir B. The average thicknesses of these reservoirs are about 20 ft for reservoir zone A and 30 ft for reservoir zone B. These two reservoirs contain an estimated total of 197 MMSTB OOIP.

This work is to evaluate reservoir wettability and its effects on oil recovery from these carbonate reservoirs by integrating multi-scale laboratory techniques. We employed and compared the results from contact angle test, Amott-Harvey index and USBM method, and NMR wettability index techniques. The effects of wettability on the distribution of multi-phase saturation and local trapping of residual phases were discussed.

THEORY

Wettability and NMR surface relaxation are related to each other. The basic physics is that NMR surface relaxation dictates that the fluid in contact with the mineral surface has a relaxation time shorter than its bulk value. It has been noticed that the reduction in relaxation time of oil from its bulk value can be utilized as a qualitative wettability indication [8, 9], and in specific cases, as a quantitative method [10, 11].

For a system of intermediate wettability, both water and oil molecules will have access to the pore surface and the relaxation time depends on the amount of wetted surface and strength of the interactions. *Fleury and Deflandre* (2003) proposed a NMR wettability index based on fluid distributions. Their NMR wettability model has the form below [10]:

$$I_{NMR} = \frac{S_w\left(\frac{1}{T_w}-\frac{1}{T_{bw}}\right)-C_\rho S_o\left(\frac{1}{T_o}-\frac{1}{T_{bo}}\right)}{S_w\left(\frac{1}{T_w}-\frac{1}{T_{bw}}\right)+C_\rho S_o\left(\frac{1}{T_o}-\frac{1}{T_{bo}}\right)} \quad \text{...} (1)$$

$$C_\rho = \frac{\rho_w}{\rho_o} = \frac{1/T_{w,Sw=1}-1/T_{bw}}{1/T_{o,So=1}-1/T_{bo}} \quad \text{...} (2)$$

Chen and Hirasaki (2006) proposed a concept of effective surface relaxivity, which quantified rock wettability by two NMR wettability indices from either water or oil response [11].

$$I_{NMR} = I_W^{NMR} - I_O^{NMR} = \frac{\left(\frac{1}{T_w}-\frac{1}{T_{bw}}\right)}{\left(\frac{1}{T_{w,S_w=1}}-\frac{1}{T_{bw}}\right)} * S_w - \frac{\left(\frac{1}{T_o}-\frac{1}{T_{bo}}\right)}{\left(\frac{1}{T_{o,S_o=1}}-\frac{1}{T_{bo}}\right)} * S_o \quad \text{..................................} (3)$$

where, I_W^{NMR} is water index and I_O^{NMR} is oil index. $T_{w,S_w=1}$ and $T_{o,So=1}$ correspond to T_2 relaxation time when S_w = 100% or S_o =100%, respectively. T_{bw} and T_{bo} are T_2 relaxation times of bulk brine or bulk oil, respectively. S_w and S_o are the end-point water or oil saturation after forced displacement in centrifuge, respectively. T_w and T_o are T_2 relaxation time @ any Sw and any So, respectively.

METHODS AND MATERIALS

Sample Description and Preparation

The sample selection and preparation was focused on having the widest possible range of wettability from various rock types within a carbonate reservoir in Middle East. The selected core plugs had a porosity range of 13-24% and wide permeability range of 0.2 to 350 md. Since a rigorous core-preservation program was not implemented, the fluid saturation and wettability of these core samples were not preserved. The core samples "as-received" were reconditioned to initial water saturation in centrifuge without aging. Then NMR, AH and USBM tests were conducted on these plugs. Next, the same batch of core samples was cleaned by hot solvents, in the sequence of toluene, azeotrope and methanol, using vigorous flow-through cleaning program. The core plugs were then saturated with brine and oil, and then reached to initial water saturation (S_{wi}). A restored wettability state was established by aging the plugs with live crude oil under high pressure and elevated temperature conditions. The formation brine used in this study contains 22% total dissolved salts (TDS), and the crude oil has an API gravity of ~ 40.0.

Contact Angle Measurements

Contact angle measurement was conducted on the polished calcite plates under both ambient condition and reservoir conditions (Temp = 250degF, Pressure = 3800psig). These calcite plates were aged in crude oil for 4 weeks at an elevated temperature. It should be noted that we the contact angle measurement under high temperature and high pressure (HTHP) conditions was performed using a designed apparatus by Intertek Westport Technology Center in Houston, Texas, which can be set up to temperature of 350 degF and pressure of 5000 psi.

Amott-Harvey and USBM Data Acquisition

Eight 1.5" diameter plugs were selected for capillary pressure and Amott-Harvey & USBM wettability measurements on their as-received state and restored state. The forced imbibition and drainage capillary pressure tests were performed in a BECKMAN L8-M model centrifuge with imaging system using the fluid pairs. The rotational rates were increased incrementally to generate equivalent capillary pressures ranging from 1.0 to approximately 150.0 psi (inlet face). The industrial standard procedures were followed in setting up experimental procedures and calculation of AH and USBM index [12, 13].

NMR Data Acquisition

The proposed NMR wettability index requires the measurement of T_2 relaxation time distribution for at least four different saturation states: 1) 100% Sw; 2) 100% So; 3) after forced imbibition to S_{or}; 4) after forced drainage to S_{wr}. The reasons for selecting the two extreme saturation cases are that the saturation for brine after forced imbibition and for oil after forced displacement is relatively higher, so that better resolution of the NMR measurement is gained for the corresponding water and oil phases. Additionally, we added the T_2 measurements before and after aging to investigate the effects of wettability restoration on T_2 profiles.

NMR T_2 relaxation time measurements were performed simultaneously with capillary pressure measurements by centrifuge on the same 8 plug samples. NMR measurements were made using NUMAR's CoreSpec - 1000™ at a Larmor frequency of approximately 1 MHz. Each sample was stored in an air-tight vial and allowed to equilibrate at system temperature prior to loading into the NMR instrument. The tests were performed under a homogenous magnetic field at interecho spacings (T_E) of 0.6 ms.

RESULTS AND DISCUSSIONS

1. Interpretation from Contact Angle Measurements

Calcite was used as a model mineral to perform contact angle measurement since the reservoir of interest is a carbonate reservoir. The objective of measurement is to study if a crude oil could render the calcite oil-wet. The contact angle measurements of at least three oil droplets were performed in each test and the average contact angle was reported.

The test conditions are listed in Table 2. Under ambient test conditions, an average contact angle of oil droplets on calcite plates was determined to be 144.7 ± 3.2^{o}, as shown in Figure 1A. While under reservoir conditions (temperature of 250 deg F and pressure of 3800 psig), the contact angle on the calcite plates reduced significantly to 111.4 ± 2.6°. In summary, the synthetic live oil was able to render the calcite plates towards oil-wet.

2. Amott-Harvey Index and USBM Method

The summary of AH index and USBM index is presented in Table 3. In the samples of as-received state, the wettability varies from strongly water-wet (RRT 6 and 8) to slightly oil-wet (RRT 2). After cleaning and being wettability-restored, these samples became towards more oil-wet, expecially in RRT- 4, 6 and 8. As seen in Figure 2, the absolute values of AH index and USBM index agree very well, especially in the range of [-0.5, 1], indicating that both tests are equivalent.

3. Quantitative Interpretation from NMR T_2 Relaxation Times

As described in theory and method section, the NMR index requires the determination of the dominant relaxation times at at least 4 saturation states. An example of a measurement sequence is shown in Figure 3. The vertical dashed line shows that the surface relaxation time shifted towards shorter time after aging process. It implies that more oil molecules have contacted with mineral surface after aging and some portion of surface became oil-wet.

Since wettability index is a macroscopic term reflecting the average property of core samples, we extracted the avearge property of T_2 relaxation time, including T_2 mode and T_2 log mean values, instead of focusing on the microscopic behaviors. As an example, Table 4 presents the summary of data for NMR wettability study from sample 6A. After feeding the data into Equations 1-3, the NMR wettability index was obtained from both the Fleury and Hirasaki Models, as shown in Table 5.

As shown in Figure 4, the NMR wettability indices derived from two models are in good agreement with a correlation coefficient $R^2 > 0.90$, especially in the range of [-0.5 0.5]. There is difference in NMR index calculated using T_2 mode or T_2 Log mean for the same wettability test, while they correlate well with each other (R^2=0.86), as shown in Figure 5. Moreover, NMR wettability index correlates reasonably well with Amott-Harvey index and USBM index in the range of [-0.3, 1], as seen in Figure 6. Therefore, all three wettability indices (AH, USBM, NMR) have shared the same confidence in the measurement when the sample wettability lies between neutral and water-wet state.

4. Effects of Wettability on Residual Oil Saturation

After centrifuge-based forced imbibition test, the residual oil saturation (ROS) in each plug samples varies. In order to understand the physics behind ROS, it is helpful to calculate the Trapping number (N_T) for each test. Trapping number is a dimensionless number to integrate the effects of both capillary and viscous forces [14, 15]. Viscous force is negligible in a centrifuge-based forced imbibition test. It is then assumed that the Trapping number equals to the microscopic Bond number, *i.e.*

$$N_T \approx N_B = \frac{k \cdot \Delta\rho \cdot \omega^2 R}{\sigma} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

where k is absolute permeability (m^2), ω is angular velocity (revolution/second), R is the distance from the center of rotation to the center of the plug (m). $\Delta\rho$ is the difference of phase densities (kg/m^3), and σ is the water/oil interfacial tension (N/m).

The values and correlations of ROS (at the inlet) and Bond numbers are presented in Table 6 and Figure 7 for each imbibition test associated with wettability studies. As expected, the values of ROS continue to drop when the Bond number of a centrifuge displacement increases in carbonate rocks, with no presence of definitive critical trapping number [15, 16]. The ROS drops to 0.15 PV when trapping number is around 10^{-5}.

The effect of rock wettability on ultimate oil recovery and residual oil saturation (ROS) has been generally focused on water flood. In this study, we presented the correlation of ROS versus wettability index for carbonate rocks in a forced imbibition process. As shown in Figure 8, the plot of ROS as a function of wettability index indicates a gradually decrease in ROS from strongly water-wet to neutral wet conditions. A clear plateau of lowest ROS exists when the wettability is near intermediate-wet domain.

CONCLUSIONS

1. The wettability study of a carbonate reservoir in the Middle East by integrating multi-scale lab techniques has shown that the reservoir is neutral wet to slightly oil-wet. The degree of oil wetness is varied on the rocks from different petrophysical groups.
2. Contact angles of oil droplets on aged calcite plates under HTHP reservoir conditions have shown that reservoir crude is able to render oil-wetness on the calcite surfaces.
3. Comparing with restored wettability after aging, the “as-received” state was towards more water-wet, possibly due to the contamination of drilling fluid.
4. NMR wettability index was calculated using *Fleury and Deflandre* (2003) model and *Chen and Hirasaki* (2006) model. Correlations show that both NMR indices generally agree with the AH and USBM wettability index, suggesting that quantitative information of reservoir rock wettability can be gained from NMR measurements.
5. In a capillary desaturation curve (CDC), the post-imbibition residual oil saturation (ROS) decreases while trapping number increases in carbonate rocks, without a critical trapping number. There is a lowest plateau of ROS when the sample possesses the neutral wettability.
6. The full integration of reservoir wettability determination in multiple scales showed consistent trends in reservoir characteristics, and show slightly variation in different rock types.

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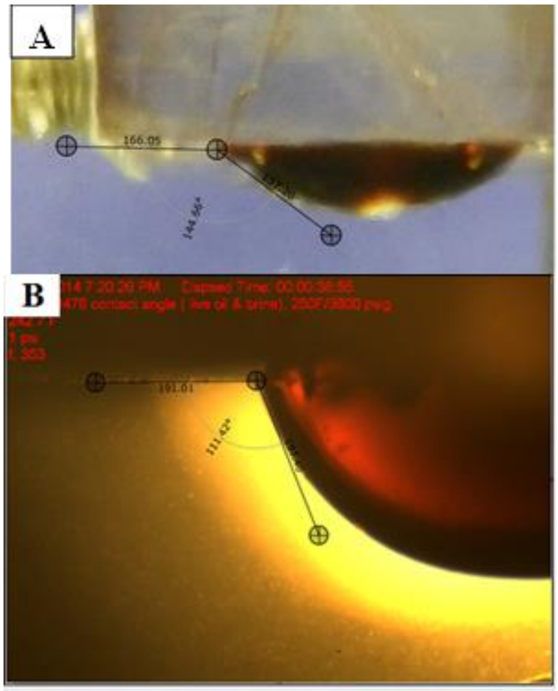

Figure 1. Contact angle measurement on aged calcite plates. (A) Average θ = 144.7° under ambient conditions; (B) average θ = 111.4° under reservoir conditions.

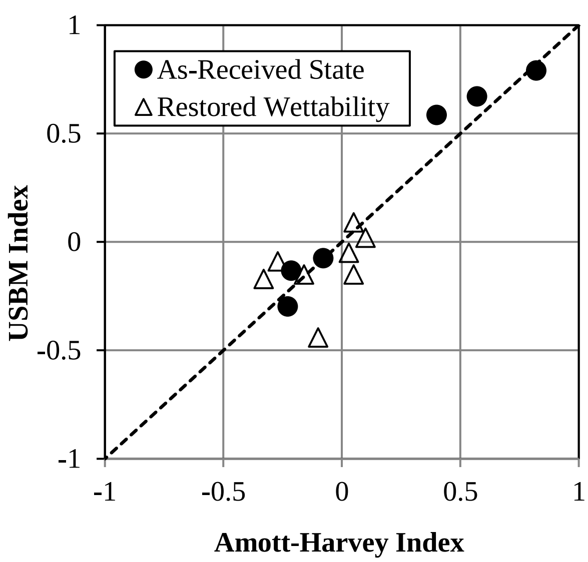

Figure 2. The cross-plot of Amott-harvey index with USBM index.

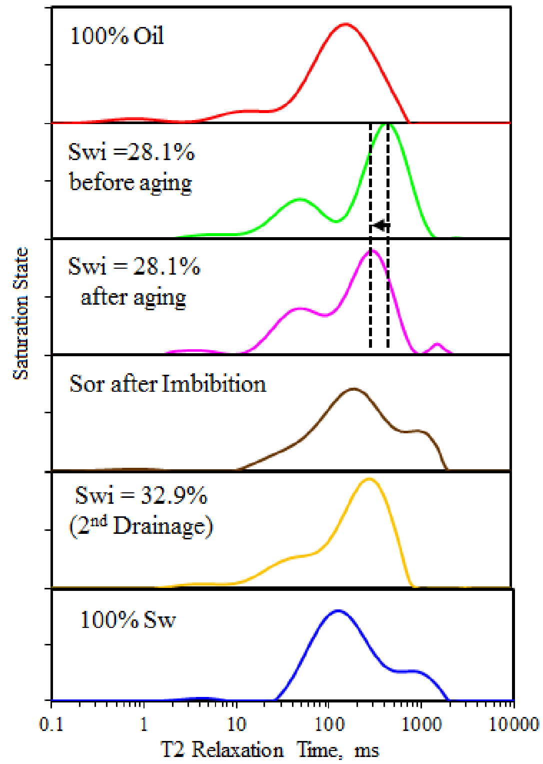

Figure 3: The NMR T_2 relaxation times ate different saturation states. The vertical dashed lines indicate the T_2 mode relaxation time is reduced after aging process.

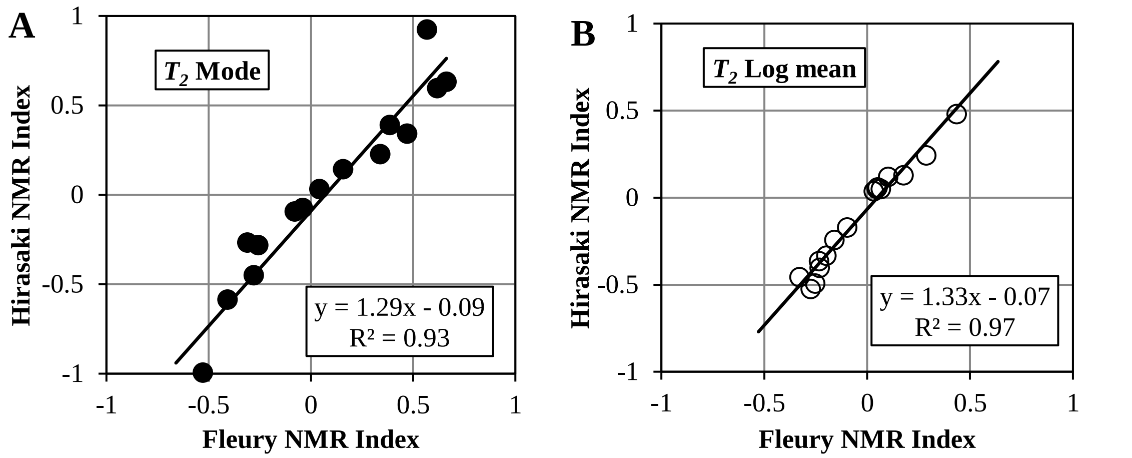

Figure 4: Comparison of NMR Wettability Indices derived from Fleury and Hirasaki Models. A) T_2 Mode was used for calculation; B) T_2 Log mean was used for calculation.

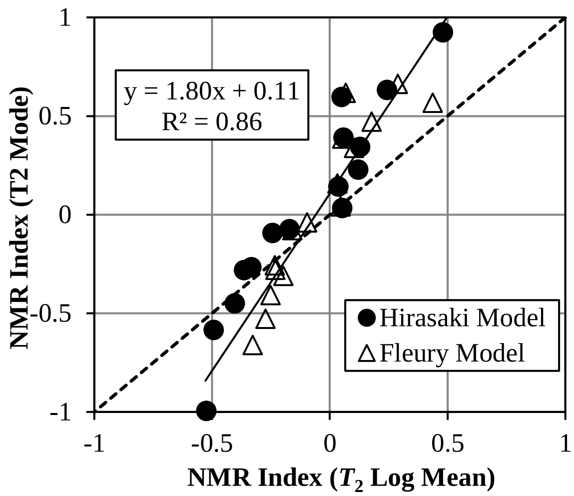

Figure 5. NMR Wettability Index derived from T_2 Log mean and T_2 mode.

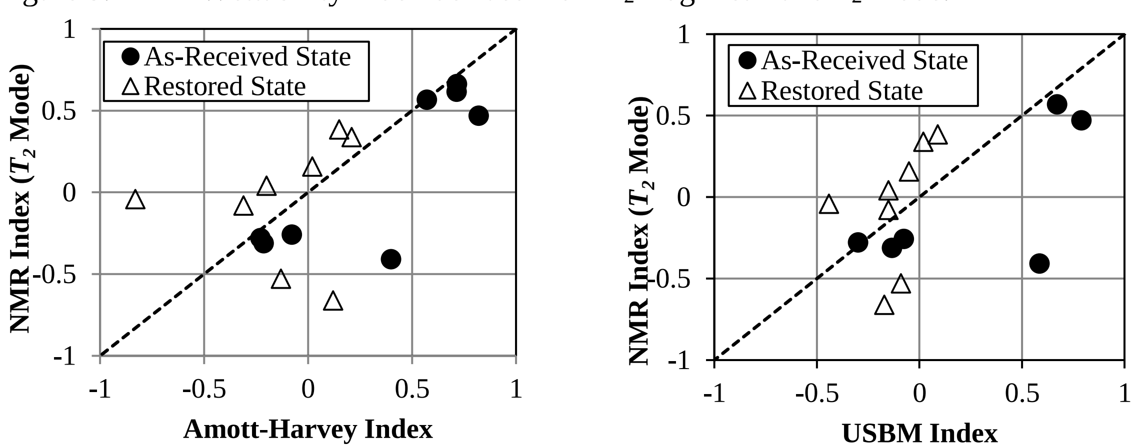

Figure 6. Cross-plots of NMR Wettability Index and AH Index (A) and USBM Index (B).

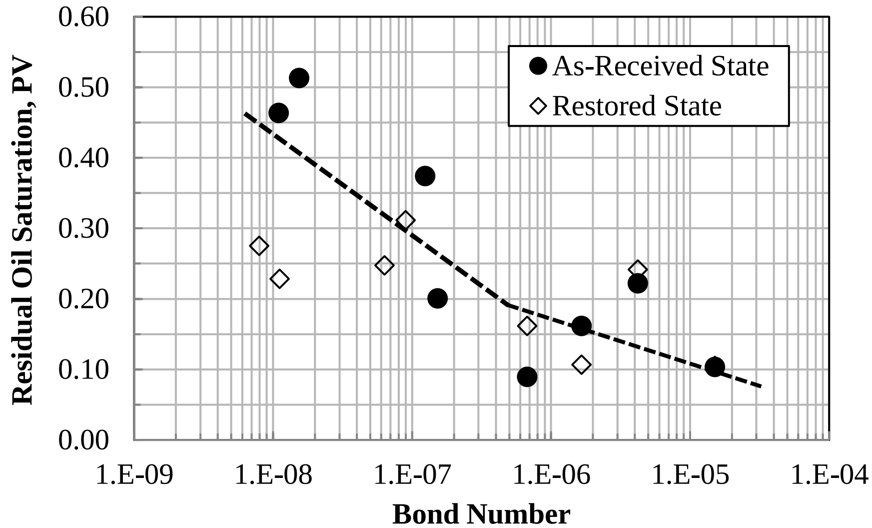

Figure 7: The residual oil saturation (inlet S_{or}) vs. microscopic Bond number in carbonate rocks. The dashed line indicates the continuous reduction of ROS along the increase of Bond number in the non-water wet cores, without the presence of critical Bond number.

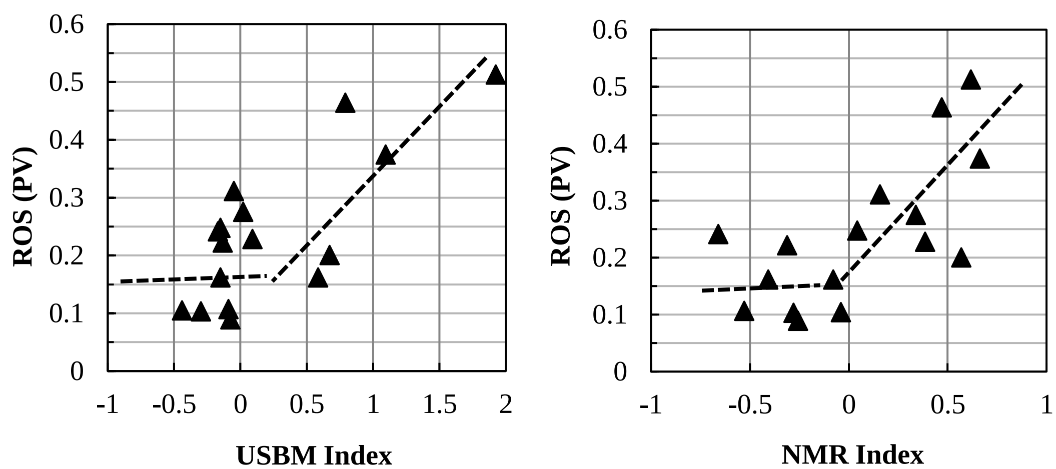

Figure 8: The residual oils saturation vs. wettability indices. The dashed lines imply the presence of stabilized ROS when the wettability index less than 0.

Table 1: The lists of quantitative and qualitative methods to measure wettability

Quantitative Methods	Qualitative Methods
Contact Angle	Imbibition
Amott-Harvey	Floatation
USBM	Relative Permeability
Amott-USBM	Capillary Penetration
NMR Measurement	Glass slide
	Electrical resistance

Table 2. The results of contact angle measurement (1A: ambient; 1B: reservoir conditions)

Figure No.	**Temp** °F	**Pressure** Psig	**Formation Brine Density** g/cm³	**Oil Density** g/cm³	**Contact Angle** degree
1A	71	0	1.140	0.816	144.7
1B	250	3800	1.108	0.685	111.4

Table 3: Summary of AH and USBM indices for four rock types

Wettability State	**Sample**	**RRT**	**Depth (ft)**	**AH Index**	**USBM Index**	**Wettability Description**
As-Received State	2A	2	8289.75	-0.23	-0.30	Slightly oil-wet
	2B	2	8384.00	-0.21	-0.13	Slightly oil-wet
	4A	4	8289.90	-0.08	-0.07	Neutral wet
	4B	4	8289.50	0.40	0.59	Water-wet
	6A	6	8297.30	0.57	0.67	Strongly water-wet
	6B	6	8396.98	0.72	1.09	Strongly water-wet
	8A	8	8363.90	0.71	1.92	Strongly water-wet
	8B	8	8374.61	0.82	0.79	Strongly water-wet
Restored Wettability State	2A	2	8289.75	-0.10	-0.44	Slightly oil-wet
	2B	2	8384.00	-0.33	-0.17	Slightly oil-wet
	4A	4	8289.90	-0.16	-0.15	Neutral wet
	4B	4	8289.50	-0.27	-0.09	Neutral wet
	6A	6	8297.30	0.05	-0.15	Neutral wet
	6B	6	8396.98	0.03	-0.05	Neutral wet
	8A	8	8363.90	0.05	0.09	Neutral wet
	8B	8	8374.61	0.10	0.02	Neutral wet

Table 4: Summary of core saturation and NMR T_2 relaxation time for Plug 6A

DESCRIPTION	**CORE S_w%**	**T_2 Mode (ms)**	**T_2 Log Mean (ms)**
As-Received Wettability State			
100% S_w	100.0	125.9	167.9
S_{wi} to Oil	15.9	501.2	159.6
S_{or} to brine	23.7	79.4	167.6
S_{wi} to Oil 2nd drainage	12.6	398.1	200.5
100% S_o	0.0	158.5	98.7
Restored Wettability State			
100% S_w	100.0	125.9	167.9
S_{wi} to Oil before aging	28.1	398.1	203.5
S_{wi} to Oil after aging	28.1	316.2	148.2
S_{or} to brine	31.6	199.5	187.1
S_{wi} to Oil 2nd drainage	32.9	316.2	146.6
100% S_o	0.0	158.5	98.7
Bulk Fluid T_2 Measurement			
Crude Oil ($T_{2b,\,oil}$)	Bulk fluid	1259	711
Formation brine ($T_{2b,w}$)	Bulk fluid	2512	2512

Table 5. The wettability index derived from Fleury model and Hirasaki Model

Sample	RRT	Depth (ft)	Fleury Model		Hirasaki Model	
			NMR Index (T_2 Mean)	NMR Index (T_2 Mode)	NMR Index (T_2 Mean)	NMR Index (T_2 Mode)
Wettability Index: As-Received State Plugs						
2A	2	8289.75	-0.23	-0.28	-0.23	-0.30
2B	2	8384.00	-0.20	-0.31	-0.21	-0.13
4A	4	8289.90	-0.23	-0.26	-0.37	-0.28
4B	4	8289.50	-0.25	-0.41	-0.49	-0.59
6A	6	8297.30	0.44	0.57	0.48	0.92
6B	6	8396.98	0.29	0.66	0.24	0.63
8A	8	8363.90	0.07	0.62	0.05	0.60
8B	8	8374.61	0.18	0.47	0.13	0.34
Wettability Index: Restored State Plugs						
2A	2	8289.75	-0.10	-0.04	-0.17	-0.07
2B	2	8384.00	-0.33	-0.66	-0.46	-1.12
4A	4	8289.90	-0.16	-0.08	-0.24	-0.09
4B	4	8289.50	-0.27	-0.53	-0.53	-0.99
6A	6	8297.30	0.05	0.04	0.05	0.03
6B	6	8396.98	0.03	0.16	0.04	0.14
8A	8	8363.90	0.05	0.39	0.06	0.39
8B	8	8374.61	0.10	0.34	0.12	0.23

Table 6. Residual oil saturation after forced imbibition vs. wettability indices

Wettability State	**Sample**	**NMR Index (T_2 Mode)***	**USBM Index**	**Abs. Perm Kw, md**	**Trapping Number**	**S_{or} after imbibition***
As-Received State	2A	-0.28	-0.30	357.03	1.51E-05	0.10
	2B	-0.31	-0.13	103.79	4.22E-06	0.22
	4A	-0.26	-0.07	16.16	6.75E-07	0.09
	4B	-0.41	0.59	40.28	1.66E-06	0.16
	6A	0.57	0.67	1.62	1.53E-07	0.20
	6B	0.66	1.09	2.24	1.24E-07	0.37
	8A	0.62	1.92	0.28	1.54E-08	0.51
	8B	0.47	0.79	0.20	1.10E-08	0.46
Restored Wettability State	2A	-0.04	-0.44	357.03	1.51E-05	0.10
	2B	-0.66	-0.17	103.787	4.22E-06	0.24
	4A	-0.08	-0.15	16.16	6.75E-07	0.16
	4B	-0.53	-0.09	40.28	1.66E-06	0.11
	6A	0.04	-0.15	1.62	6.35E-08	0.25
	6B	0.16	-0.05	2.24	8.99E-08	0.31
	8A	0.39	0.09	0.28	1.12E-08	0.23
	8B	0.34	0.02	0.20	7.95E-09	0.28

*Note: S_{or} was calculated as the inlet oil saturation using Forbes 2nd solution.