FIFTY YEARS OF WETTABILITY MEASUREMENTS IN THE ARAB-D CARBONATE

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ABSTRACT

The Ghawar field in Eastern Saudi Arabia contains the largest accumulation of carbonate reservoirs in the world. The majority of wells in the field produce from the Arab-D reservoir, an Upper Jurassic limestone sealed by anhydrite. Oil production from the field started approximately 55 years ago. Water injection started in the 1970's. Long before water injection was considered for the reservoir, the evaluation of wettability was considered essential.

Our present day evaluation of Arab-D wettability takes into account a long historical record of wettability measurements and production history. The procedures, results and *caveats* of the original measurements have changed slightly but they also show a strong consistency fifty years later. Wettability indices obtained from initial tests, Amott, and USBM methods generally indicate neutral to slightly oil-wet character for cores processed and tested in a preserved state. Comparisons with restored state cores did not indicate major differences. Over the years fluids used in coring operations and core preservation have shown little impact on the observed results.

Local variations in wettability indicating mixed wettability and oil-wet tendencies can be observed when tar is present in a significant amount and in areas high on structure. The combination of methods from advanced SEM observations, to qualitative contact angle measurements, to relative permeability results all point to a common wettability value.

INTRODUCTION

It has become evident that about 50 % of the world proven oil reserves are contained in carbonate reservoirs [1]. The wetting properties of carbonate reservoirs are fundamental to the understanding of fluid flow in all aspects of oil production, and can affect the production characteristics greatly during water flooding. So, knowledge of the preferential wettability of reservoir rock is of utmost importance to petroleum engineers and geologists. Due to this importance many reviews of wettability and its effect on oil recovery have been conducted [2-4].

Carbonate reservoirs are heterogeneous in nature due to the wide spectrum of environments in which carbonates are deposited and subsequent diagenetic alteration of the original rock fabric. These heterogeneities and effect of wettability on residual oil saturation, capillary pressure, electrical properties, relative permeability, and oil recovery encouraged many researchers to perform various studies to characterize and evaluate wettability of carbonate reservoirs. In the past, many engineers assumed that most reservoir rocks are water-wet. The reasons for this conviction are the work of Leverett [5] and test methodology of determination of wettability after thoroughly cleaning cores that were likely to have been contaminated and exposed to air. The paper published by Treiber et al. [6] was the major breakthrough in showing that many carbonate reservoirs are oil-wet. Subsequent studies showed that the wettability of carbonate rocks is oil-wet, neutral or mixed [7-9].

This paper provides a detailed study and survey of wettability evaluation for the Arab-D carbonate reservoir (Upper Jurassic), Saudi Arabia. The wettability results presented in this paper combine data obtained from various quantitative and qualitative methods over fifty years using preserved and restored core material. The studied areas are Uthmaniyah, Hawiyah, and Haradh.

ARAB-D RESERVOIR

The Ghawar field in Eastern Saudi Arabia contains the largest accumulation of carbonate reservoirs in the world. The majority of wells in the field produce from the Arab-D reservoir, an Upper Jurassic limestone sealed by anhydrite. The Arab-D reservoir was discovered in 1948. Following further separate discoveries along the structure's main axis, five areas were quickly identified as parts of giant Ghawar oil field (**Figure 1**): from north to south they are Ain Dar, Shedgum, Uthmaniyah, Hawiyah, and Haradh. At the Arab-D level, the field is NNE-trending composite anticline 230 km long and about 30 km wide [10]. The largest oil accumulations occur in the lowest grainstone cycle of the Arab Formation, the Arab-D reservoir. The vertical oil column reaches a maximum of 1,300 ft. The oil-saturated interval extends about 250 ft below the anhydrite that separates the Arab-D reservoir from overlying Arab-C carbonate beds (**Figure 1**).

XRD and XRF analyses revealed that the most predominant mineral in the Arab-D reservoir is calcite (80-100 weight %). While dolomite constitutes a second minor mineral (0-20 weight %), and trace amounts (< 5 weight %) of quartz, pyrite, ankerite, and halite.

PLUG SELECTION AND TEST FLUIDS

Before 1970, Arab-D reservoir cores were cut using high pH, lime-starch-caustic drilling fluid. Core plugs were drilled (1.5 inches in diameter) from whole cores, placed in glass jars and covered with drilling fluids. To evaluate the effect of drilling fluids on wettability, a 69 lb /ft3 brine and a carboxymethyl cellulose (CMC)-bentonite-barite mud were used. In this case, the whole cores were immersed in water immediately after being removed from the core barrel. They were submerged in water until tested in the laboratory located at the well site. Reservoir brine and dead oil were used as aqueous and oleic phases in the static brine and oil imbibition tests.

After 1970, core material from Arab-D carbonate reservoir was cut with a KCl brine and packed under de-aerated KCl brine in plastic tubes. No chemical additives like soda ash, diesel, defoamer, caustic or surfactant were used to minimize any possible alteration of the core wettability. Core plugs of approximately 3 inches in length and 1.5 inches in diameter were drilled from the whole core at 0.5-foot intervals with brine identical to the preserving brine. The drilling direction is perpendicular to the axis of the whole core. After trimming, the plugs were wrapped with aluminum foil and then placed in a sealed container completely submerged in evacuated brine.

Visual, brine permeability at remaining oil saturation, and CT scans were performed as screening tests to assist in sample selection. The screening tests were combined with a review of conventional core data and geological description of the core material to ensure that anomalous samples were not tested. Cores that were fractured, broken, or displayed brine permeability less than 1 millidarcy (mD) were excluded from further testing.

Wellhead oil from the Arab-D carbonate reservoir at the three selected areas was used as the oleic phase in the wettability experiments (Amott, USBM, and contact angle methods) and recombined live oil at reservoir conditions (temperature=190 ^{o}F and pressure=2500 psig) was used in relative permeability tests. Synthetic brine was prepared based on geochemical analysis of the produced water and was filtered through 0.2 μm filter paper. The composition of the synthetic brine (similar to reservoir brine), used to saturate the core plugs and carry out the wettability and relative permeability tests, is listed in **Table 1**. In addition to sodium and chloride ions as the main components of the brine, divalent calcium and magnesium are also abundant.

EXPERIMENTAL PROCEDURE

Wettability Measurements (Quantitative Methods)

<u>Carter Oil Company Research Method (1956)</u>

The Amott Wettability method was introduced in 1959 [11] as an excellent technique for determination of rock wettability. Earlier in-house work in 1956 by Carter Oil Company Research developed a method for wettability determination based on comparing static water and oil imbibitions [12].

In this method, two adjacent samples were obtained from preserved core and were arbitrarily designated “A” and “B”. The “A” samples were tested for water-wetness and the “B” for oil-wetness. The “A” samples were evacuated for 30 minutes, saturated with degassed crude oil and then flushed with oil to insure high initial oil saturation. Water imbibition of these samples was then measured against time by placing the samples in volumetric imbibition cells filled with distilled water. Water-wet index was obtained by dividing the produced oil by the pore volume. The “B” samples were evacuated in a similar manner to the “A’s”. The voids saturated with de-aerated distilled water and then flushed with the same liquid. These samples were then placed in inverted volumetric imbibition cells filled with degassed crude oil and the amount of oil imbibed measured against time. Oil-wet index was obtained by dividing the produced water by the pore volume. Finally, a wettability index similar to the Amott index was calculated by subtracting the water-wet index from the oil-wet index.

Amott Method

Samples selected for the Amott tests (done after 1970) were flushed with synthetic brine (200-300 cm^3) to remove drilling fluid contaminants and to establish residual oil saturations (**Table 1**). Wettabilities of preserved core plugs were measured by a modified Amott method using dynamic flow-through displacement [11]. The method combines spontaneous imbibition and dynamic displacement performed under ambient conditions with simulated formation brine and stock tank oil. If a sample spontaneously imbibes only brine, it is considered water wet. Similarly, if it imbibes only oil, it is considered oil wet. If the sample imbibes neither, it is described as neutrally wet.

USBM Method

The United States Bureau of Mines (USBM) method was also used to measure wettability. USBM wettability index is obtained from the drainage/imbibition hysteresis loop given by centrifuge capillary pressure curves [13]. The areas under the curves represent the thermodynamic work required for the respective fluids to displace each other. The logarithm of the ratio of the area of oil-displacing-brine (A1) to brine-displacing-oil (A2) is used to identify the USBM wettability index. For purposes of discussion, the wettability index range from +1 to –1 was subdivided and classified as follows: neutral or mixed (-0.1 to 0.1), slightly water-wet (+0.1 to +0.3), water-wet (+0.3 to +1), slightly oil-wet (-0.1 to –0.3), and oil-wet (-0.3 to –1).

Qualitative Methods

Relative Permeability Method

The procedure for relative permeability measurements included the use of composite core [14] assembled from core material cut with KCl brine and preserved at the well site. The unsteady-state relative permeability tests were conducted at simulated reservoir conditions of 190 ^oF, 2500 psig pore pressure, and 5000 psig confining pressure using recombined (live) and synthetic brine similar to reservoir brine. Relative permeabilities were calculated using JBN method [15]. Using Craig's rule of thumb [16], the end-point values of relative permeability curves (irreducible water saturation and relative permeability to water at residual oil saturation) and the crossover saturation value at which $K_{rw}=K_{ro}$ could be used to characterize wettability of preserved core plugs used in relative permeability tests.

Contact Angle Method

The contact angle measurements were made with Arab-D dead oil/ brine/ calcite system at room temperature (78 ^oF) and at reservoir conditions (190 ^oF and pressure of 2500 psig). Contact angles were measured on a smooth substrate (calcite plate) using a pendent drop apparatus. The system permitted measurements of the angle made by an oil drop contacting the brine-calcite interface. Calcite was chosen since it represented the major component of Arab-D reservoir.

Contact angle is a measure of the intrinsic wettability of a reservoir rock. It ranges from 0^o to 180^o. When contact angle is less than 60^o, the surface is referred as water-wet, and when it is greater than 120^o, the surface is considered to be oil-wet. It is defined as neutrally or intermediately wet system if the contact angle ranges from 60^o to 120^o.

Microscopic Method

Recent advances in scanning electron microscopy (SEM) allow researchers to observe oil and water distribution at the pore level. Both Cryo-SEM and environmental scanning electron microscope (ESEM) can be used to evaluate the local wettability state within the pores. The Peltier stage supplied with the ESEM, in conjunction with water vapour as the imaging gas, allows for accurate control of a sample's relative humidity; through manipulation of temperature and pressure. This feature makes it possible to condense water droplets on to the specimen's surface and to observe the contact angle between mineral phases and water droplet. The contact angle gives direct information as to the wettability state. With water as the reference phase, high contact angles indicate oil-wet conditions while low contact angles represent water wetness.

RESULTS

Quantitative Methods (Amott and USBM Methods)

Wettability is a surface phenomenon. It is defined as the tendency of one fluid to spread on or adhere to a rock surface in the presence of another immiscible fluid. It has a significant effect on oil recovery produced by waterflood or by water-drive mechanisms. Therefore, it is necessary to determine preferential wettability of the reservoir, whether this be to water, or oil or somewhere between the two extremes, i.e. intermediate.

Uthmaniyah Area

In 1956, wettability tests on preserved core plugs, obtained using a high pH, lime-starch-caustic drilling fluid, recovered from UTMN-C were performed using the Carter Oil method. Static imbibition test at the well site was conducted [12]. The results indicated that the tested plugs ranged from neutral to mildly water-wet character. The wettability index varied between -0.1 and 0.1. There was some concern that the high pH, lime-starch-caustic drilling fluids could make the rock surfaces more water-wet.

To examine the effect of type of the drilling fluids on wettability of Arab-D reservoir, two types of drilling fluids were used to cut the core material and displace the reservoir brine from wettability plugs (UTMN-D). The first one was 69 lb /ft3 brine and the second was a CMC-bentonite-barite mud. Wettability indices using the 69 lb/ft^3 brine ranged from -0.002 to 0.1 while, wettability index using a CMC-bentonite-barite mud varied between 0.03 and 0.06.

Since both tests indicated neutral to moderately water-wet character of the UTMN-D core material [17], no difference between the two drilling fluids could be discerned. Wettability index values using both drilling fluids are listed in **Table 2**.

Foster J. F. [18] conducted a study to compare wettability data for samples tested at the well site after drilling and other samples which were preserved by placing them in glass jars filled with distilled water and then sealed until testing. The preserved cores were kept in laboratory and aged for five months. **Table 3** summarizes wettability index results for samples tested at the rig site and preserved samples aged for five months. Data in **Table 3** showed insignificant changes in wettability as a result of preservation with distilled water in glass jars for five months. This indicated that core samples could be preserved and wettability tests can be made under controlled laboratory conditions with proper precautions taken in coring and preserving samples.

In the early 1990's other distinct wells (UTMN-A and B) were tested using the Amott method. Amott wettability indices for UTMN-A core material varied between 0.03 and 0.68 while for UTMN-B they ranged from 0.2 to 0.41. **Figure 2** shows a plot of Amott wettability indices as a function of depth for UTMN-A, B, C, and D wells. The plot indicates that core materials recovered from these wells are neutral to slightly water-wet.

Three additional wells (UTMN-E, F, and G) were cored and preserved plugs were tested for wettability determination using USBM method. **Figure 3** shows a plot of USBM indices as a function of core depth for three wells from Uthmaniyah area. The results indicate a general trend of intermediate wettability to slightly oil-wet behavior. However, samples located below the oil water contact (OWC) demonstrate an intermediate to slightly water-wet behavior.

Wettability results obtained in this study, for Uthmaniyah area are in agreement with data reported by Lichaa, P. M. et al. [19]. They showed that wettability of Arab-D reservoir rock is generally oil-wet to intermediate. This may be due to interaction between the slightly acidic nature of the Arab-D crude oil and slightly basic carbonate surfaces of Arab-D carbonate material. The results revealed that Arab-D rocks were neutral to slightly oil-wet in the preserved state, neutral to very weakly water-wet after cleaning, and remained neutral to slightly oil-wet in restored state. This could indicate that the cores as preserved by Saudi Aramco did not undergo major wettability alteration due to the coring mud fluid used, evaporation, oxidation, and or contamination. Our results and Lichaa's results are in agreement with wettability data obtained on similar rocks and reported by Cuiec and Yahya, 1991 [7].

<u>Hawiyah Area</u>

Two wells from Hawiyah area (HWYH-A, and B) were tested using both Amott and USBM method. The distribution of wettability versus depth for HWYH-A and HWYH-B are shown in **Figures 4 and 5**, respectively. Samples tested from HWYH-A are located at lower depth than those selected from HWYH-B. The results in **Figure 4** showed a general trend of neutral to slightly water-wet characteristics. USBM indices ranged from -0.4 to 0.1; while Amott indices varied between 0.03 and 0.35. Data in **Figure 5** show that core plugs had oil-wet to neutral to slightly water-wet character. USBM index ranged from -0.38 to -0.62; while Amott index varied between 0.07 and 0.37.

Three additional wells (HWYH-C, D, and E) were tested using Amott method. Amott wettability indices distribution as a function of depth compiling data from five wells in Hawiyah area is shown in **Figure 6**. Data indicted that the tested pugs showed neutral to slightly water-wet character with a tendency of increasing water-wet behavior with depth. Unlike samples in the UTMN area, samples in HWYH located below the oil water contact

(OWC) showed strongly water-wet character. Amott wettability indices ranged from 0.0 to 0.87.

Haradh Area

Four wells from Haradh area were tested using Amott method and wettability distribution versus depth is shown in **Figure 7**. Wettability indices varied between -0.02 and 0.68. The results revealed that the tested core material had neutral to slightly water-wet to water-wet characteristics with a tendency for increased water-wet characteristics with depth. Samples located below oil water contact showed stronger water-wet character than those above OWC.

DISCUSSION

The cross-plotting of Amott indices to water and Amott indices to oil in a ternary plot was proposed by Mitchell et al. [20] as a way of illustrating wettability characterization. This approach was adopted in this work as shown in **Figure 8**. The data shows neutral to intermediate and slightly water-wet characteristics of the Arab-D core materials. **Figure 9** shows that the wettability index to water for Arab-D reservoir decreases as the sample height above the water-oil contact increases. Samples close to the oil-water contact are water-wet, whereas intermediate wettability is obtained high above the oil-water contact. However, the cross-plotting technique does not highlight the variations between quantitative methods illustrated by the results for HWYH-A and HWYH-B wells in **Figures 4 and 5**.

Although differences are less in HWYH-A than in HWYH-B there is a tendency for USBM tested samples to appear more oil wet. Other researches have observed similar results particularly in intermediate wettability systems as reported by Lichaa [19], Crocker, et al. [24], and Esfahani et al. [25].

The results indicate that core material of Jurassic Arab-D carbonate reservoir tend to be intermediate to slightly water-wet in the absence of systematic variations and in the absence of strong oil property changes. Stronger oil-wet tendencies particularly beneath the oil-water contact as seen in UTMN-E, F, and G can also be attributed to the close proximity of the UTMN tar mat. Variations may also be related to variation of rock fabric, facies and environment of deposition, which result in variation of pore size distribution [21].

In relation to position on structure the combined historical data for the Arab-D confirm the conclusions of Cuiec [7] and Marzouk [21] where wettability variation of carbonate reservoirs shows increasing water wet character below the oil-water contact.

Qualitative Methods

Relative Permeability

Many waterflooding experiments were conducted to generate relative permeability curves for Arab-D reservoir from the three areas. All measurements were taken on composites of three or four core plugs. Composites are used because they are believed to be least impacted by core-scale heterogeneities. They provide more precise data because the pore volume and pressure drop are both larger, and are least impacted by capillary and inlet end effects. **Figure 10** shows typical relative permeability curves for three composites from Arab-D reservoir at the three areas. Results of oil/water relative permeability tests on Arab-D reservoir indicated that oil recovery ranged from about 26 to 45 % at breakthrough and reached an ultimate recovery in the range of about 46 to 62 % of original oil in place. The residual oil saturation (Sor) varied between 39 % and 45 % of pore volume at the end of waterflooding. The relative permeability results suggested a slightly oil-wetting core material based on Craig's rule of thumb [22]. Initial water saturations (S_{wi}) were generally less than 20 % of pore volume. The crossover points at which $K_{rw}= K_{ro}$ were generally below 50 % water saturation. Relative permeability to water at residual oil saturation (K_{rw} at S_{or}) ranged from 40 to 95 percent.

From wettability and relative permeability results described above, it can be stated that trends in relative permeability and wettability for Arab-D carbonate reservoir are consistent.

Contact Angle

Advancing contact angle results, for Arab-D crude oil/brine/calcite system at room temperature ranged between 40^o and 43^o. At reservoir conditions they varied between 50^o and 53^o. These results showed weakly water-wet behavior for Arab-D crude oil/brine/calcite system under measurement conditions. In 1992, Lichaa et al. [19] showed that receding contact angle for the Arab-D crude oil/brine/Arab-D rock material system ranged from 100^o to 105^o (T = 158 ^{o}F and P = 50 psig). This revealed intermediate wettability character. Based on the variation of contact angle results and hysteresis caused by surface roughness, the obtained contact angle data can be used only for rapid qualitative screening of trends, but under no circumstances should any generalizations be made with respect to the systems of fluids in rocks [22].

Microscopic observations

Figure 11 presents water distribution on the rock sample as received and flushed with synthetic brine (similar to reservoir brine). The contact angle shown in this figure is around 80^o. This is reflects intermediate wettability character of the tested sample. Al-Yousef et al. [23] observed from a Cryo-SEM study conducted on Arab-D rock material that either oil or brine could be seen filling pores or lining the pore walls. Their observations suggested the existence of a mixed-wettability system.

CONCLUSIONS

1. Amott wettability results and USBM wettability indices indicate a general trend of slightly oil-wet to intermediate wettability behavior of Arab-D core material. However, in the absence of tar, samples located below the oil-water contact (OWC) demonstrate an intermediate to slightly water-wet behavior.
2. Amott wettability data implies that various drilling fluids used by Saudi Aramco to core the wells and the brines used in preserving the core plugs are adequate and have insignificant effect on wettability alteration.

3. Unsteady-state oil/water relative permeability results suggest a slightly oil-wetting core material based on Craig's rule of thumb. Trends in relative permeability and wettability for Arab-D carbonate reservoir are in agreement.
4. Observations from qualitative wettability evaluation methods showed some agreements with data obtained from Amott and USBM methods.

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Table 1. Synthetic Brine Composition used in Wettability, Contact Angle and Relative Permeability Tests.

Salt	**Value**
Sodium Chloride (NaCl), g/L	**16.7**
Calcium, Chloride ($CaCl_2$), g/L	**3.62**
Magnesium, Chloride ($MgCl_2.6H_2O$), g/L	**1.28**

Table 2. Wettability Index for UTMN-D using different drilling fluids (Bobek J. E., May 1956).

Plug No.	Permeability to Air (mD)	Drilling Fluid	Wettability Index	Plug No.	Permeability to Air (mD)	Drilling Fluid	Wettability Index
1	273	A 69 lb/ft^3 brine	0.07	1-A	526	A CMC-bentonite-barite-mud	0.06
2	356		0.1	2-A	307		0.04
3	389		0.06	3-A	864		0.038
4	806		0.09	4-A	349		0.062
5	71		0.01	5-A	49		0.06
6	4		0.01	6-A	172		0.05
7	2		-0.002	7-A	264		0.06

Table 3. Comparison of Wettability Index Tests at Rig-Site and Preserved cores at Laboratory, (UTMN-D), Foster J. F., 1956.

Plug No.	Permeability to air (mD)	Rig-Site Wettability Index	Plug No.	Permeability to air (mD)	Preserved (5 Months) Wettability Index
11	32	0.084	11-A	19	0.095
12	662	0.055	12-A	660	0.034
13	307	0.034	13-A	1.1	0.009
14	864	0.037	14-A	954	0.042
15	549	0.057	5-A	539	0.026
16	49	0.055	16-A	80	0.058
17	264	0.059	17-A	57	0.045
18	71	0.031	18-A	168	0.037
19	724	0.046	19-A	447	0.047

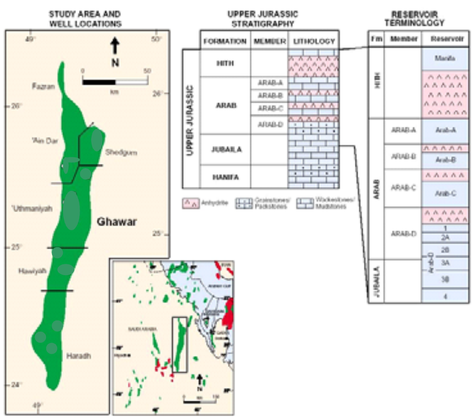

Figure 1: Ghawar Field Location Map. From North to South the Ghawar Field is Divided into the following Areas: Ain Dar, Shedgum, Uthmaniyah, Hawiyah, and Haradh.

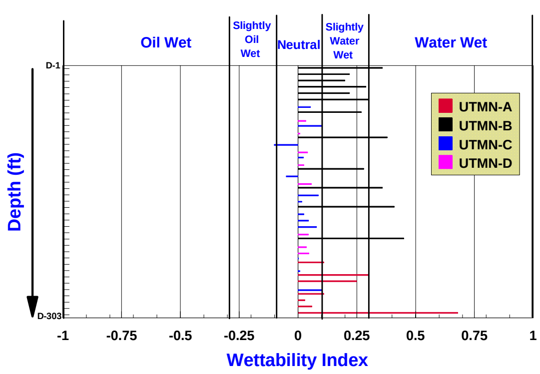

Figure 2: Amott Wettability Indices Distribution vs. Depth for Arab-D Reservoir, Uthmaniyah Area.

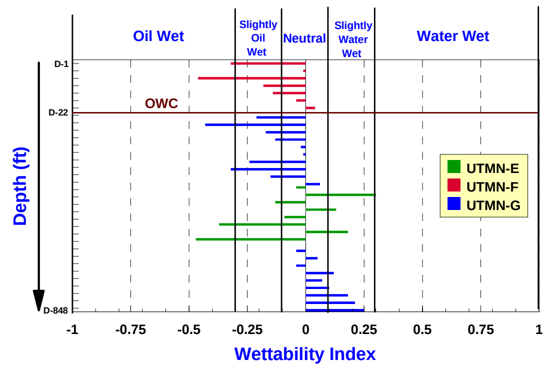

Figure 3: USBM Wettability Indices Distribution vs. Depth for Arab-D Reservoir, Uthmaniyah Area.

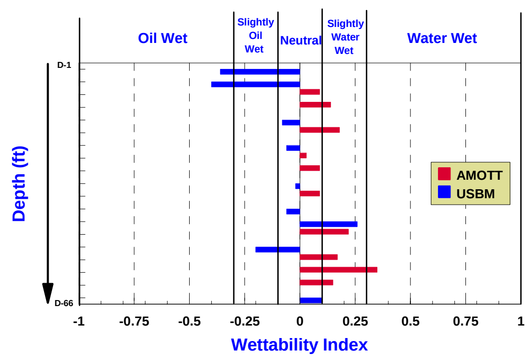

Figure 4: Wettability Indices Distribution vs. Depth for Arab-D Reservoir, Hawiyah Area (HWYH-A).

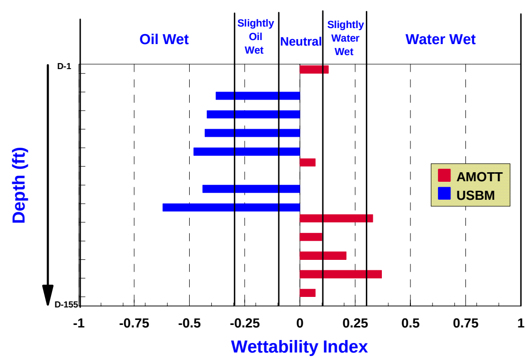

Figure 5: Wettability Indices Distribution vs. Depth for Arab-D Reservoir, Hawiyah Area (HWYH-B).

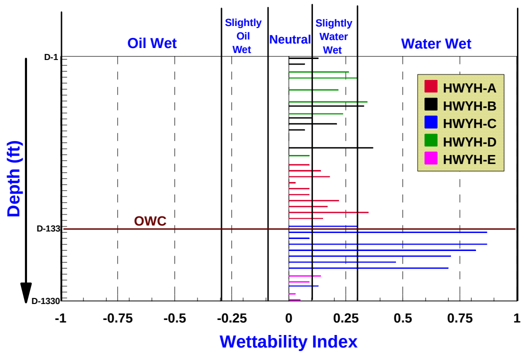

Figure 6: Amott Wettability Indices Distribution vs. Depth for Arab-D Reservoir, Hawiyah Area.

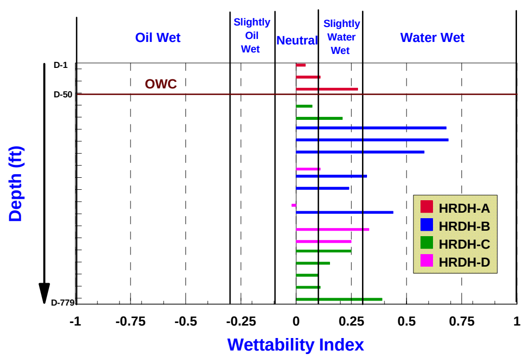

Figure 7: Amott Wettability Indices Distribution Vs. Depth for Arab-D Reservoir, Haradh Area.

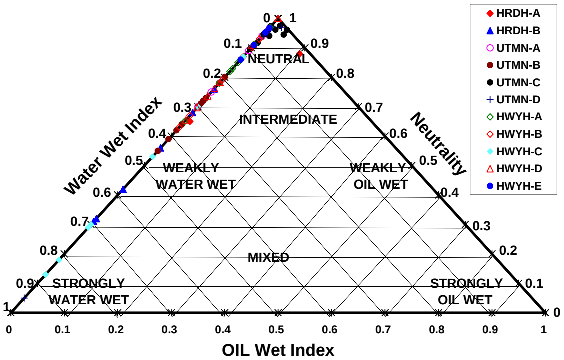

Figure 8: Ternary Plot Diagram of wettability Indices for Arab-D Reservoir.

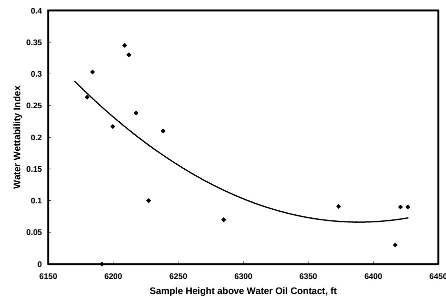

Figure 9: Relationship between Wettability Index to Water (WI) and Structural Position.

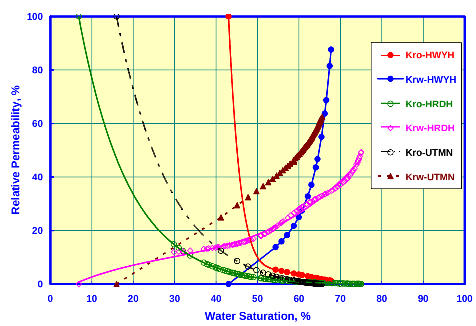

Figure 10: Typical oil/water relative permeability curves for Arab-D Reservoir.

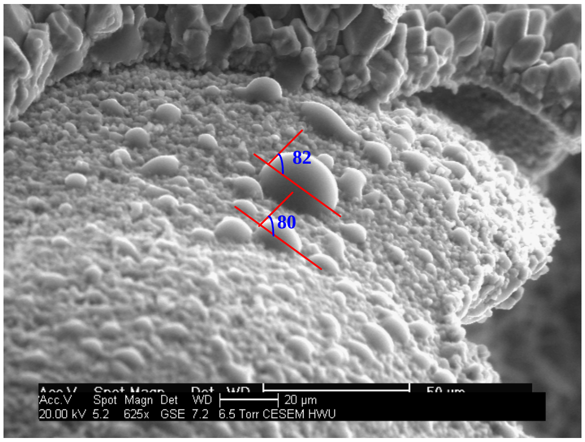

Figure 11: Arab-D carbonate rock. Appearance of water distribution and intermediate wetting characteristics of grains.