Wettability Evaluation of Arabian Carbonate Reservoir after Prolonged Water Injection: A Case Study*

Taha M. Okasha[1]

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[1]Saudi Aramco, Dhahran, Saudi Arabia

Abstract

Most of the current hydrocarbon production in Saudi Arabia is from Arab-D carbonate reservoir (Upper Jurassic limestone). Oil production started more than 50 years ago. So, the various fields had been subjected to prolonged pressure support by waterfloods (since 1970) using Arabian Gulf seawater.

Wettability of carbonate reservoirs 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 (mixed).

The study indicated a unique feature of wettability characteristics of Arab-D carbonates. Data obtained at the early stage of production and latest data obtained after prolonged water injection revealed neutral to slightly oil wet wettability character. In addition, data from relative permeability tests confirmed the flow performance of wettability behavior determined by different wettability techniques. Therefore, it can be stated that changes in the original wettability of carbonate reservoir by prolonged water injection are not significant.

Introduction

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. Therefore, knowledge of the preferential wettability of reservoir rock is of utmost importance to petroleum engineers and geologists to evaluate reservoir performance and oil recovery. Due to this importance, many reviews of wettability and its effect on oil recovery have been conducted (Anderson, 1986, Morrow, 1990, Cuiec, 1991).

In the past, many engineers assumed that most reservoir rocks are water-wet. The reasons for this conviction are the work of Leverett (1941) 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. (1971) was the major breakthrough in showing that the large numbers of carbonate reservoirs are oil-

wet. Consequently, various studies showed that the wettability of carbonate rocks is oil-wet, neutral or mixed (Cuiec and Yahya, 1991, Chilingarian et al., 1992, Webb et al., 1996).

This paper provides detailed study and survey of wettability evaluation for Arab-D carbonate reservoir (Upper Jurassic), Saudi Arabia. The wettability results presented in this paper combine data obtained from various quantitative and qualitative methods at the early stage of production and after prolonged time of water injection using preserved and restored core material. The studied areas are Uthmaniyah, Hawiyah, and Haradh.

Test Methods

Wettability of core plugs recovered from different wells in Arab-D carbonate reservoir were determined using different methods like Amott's (1959) method, United States Bureau of Mines (USBM) method (Donaldson et al., 1969), contact angle method (Collins and Cook, 1959), microscopic method using Environmental Scanning Electron Microscope (Buckman, 2000) and relative permeability method (Craig, 1971).

Results and Discussion

In this study, wettability indexes were obtained from quantitative methods. Qualitative methods were used to describe and match wettability results obtained from quantitative methods. The study indicated a unique feature of wettability characteristics of Arab-D carbonates. Data obtained and discussion will concentrate on wettability evaluation of three major areas (Uthmaniyah, Hawiyah, and Haradh) in Ghawar field.

Wettability at Early Stage of Production (1956-1969)

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 static imbibition method at the well site (Bobeck et al., 1956a). The results indicated that the tested plugs had neutral to mildly water-wet to intermediately water-wet character.

The wettability index varied between -0.1 and 0.1. It was stated that the high pH, lime-starch-caustic drilling fluids has a slight tendency to 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 is 69 lb/ft3 brine and the second is a CMC-bentonite-barite mud. Wettability data showed that both used drilling fluids had insignificant to minor effect on changes of wettability. Wettability index using a 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. Data revealed neutral and moderately water-wet character of UTMN-D core material (Bobeck et al., 1956b). Wettability index values using both drilling fluids are listed in Table 1.

Foster (1956) 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 2 summarized wettability index results for samples tested at the rig site and preserved samples aged for five

months. Data in Table 2 showed insignificant changes in wettability resulted from preservation with distilled water in glass jars for five months. Therefore, such data indicate that core samples could be preserved and wettability tests can be made under controlled laboratory conditions with proper precautions in coring and preservation samples.

Wettability at Mid Stage of Production (1970-1999)

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 was used to minimize any possible alteration of the core wettability.

Three wells (UTMN-E, UTMN-F, and UTMN-G) were cored and preserved plugs were tested for wettability determination using USBM method. Figure 1 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 far away from oil water contact (OWC) demonstrate an intermediate to slightly water-wet behavior.

Wettability results obtained in this study (Uthmaniyah area) are in agreement with data reported by Lichaa, et al. (1992). They showed that wettability of Arab-D reservoir rock is generally oil-wet to intermediate. Also, results revealed that Arab-D rock were a 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 (Table 3). 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. Therefore, our results and Lichaa's results are in agreement with wettability data obtained on similar rocks (ASAB reservoir) and reported by Cuiec and Yahya (1991).

Three wells from Haradh area were tested using Amott method and wettability distribution versus depth is shown in Figure 2. Wettability indices varied between -0.02 and 0.42. 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 strong water-wet character than those above WOC.

Wettability at Late Stage of Production (2000-2012)

Water injection continues as secondary recovery mechanism in different areas in Ghawar field up to now. From 2000 to 2012, many wells have been cored. Wettability was determined for core material using regular methods (Amott, USM, contact angle, relative permeability and recent method (ESEM).

Two wells (UTMN-A and UTMN-B) were tested using Amott method. Amott wettability indices for UTMN-A core material varied between 0.03 and 0.68 while; for UTMN-B it ranged from 0.2 to 0.41. Figure 3 shows a plot of Amott wettability indices as a function of depth for UTMN-A and B and D wells. The plot indicates that core materials recovered from these wells are neutral to slightly water-wet.

Two wells from Hawiyah area (HWYH-A and HWYH-B) were tested using both Amott and USBM method. The distribution of wettability versus depth for HWYH-A and HWYH-B are shown in Figure 4 and Figure 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 index ranged from -0.4 to 0.1; while Amott index varied between 0.03 and 0.35. Data in Figure 5 showed 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, HWYH-D, and HWYH-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 indicated that the tested pugs showed neutral to slightly water-wet character with a tendency of increasing water-wet behavior with depth. Samples located below oil water contact (OWC) showed strongly water-wet character. Amott wettability indices ranged from 0.03 to 0.87.

Qualitative Methods

Relative Permeability

Large number of waterflooding experiments was 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. Figure 7 shows typical relative permeability curves for three composites from Arab-D reservoir at the three areas. The results of relative permeability results suggested a slightly oil-wetting core material based on Craig's rule of thumb (Craig, 1971). 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

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

Receding contact angle measurements showed that receding contact angle for Arab-D crude oil/brine/Arab-D rock material system ranged from 100° to 105° (T = 70°C and P = 50 psig). This is 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 (Lichaa et al., 1992).

Microscopic observations

Figure 8 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°. This is reflects intermediate wettability character of the tested sample. Al-Yousef et al. (1995)

observed from Cryo-SEM study conducted on Arab-D rock material that both oil and brine were either filling or lining the pore walls. Their observation 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, samples located far away from 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 for 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 suggested 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.
5. Changes in the original wettability of carbonate reservoir by prolonged water injection are not significant.

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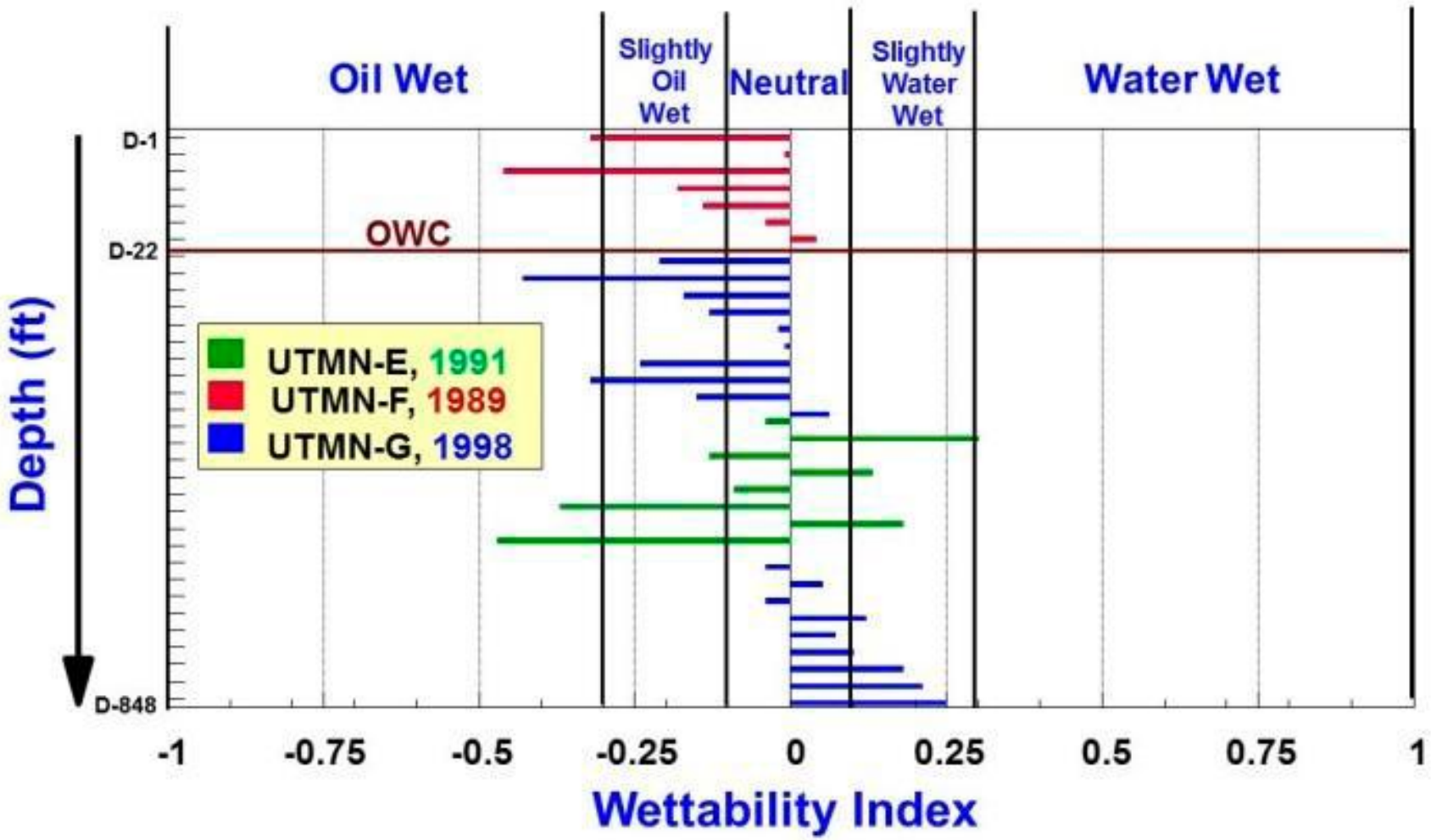

Figure 1. USBM Wettability Indices Distribution vs. Depth for Arab-D Reservoir, Uthmaniyah Area (UTMN-E, F, and G).

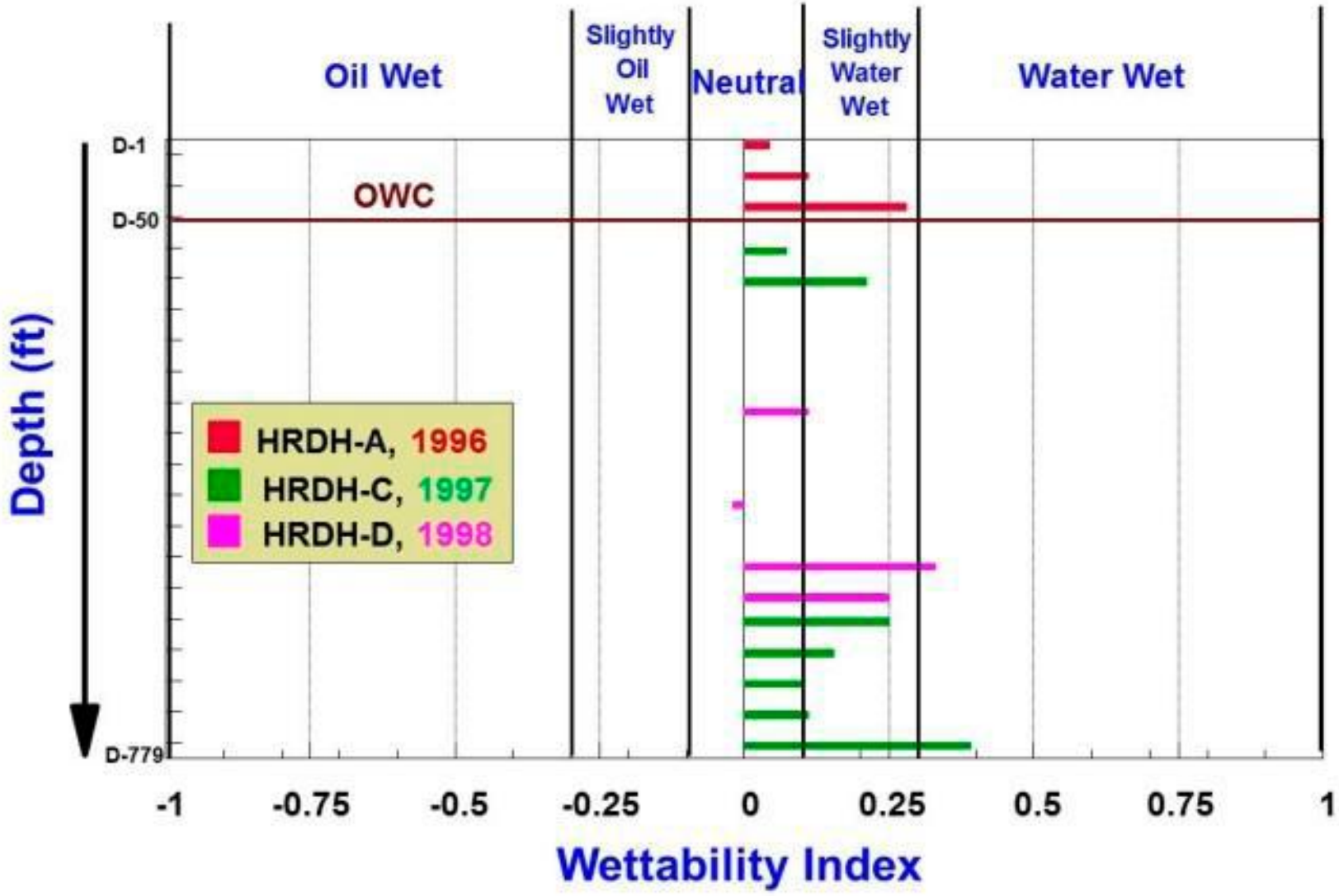

Figure 2. Amott Wettability Indices Distribution vs. Depth for Arab-D Reservoir (Haradh Area).

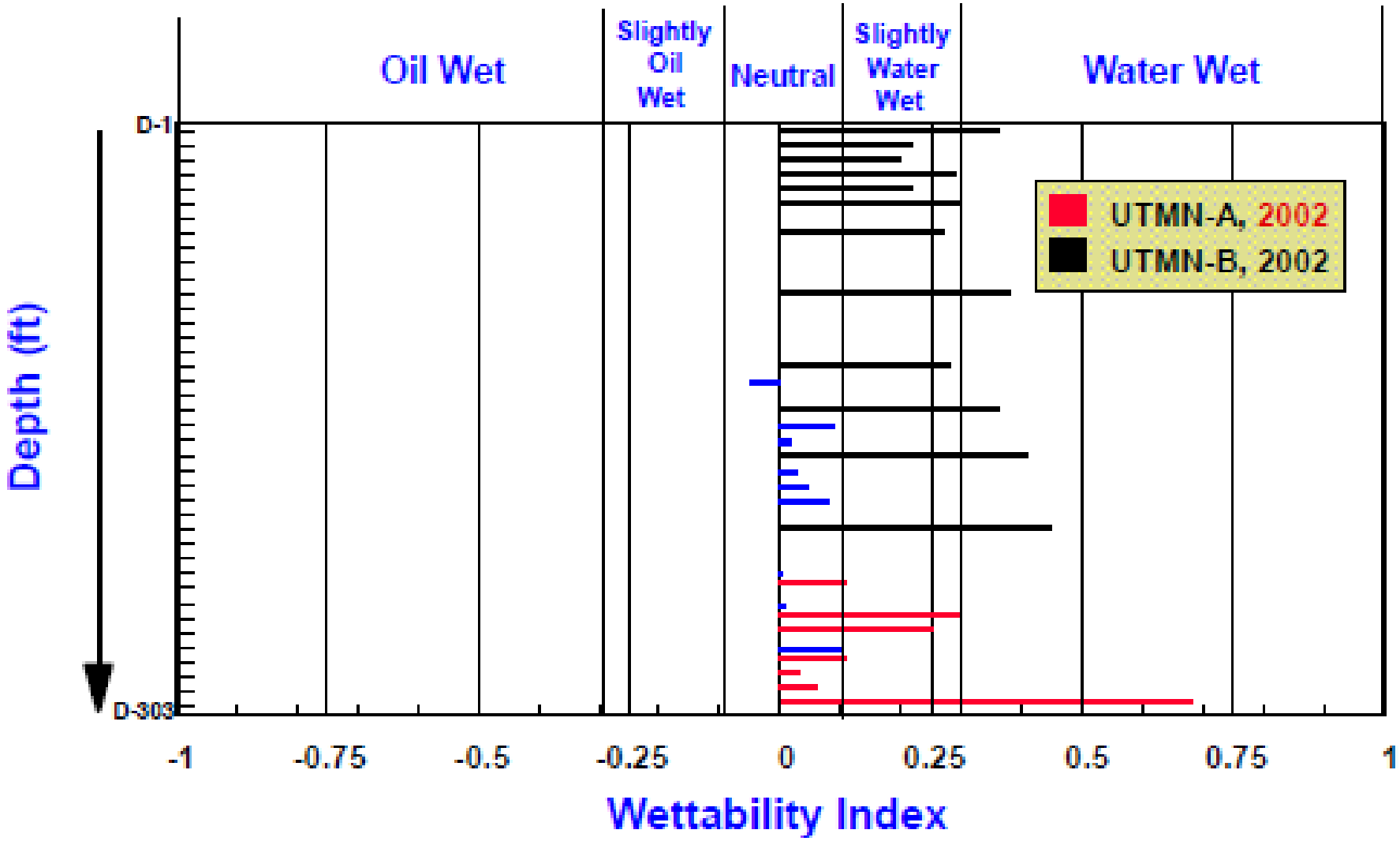

Figure 3. Amott Wettability Indices Distribution vs. Depth for Arab-D Reservoir, Uthmaniyah Area (UTMN-A and B).

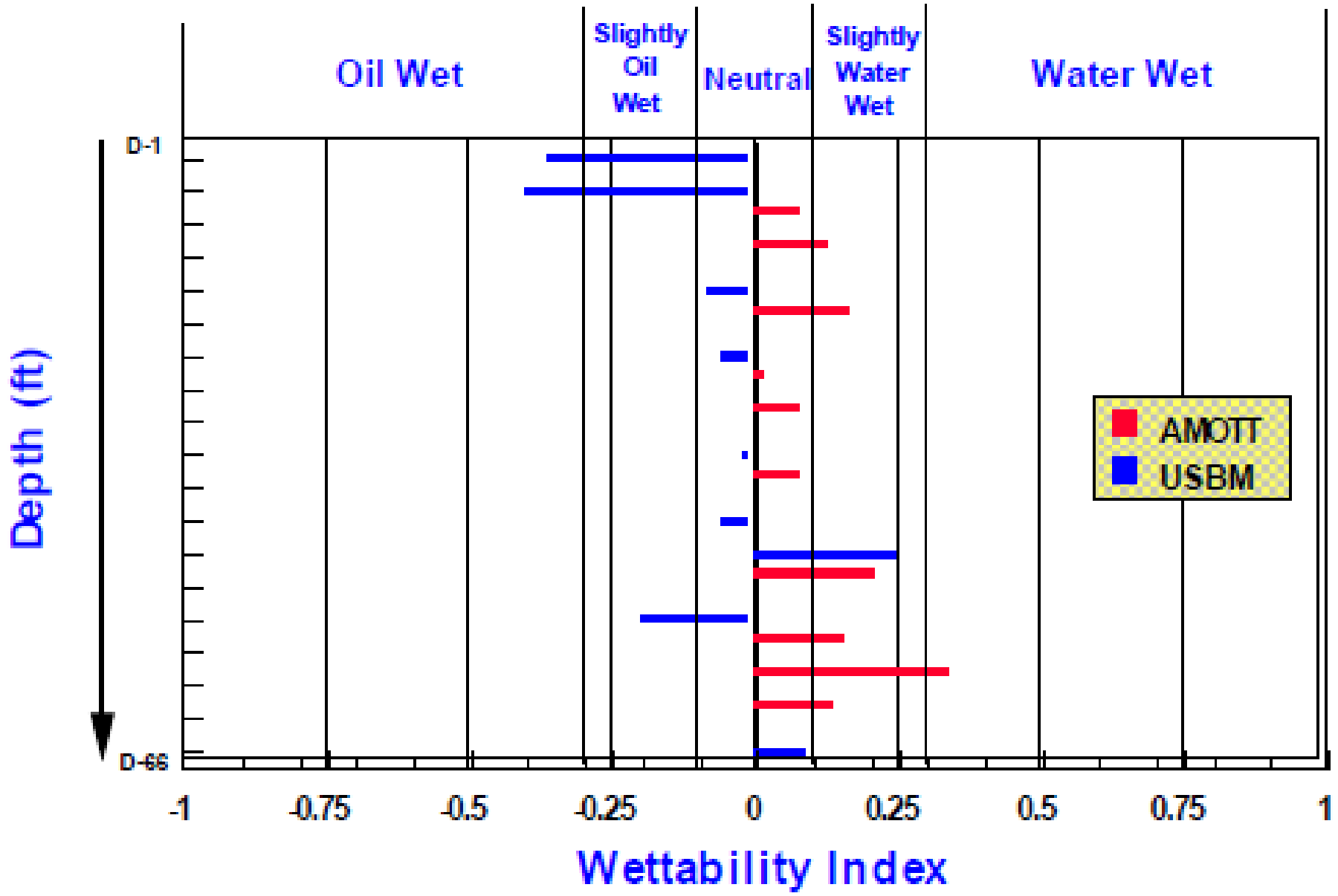

Figure 4. Amott and USBM Wettability Indices Distribution vs. Depth (Hawiyah Area, HWYH-A), 2001.

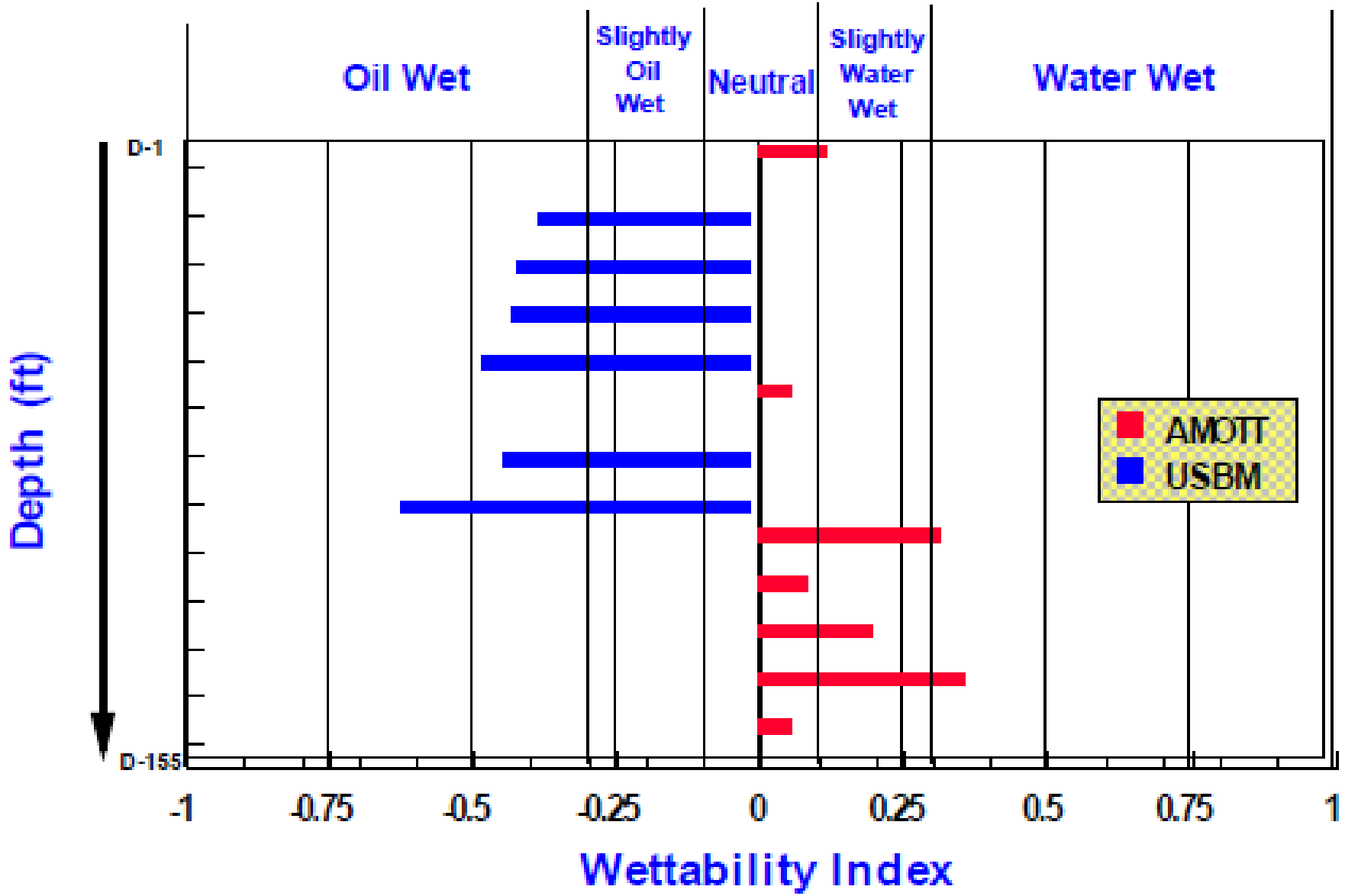

Figure 5. Amott and USBM Wettability Indices Distribution vs. Depth (Hawiyah Area, HWYH-B), 2003.

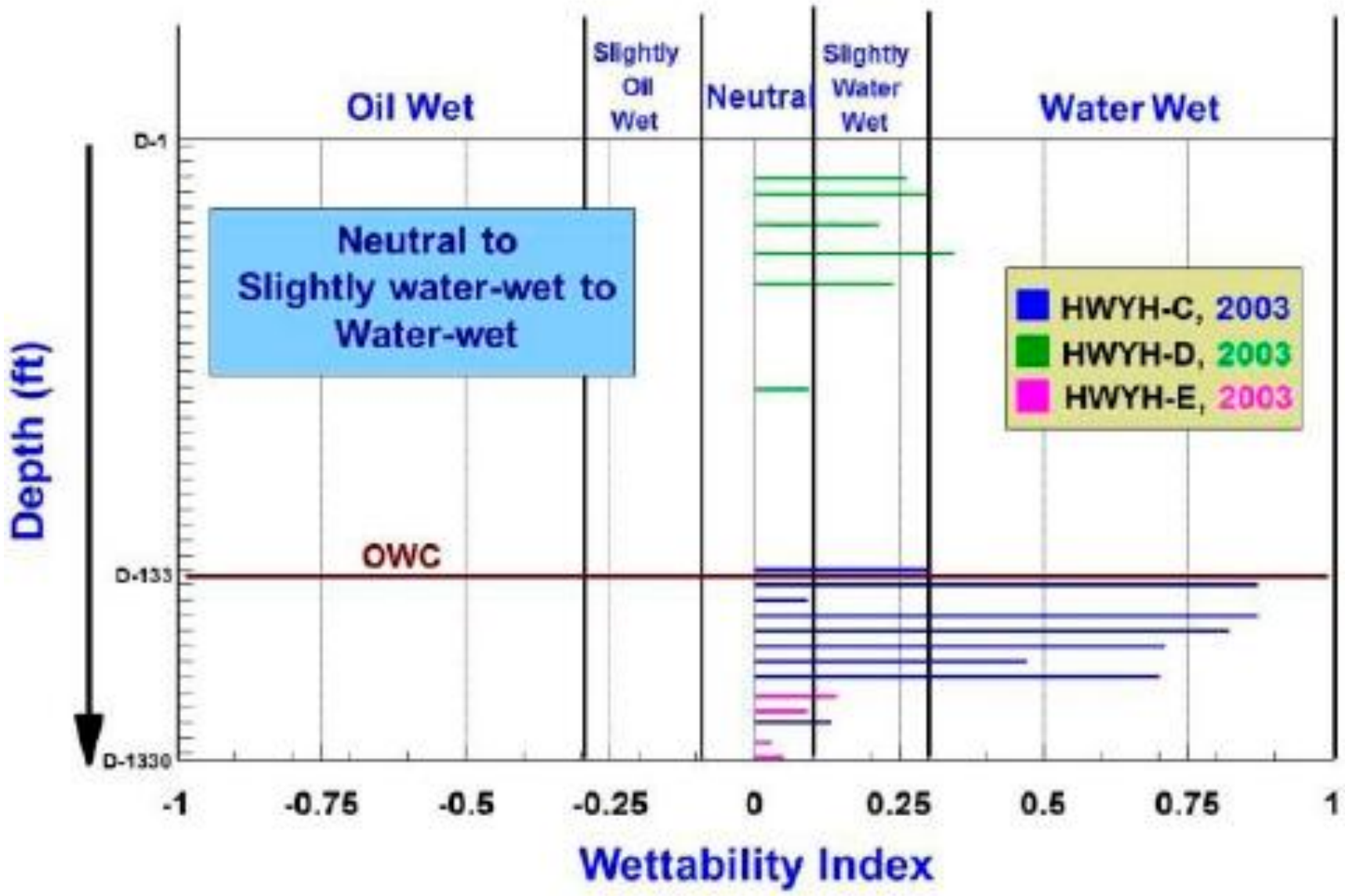

Figure 6. Amott Wettability Indices Distribution vs. Depth for Arab-D Reservoir (Hawiyah Area).

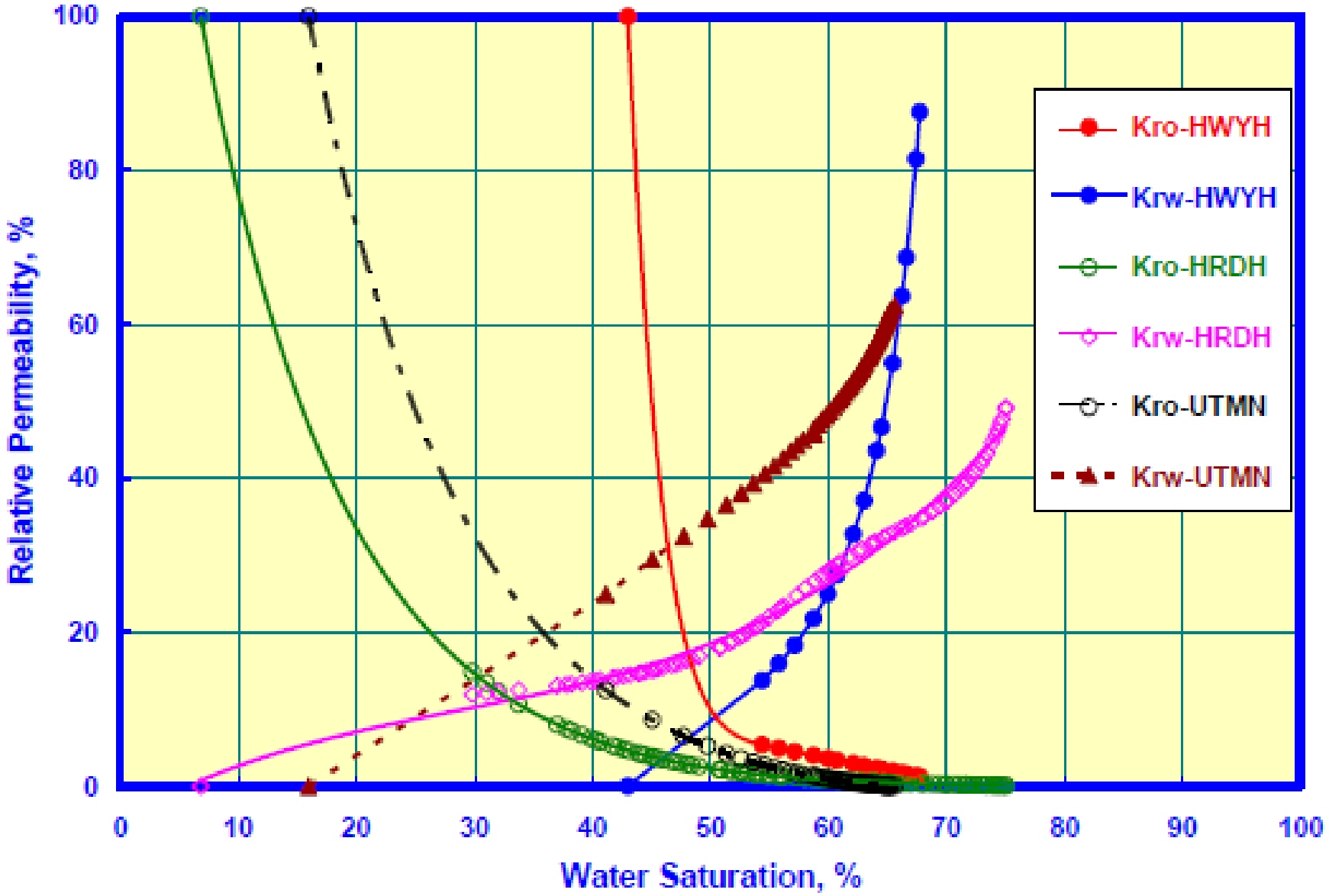

Figure 7. Typical Oil/Water Relative permeability Curves for Three Composite from Ghawar Field.

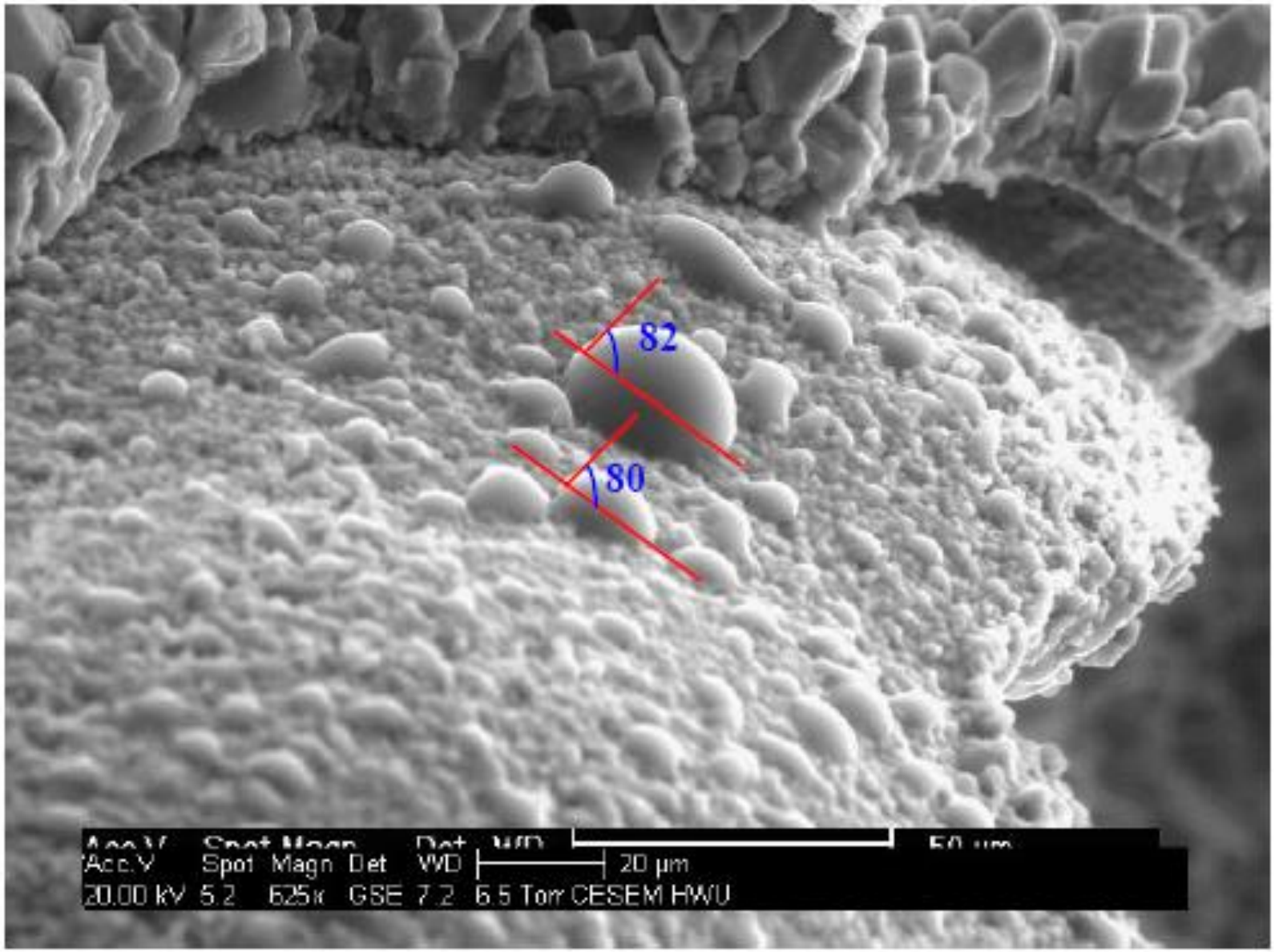

Figure 8. Appearance of Water Distribution and Intermediate Wetting Characteristics of Grains, Arab-D Carbonate Rock.

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 1. Wettability Index for UTMN-D using different drilling fluids.

Sample No.	Permeability to air (mD)	Rig-Site Wettability Index	Sample 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

Table 2. Comparison of Wettability Index Tests at rig-site and preserved cores at Laboratory, (UTMN-D).

USBM Wettability Index at 75 °C		
As Received	Cleaned	Restored
-0.31	0.07	-0.35
11	32	0.084
0.07	0.09	0.04
-0.11	0.09	0.31
-0.11	0.08	0.20
-0.12	0.07	0.00
-0.10	-0.21	-0.17

Table 3. USBM Wettability Index for Arab-D Core Material at different state (Lichaa, et al., 1992).