THE INFLUENCE OF WETTABILITY ON PETROPHYSICAL PROPERTIES

Saif Alsayari[1], Moustafa Dernaika[2] and Martin J Blunt[1]
[1] Department of Earth Science and Engineering, Imperial College London, UK
[2] Weatherford Laboratory, EL ResLab, Abu Dhabi, UAE

This paper was prepared for presentation at the International Symposium of the Society of Core Analysts held in Noordwijk, The Netherlands 27-30 September, 2009

ABSTRACT
We measured capillary pressure, relative permeability, electrical resistivity and NMR response on carbonate samples from a producing field in the Middle East. The pore throat distribution from mercury injection was successfully compared with the pore size distribution inferred from the NMR T_2 relaxation curve. Some samples were aged in crude oil at elevated temperature and underwent the same experiments to evaluate the influence of wettability changes on these properties.

The experimental data show that there is a significant difference in the relative permeability and capillary pressure of clean and aged samples; the results are explained in terms of the pore-scale configurations of fluids. In contrast, electrical resistivity did not encounter significant changes for different wettability, suggesting that electrical properties in these carbonates are mainly affected by the porosity that remains water-wet, or is only neutrally-wet. This conclusion is supported by the significant displacement that is observed in the aged sample at capillary pressures close to zero.

INTRODUCTION
Many wettability studies have been conducted on sandpacks and sandstones to examine the optimum wettability state for fluid recovery in hydrocarbon reservoirs. Reviews of the effects of wettability on petrophysical properties can be found in [1-6]. In carbonate samples studies, opinion varies widely on whether strongly oil-wet [7], strongly water-wet [8-10] or intermediate-wet [11,12] conditions are optimal for waterflood recovery. This ambiguity is principally due to the scarcity of good-quality experimental data. Furthermore, the heterogeneity of carbonate pore geometry makes it difficult to assign an inferred wettability accurately. Previous studies in the literature have tended to focus on either experimental measurement of one property or simulation studies. In this work, we will measure a range of properties on a benchmark series of carbonate cores of different wettability.

EXPERIMENTAL MATERIALS, APPARATUS AND PROCEDURE
Experimental materials
The reservoir core samples were 0.038 *m* in diameter and had porosity ranging from 22-32% and permeability ranging from 0.2-1.1x10^{-13} m^2. The lithofacies of this resevoir is known to be a skeletal, peloid packstone. The brine used throughout the displacement experiments was de-ionized water, with different percentages of NaCl, $CaCl_2$, $MgCl_2$, Na_2SO_4 and $NaHCO_3$. The density of the brine used for the experiments was 1128 kg/m^3 and resistivity of 0.051 *ohm.m.* Isopar-L was the oil used. The density of isopar-L at

15 ^{o}C is 765 kg/m^3. Dead crude oil from the same producing field was used to alter the wettability of the samples.

Experimental apparatus and procedure

The samples underwent standard soxhlet cleaning using toluene and methanol to remove water, oil and salts. Then, the samples were loaded in core holders and flush cleaning was commenced using series of hot miscible cycles of toluene, a mixture of toluene and methanol and methanol. Then conventional and special core analyses commenced. The apparatus used for the conventional core analysis, NMR and electrical measurements are similar to those described in the literature [1-6].

Steady-state relative permeability

A core plug (sample 1) at initial water saturation is flooded with brine and oil at a specified fractional flow. The flooding is continued until equilibrium is reached (steady state). After reaching equilibrium, the fractional flow of water is increased. The total rate (sum of the oil and water rate) is kept constant. At each steady state, the flow-rate, differential pressure, temperature and saturation fraction for each phase in the core plug were recorded, from which the relative permeability is calculated using Darcy's Law. Then, the core plug was cleaned, saturated with brine and flooded with crude oil at 110 ^{o}C. When no more water was produced the sample was kept in the crude oil at 110 ^{o}C for forty days to allow the alteration of wettability. Then, the relative permeability experiment was repeated on this aged sample.

Capillary pressure and resistivity index by the porous plate technique

Water-wet ceramic plates were installed in the bottom of the cleaned and brine saturated samples 4 and 5. The core plugs were de-saturated using mineral oil by increasing the capillary pressure in steps and recording resistivity at each saturation step (Drainage curve). Sample 4 was then separated from the apparatus and the mineral oil was displaced by crude oil. The sample was kept in oven at 110 ^{o}C for forty days. Afterwards, the crude oil was displaced by decalin buffer (to prevent asphaltene precipitation) followed by mineral oil and the experiment was performed as above.

At the highest capillary pressure, the plugs were allowed to imbibe brine spontaneously (positive capillary pressure) at ambient temperature and net overburden pressure (2650 psi). After attaining equilibrium data (stable water reading and stable resistivity) at zero capillary pressure, the water valves were shut. The confining pressure was then carefully lowered to zero allowing the sample to admit oil slowly to fill the increasing pore volume. The porous plate was then removed and an oil-wet porous plate saturated with laboratory oil was installed. The samples were then saturated with brine by forcing water into the samples. This was achieved by increasing the water pressure over the oil pressure and the capillary pressure becomes negative; capillary pressure was decreased in steps and resistivity and volume of brine were recorded at each saturation step.

RESULTS

Conventional core analysis

Table 1 shows the measured porosity and permeability for the five carbonate samples studied. Excellent was found for porosity and permeability measured using different techniques: conventional analysis on plugs (helium gas expansion porosity and nitrogen gas permeability), NMR and mercury analysis on trims.

Mercury injection capillary pressure
Mercury injection capillary pressure data has been measured for clean dry trims from each sample using a Micromeritics Autopore IV 9520. Figure 2 shows the measured drainage capillary pressure and inferred throat size distribution from these curves. Note that most of the throat diameters are around 1 μm.

NMR results compared to mercury injection data
Figure 2 (a-e) compares the pore diameter derived from the NMR response to the throat size distribution from the mercury injection capillary pressure. The two ways to estimate pore size are in good agreement, again confirming that the majority of the pore space has an effective radius less than 1 μm. The relative position of the T_2 distribution on the pore diameter axis is altered by changing a scaling factor (Figure 3f). The scaling factor has the unit microns/millisecond. The scaling factor can be used to convert T_2 times to pore diameter. The comparison is optimized by changing the scaling factor to obtain the best match between the mercury injection and T_2 distribution curves.

The measured samples in general, show an excellent match between T_2 distributions and mercury injection pore size distributions. The NMR experiments were conducted on the whole plug, and capillary pressure was measured on an end-cap. The agreement in the results indicates homogeneous samples.

Capillary pressure and resistivity index
Figure 3 shows the measured capillary pressure and resisitivity indices for cleaned and aged samples 5 and 4, respectively. For primary drainage the capillary pressure curves are similar and comparable to that measured using mercury injection (the assumed air/mercury contact angle used is 130˚, and the air/mercury interfacial tension is 485 mN/m.). The irreducible water saturation for these samples is very low – only around 5%. For the cleaned sample 5, approximately half the water displacement is spontaneous, with a positive capillary pressure, while half required forced injection with a residual oil saturation of around 25%. This indicates that the samples are not strongly water-wet but display intermediate characteristics, even when cleaned. The aged sample 4, shows a small amount of spontaneous displacement of oil by water – around 5% – which may indicate some pores remain water-wet despite ageing. However, most recovery occurs during forced displacement. Most recovery is achieved for capillary pressures close to zero, indicating that much of the pore space is neutrally-wet with effective contact angles close to 90º. This is evidently not a uniformly and strongly oil-wet sample. The residual oil saturation – around 20% - is lower than for the water-wet system, as seen in other aged samples; this is likely to be due to the slow drainage of oil layers in an oil-wet system [4, 7, 13].
A surprising result is that the resistivity indices of the cleaned and aged systems are similar. This indicates that perhaps the electrical properties are dominated by porosity that remains water-wet or at least neutrally-wet – the capillary pressure curve for the aged sample, showing some spontaneous imbibition and displacement at a low capillary pressure would support this conclusion.

Relative permeability curves
The cleaned and saturated sample 1 was drained to initial water saturation using the porous plate technique. The cleaned core had a slightly higher initial water saturation

(12%) than the aged sample (8%) – this is consistent with wettability change, allowing displacement of water from the less water-wet sample.

Figure 4 compares the steady-state relative permeabilities for the cleaned and then aged sample 1. As expected, after aging, the oil relative permeability at the same saturation is lower than for a water-wet sample: in water-wet media, oil occupies the larger pore spaces, while in oil-wet systems; it preferentially occupies smaller pores or layers with low conductivity. The water relative permeability is larger, since, in oil-wet media, the water displaces oil from the larger pore spaces. The residual oil saturation for the cleaned case is 0.23. The end-point water relative permeability – 0.32 – is quite high, indicating that the system is not strongly water-wet, as discussed previously. For the aged system, the steady-state technique was unable to probe the regime where the oil relative permeability is very low, giving an apparent residual of 0.5: in reality oil will continue to flow down to much lower saturation through the slow drainage of layers as indicated by the capillary pressure measurements.

CONCLUSIONS

We have conducted a series of measurements on cleaned and aged carbonate cores. NMR and mercury injection capillary pressure measurements gave consistent estimates of the pore size distribution. The cleaned cores appeared to be weakly water-wet, with approximately half the waterflood recovery achieved by forced displacement. The aged samples showed some displacement by spontaneous imbibition and considerable displacement at a very low capillary pressure. The resistivity indices showed little difference between cleaned and aged samples, indicating that the conductance is dominated by water in water-wet or neutrally-wet pores. This suggests that resistivity alone is not a good indicator of wettability. The cleaned samples gave relative permeabilities also consistent with a weakly water-wet system, while the aged core has higher water and lower oil relative permeabilities indicating oil-wet characteristics.

It is well known that the vast majority of carbonates reservoirs are not water-wet [14]; however, these studies were performed primarily on fields in the US with heavy oils. In the present paper, the wettability of a typical Middle East carbonate reservoir is thoroughly investigated. We suggest that the typical wettability of Middle East fields is not strongly oil-wet, but shows mixed-wet and neutrally-wet characteristics. This result is consistent with recent studies performed on similar carbonate samples [15,16].

Table 1 Porosity and permeability measurements using different techniques for the carbonate samples.

Sample	ϕ_{Helium} %	ϕ_{NMR} %	$\phi_{Mercury}$ %	k_g mD	$k_{Mercury}$ mD
1	32.0	31.5	29.9	11.0	12.9
2	27.5	26.5	26.3	9.0	6.6
3	29.6	30.0	28.2	9.1	7.7
4	26.7	27.2	26.5	7.1	6.3
5	22.6	21.9	22.3	2.9	4.3

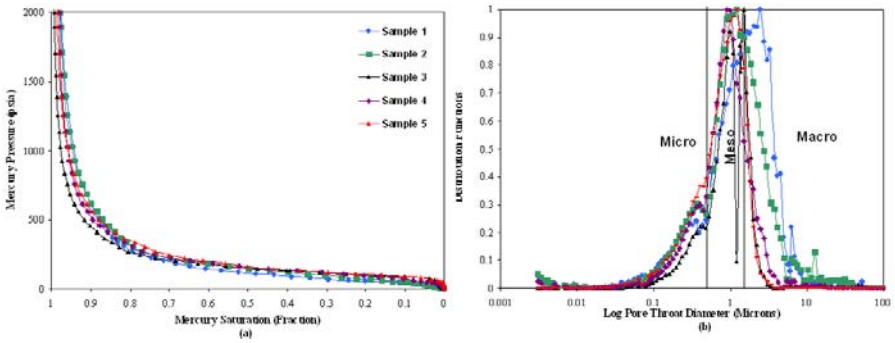
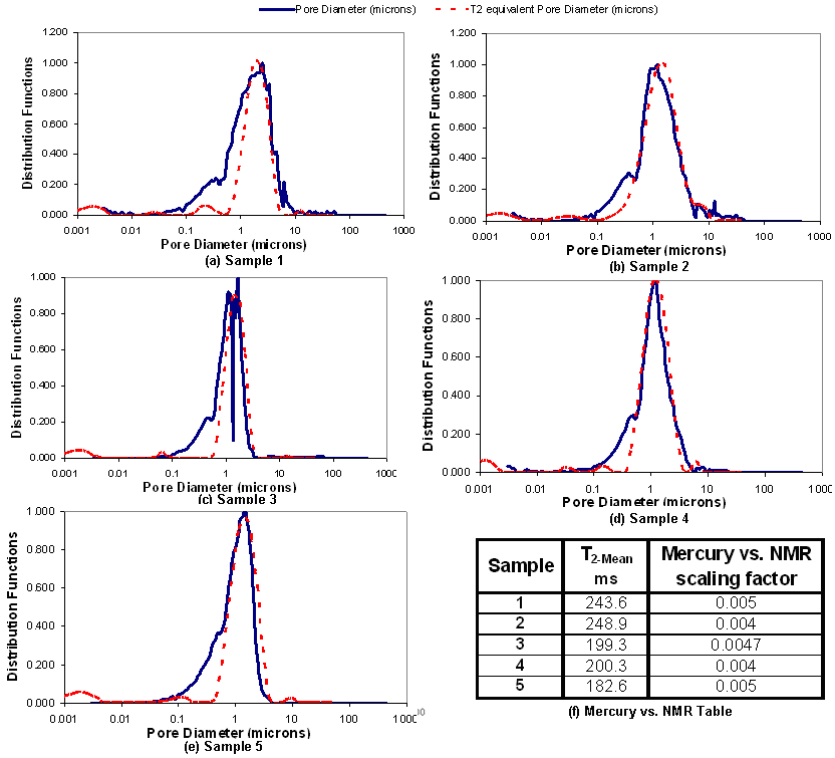


Figure 1 Mercury injection data showing (a) drainage capillary pressure and (b) the inferred pore throat distribution (diameter).



Sample	$T_{2\text{-Mean}}$ ms	Mercury vs. NMR scaling factor
1	243.6	0.005
2	248.9	0.004
3	199.3	0.0047
4	200.3	0.004
5	182.6	0.005

(f) Mercury vs. NMR Table

Figure 2 (a-e) Comparison of T_2 distribution and mercury injection derived pore size distributions (diameter). (f) Table of the scaling factor values used to best match NMR to mercury pore throat distribution.

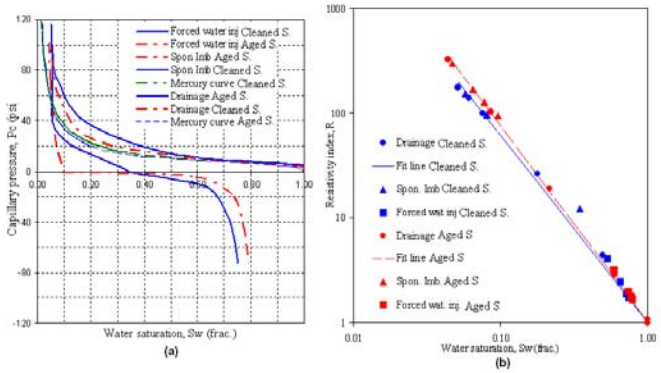


Figure 3 (a) Comparison between the capillary pressure curves for the aged and cleaned systems, samples 4 and 5 respectively, using the porous plate technique. (b) Comparison of the resistivity indices.

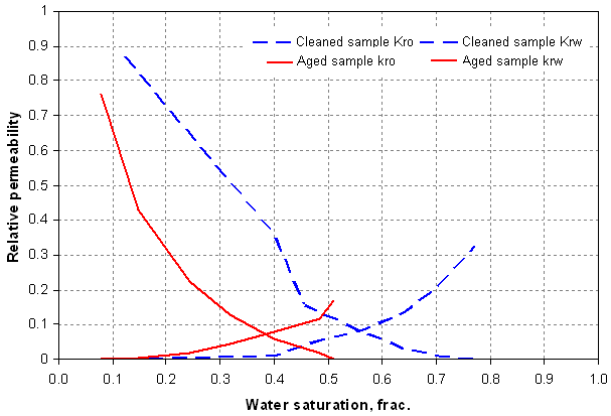


Figure 4. Steady-state relative permeability curves for the cleaned and aged sample 1.

REFERENCES

1. Anderson, W.G., "*Wettability literature survey - Part 2: Wettability measurements*": JPT (Nov. 1986), **38**, p.1246-1262.
2. Anderson, W.G., "Wettability *literature survey - Part 3: The Effects of Wettability on the Electrical properties of Porous Media*": JPT (Dec. 1986), **38**, p.1371-1378.
3. Anderson, W.G., "*Wettability literature survey - Part 4: The Effects of Wettability on Capillary pressure*" JPT (October 1987) **39**, p.1283-1300.
4. Morrow, N.R., "*Wettability and its effect on oil recovery*": JPT, (December 1990), p. 1476-1484.
5. Cuiec, L.E., "*Evaluation of reservoir wettability and its effects on reservoir recovery*": Interfacial Phenomena in Oil Recovery, N.R. Morrow (ed), Marcell Dekker, New York, 1990.
6. Buckley, J.S., Liu, Y., Xie, X. and Morrow, N.R., "*Asphaltenes and crude oil wetting - the effect of oil composition*": SPE Journal, (1997), **2**, p.107-119.
7. JE Warren, J.C., *A Study of Waterflood Efficiency in Oil-Wet Systems.* Trans. AIME, (1955), **204**: p. 22-29.
8. Morrow, N.R., *Wettability and Its Effect on Oil Recovery* Journal of Petroleum Technology, (December 1990), **42** (12), p.1476-1484.
9. N. Mungan, *Certain Wettability Effects In Laboratory Waterfloods* Journal of Petroleum Technology, (February 1966), **18**(2), p.247-252.
10. Owens, W.W. and D.L. Archer, *Effect of rock wettability on oil-water relative permeability relationships.* Journal of Petroleum Technology, (1970), **23**(7), p.873-878.
11. Tie H , M.N. Morrow, *Low Flood Rate Residual Saturations in Carbonate Rocks*, in International Petroleum Technology Company. 2005: Qatar.
12. Moore, T.F. and R.L. Slobod, *The effect of viscosity and capillarity on the displacement of oil by water*. Producers Monthly, (August 1956), **20**, p.20–30.
13. Salathiel, R.A., *Oil recovery by surface film drainage in mixed-wettability rocks.* Society of Petroleum Engineering AIME, 1972. **4104**: p. 47
14. Treiber, L.E., D.L. Archer, and W.W. Owens, *A laboratory evaluation of the wettability of fifty oil-producing reservoirs.* Society of Petroleum Engineering Journal 1971. **12**: p. 531–540
15. Okasha, T. M., Funk, J. J., and Balobaid, Y. B.: *Wettability and Relative Permeability of Lower Cretaceous Carbonate Rock Reservoir, Saudi Arabia*, paper 2001-03 proceedings of the 2001 SCA Annual Technical Conference, Edinburgh, September 16-17
16. Cuiec, L.E. and Yahya, F.A.: *Wettability of Asab Reservoir Rock : Comparison of Various Evaluation Methods, Role of Lithology*, SCA Conference Paper Number 9109 (1991).

ACKNOWLEDGEMENTS

The authors are indebted to Weatherford Laboratories (ResLab) for access to their facilities and to ADNOC (Abu Dhabi) for funding this study.