HOW CAN NMR ASSESS THE WETTABILITY OF A CHALK RESERVOIR

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ABSTRACT

Knowing the wettability of a reservoir at an early date is important for every oil reservoir, but can be vital in low-permeability reservoirs such as in off-shore chalk fields. Therefore, an extensive wettability program was designed for this field, including USBM and Amott-Harvey tests on a set of core samples. These tests followed the standard protocol of ageing in dead crude, followed by imbibition and drainage cycles with mineral oil. As a novel addition, we took individual NMR core measurements at each of the nine laboratory steps. We found a good correlation between USBM and Amott-Harvey, and also with the NMR wettability index. Whereas the USBM and Amott-Harvey techniques provide just one number, NMR can be interpreted at each analytical laboratory step. We found that the wettability index remains roughly constant during the process. This implies that the protocol of imbibing and draining mineral oil in aged samples does not affect the wettability condition.

Subsequently, the analysis was applied to the NMR logs in the same well. The wettability in the oil zone was found to be similar as what was found in the core data. As expected, the wettability gradually changes to fully waterwet over the transition zone down to the OWC. SCAL measurements at transition zone conditions are cumbersome, but this information allows modeling changes in flow properties in the transition zone.

INTRODUCTION

Nuclear Magnetic Resonance (NMR) derives its popularity as a logging technique from the sensitivity of the measured relaxation times of hydrogen nuclear spins of the wetting fluids to an interaction with the pore surface. Whereas this is normally only observed for water, it has long been known [1] that a similar effect exists for oil in non-waterwet rock. Over the years, many publications appeared showing empirical correlations, e.g. [2] or

through more complicated analyses, e.g. [3]. Recently we developed a method to derive a quantitative NMR wettability index (NWI) from just a single NMR measurement [4]. The index is computed through detailed modeling of the NMR response as a function of saturation and wetting over the pore size distribution. The validity of this method was verified on a large set of core samples against standard laboratory wettability index data (USBM). This method has been adapted to be used with NMR log data [5] allowing the wettability to be determined over the entire reservoir interval as a continuous curve, rather than on a few samples, from any standard NMR log.

The NMR Wettability Index

The surface of pores provides an additional relaxation mechanism, which adds to the bulk relaxation of the nuclear hydrogen spin of the saturating fluid. The effect is that the ith fluid in a pore relaxes a single exponential decay $exp(-t/T_{2,i})$, with :

$$\frac{1}{T_{2,i}} = \frac{1}{T_{2,bulk,i}} + \rho_i \frac{A}{V} \frac{f_i}{S_i} \tag{1}$$

with $T_{2,i}$ observed relaxation time
       $T_{2,bulk,i}$ relaxation time of bulk fluid
       ρ_i surface relaxivity
       A / V surface-to-volume ratio of the pore
       f_i wetted fraction of the surface
       S_i saturation of the pore by fluid i

The wetting index can thus be defined as the relative fraction of the total surface wetted by water minus that by oil: $NWI = f_{water} - f_{oil}$. In words:

$$NWI = \frac{Surface\ wetted\ by\ water - Surface\ wetted\ by\ oil}{Total\ Surface} \tag{2}$$

To conform to existing indices, NWI, scales from +1 for fully water-wet, through 0 for neutral, to -1 for fully oil-wet. In reality, rocks have a certain range of pore sizes (A/V values), and thus a range of T2 amplitudes. Furthermore, f_i and S_i may vary with poresize. NWI is thus computed by integration of eq. (1) over T_2. Full details of the method may be found in an earlier publication [4].

It is emphasized that the definition of NWI has some resemblance with the traditional Amott and USBM indices. However, since it is based on entirely different grounds, there is no fundamental numerical equality implied other than at the endpoints of fully water-wet and fully oil-wet. Similar to any index, it provides an indication of flow properties, but being a single number, it cannot replace a full set of SCAL data.

The challenge in the computation of NWI is in determining $f_i\ (T2)$ and $S_i\ (T2)$. In many practical cases, the oil and water distributions have significant overlap, causing the position of the oil peak to be shifted, or even to be indistinguishable. This problem has

been solved by inversion of a detailed forward model of the NMR response, taking into account as a function of pore size: (1) the microscopic distribution of oil and water, (2) the wetting fraction, (3) the T2 distributions of the rock at Sw=1 and of the bulk fluids.

NMR wettability on core samples during SCAL program

The objective of the present study was to apply the method at every preparation step of the traditional wettability workflow for the combined Amott-Harvey / USBM method.

NMR measurements were made using a Maran spectrometer, operating at 2 MHz in a homogenous field. Measurements were made on 6 samples from an oil bearing chalk reservoir, at the following steps of preparation:

1   Cleaned, Sw =1
2   Swi-crude before ageing
3   Swi-crude after ageing
4   Displace by isopar-L
5   Swirr desaturation
6   Spontaneous imbibition water
7   Forced imbibition water
8   Spontaneous imbibition oil
9   Forced imbibition oil

The samples were first vacuum-saturated with synthetic formation brine, then de-saturated to initial saturation (Swi) in crude oil–brine system by single-speed centrifuge. After aging at reservoir temperature and pressure, the samples were flushed with mineral oil (Isopar-L) in a core holder, first with decalin oil and then with isopar-L oil. The samples were further de-saturated to irreducible water saturation (Swirr) by single-speed centrifuge. The spontaneous imbibitions (step 6 step 8) were carried out in Amott cells and forced imbibitions (step 7 and step 9) were performed in multi-speed centrifuge.
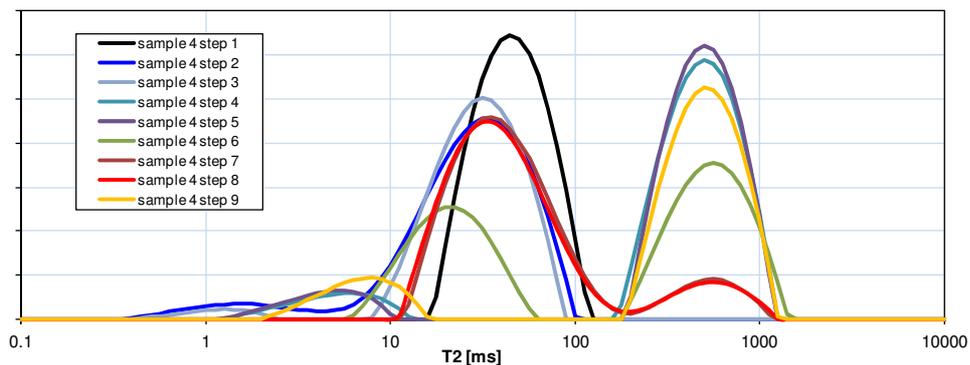

Figure 1   Observed NMR T2-distribution of sample 4 after steps 1 to 9.

The observed NMR T2-distribution after each step is shown in Figure 1 for sample 4; all other samples showed a very similar response. The interpretation of the response in terms

of fluid distribution and wettability is given in the next sections, starting with the more straightforward cases where the oil is a light refined oil (isopar-L)(steps 4 to 9), leaving the more complicated case of crude oil to the end.

Wettability interpretation after step 4 and 5

The interpretation of the T2-distribution after step 4 is relatively straightforward. An example is shown in Figure 2 for sample 4; all other samples look very similar.
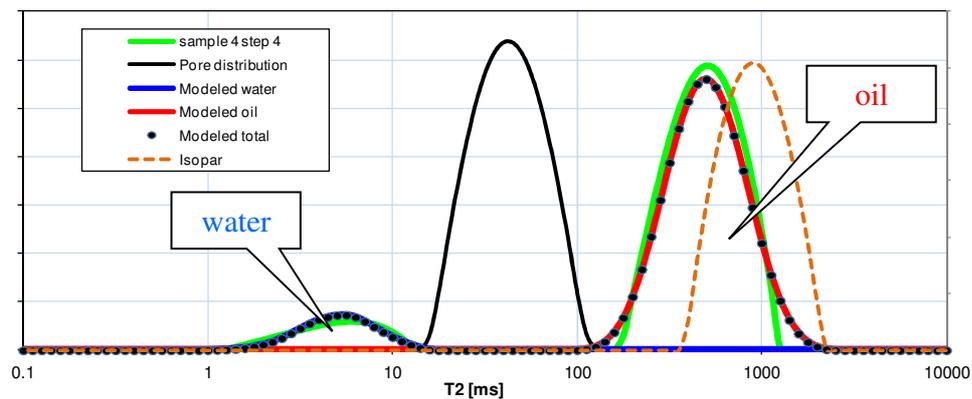

Figure 2   Observed and modeled T2-distribution of sample 4 after step 4

The "Pore distribution" (black curve) is the T2-distribution measured on the water-filled sample (step 1). Upon imbibition with crude, and subsequently isopar-L, the water saturation has reached a low value. Consequently, the amplitude is reduced, but also its T2 has shifted to a lower value. This shift can be understood from eq.(1): the volume of water has now been reduced to V*Sw. Roughly speaking, this means that T2 has reduced to T2*Sw. The actual modeling is more refined, as it takes into account that the larger pores are stronger imbibed than the smaller pores.

The stronger peak, at longer T2, is due to isopar-L. As can be seen, it has been shifted to lower T2 compared to the bulk relaxation. This is the result of wetting. The degree of shift depends on the value of ρ in eq.1; it appears that no explicit value of ρ is required, but only the ratio of the surface relaxivity of isopar-L compared to that of water [4]. Previous experience has shown a relative value of 0.2 for oils in chalk. The quantitative wettability interpretation furthermore includes pore-size dependent saturation and wetting, and integration over all pore sizes (i.e. over the T2-distribution).

As can be seen, the modeling reproduces the observed T2-distribution very well. This is seen on all samples. The water saturation can now be calculated precisely since there is a clear separation between water and oil. The integrated area under the water peak gives Sw.

The NMR response hardly changes between steps 4 and 5; the wettability index remains virtually the same.

Wettability interpretation after step 6

After step 6 water saturation has increased by spontaneous imbibition. As a consequence, the water peak has grown, and shifted to a larger T2, both by the same mechanism as explained in the previous section. The wettability index remains approximately the same.
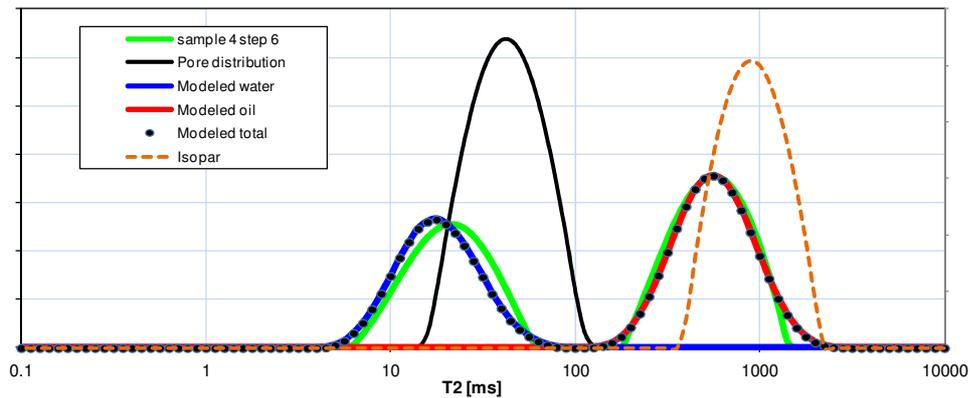

Figure 3   Observed and modeled T2-distribution of sample 4 after step 6

Wettability interpretation after step 7

Forced water imbibition continued to increase the water peak, leaving a small peak of oil. The oil peak is still lightly shifted from the bulk response as a result of partial wetting. Because the oil saturation is low, the wettability index has a larger uncertainty than in the other steps, but is still about the same as before.
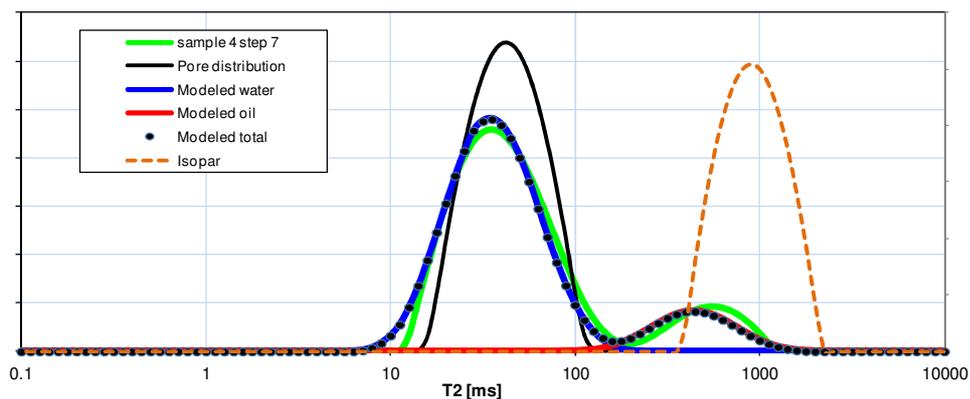

Figure 4   Observed and modeled T2-distribution of sample 4 after step 7

Wettability interpretation after step 8 and 9

Spontaneous and forced oil imbibition in steps 8 and 9 has reduced water saturation more or less back to the situation after step 5; the NMR response is also virtually the same as after step 5.
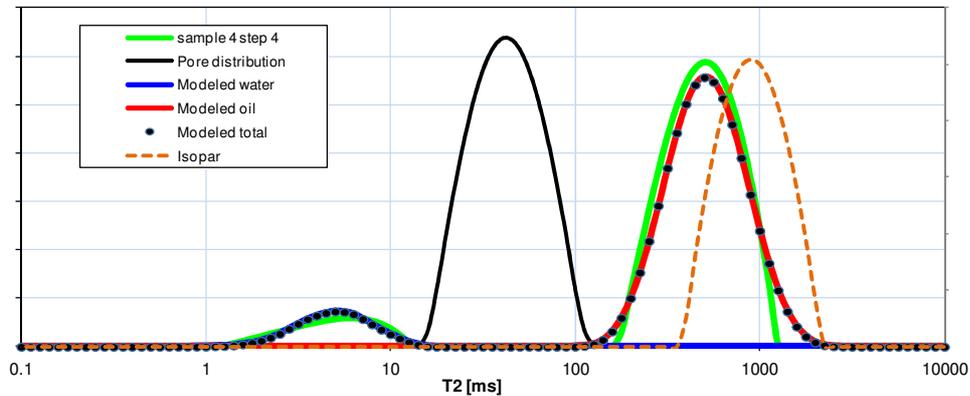

Figure 5   Observed and modeled T2-distribution of sample 4 after step 9

Wettability interpretation after step 2 and 3

When the responses of water and oil overlap, the interpretation gets more complicated. In the present case the situation is even worse: for all samples the Sw=1 response and crude oil fully overlap, which renders the interpretation virtually impossible. Even if the water saturation is taken from the SCAL analysis, the model allows almost any level of wettability. A further complication is that there was no NMR measurement made of the crude after ageing. Studies elsewhere have occasionally seen some alteration of the crude (evaporation of lighter ends) that do not impact on the ageing, but give additional uncertainty in the NMR wettability analysis. Consequently, no interpretation can be given for steps 2 and 3, except, qualitatively, that the sample is not fully water-wet.
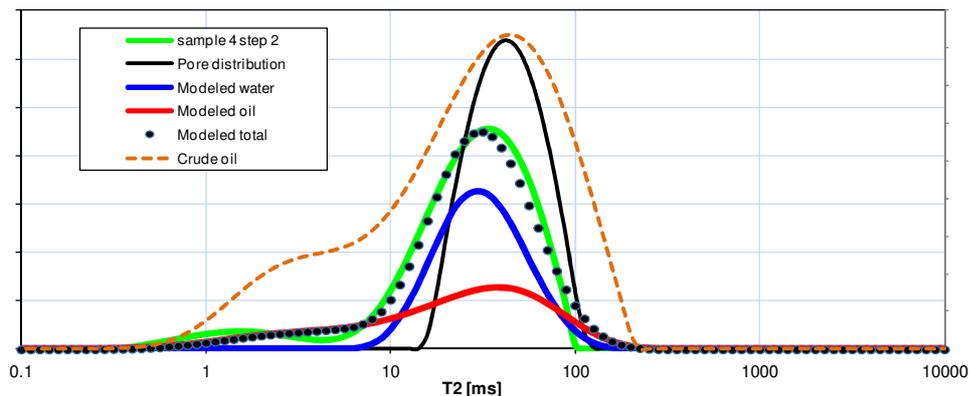

Figure 6   Observed and modeled T2-distribution of sample 4 after step 2

Discussion of results on core-derived wettability

The interpretation results are summarized in Table 1, together with the corresponding Amott and USBM indices.

Sample		After preparation step nr.						Amott Index	USBM Index
		4	5	6	7	8	9		
1	Sw_core	0.10	0.10	0.22	0.70	0.70	0.16		
	Sw_NMR	0.13	0.12	0.26	0.80	0.82	0.29		
	NWI	0.64	0.65	0.73	0.82	0.84	0.76	0.20	0.12
2	Sw_core	0.18	0.12	0.33	0.80	0.80	0.15		
	Sw_NMR	0.19	0.15	0.37	0.84	0.82	0.17		
	NWI	0.71	0.74	0.83	0.79	0.83	0.71	0.30	0.24
3	Sw_core	0.17	0.17	0.47	0.77	0.77	0.20		
	Sw_NMR	0.15	0.16	0.45	0.80	0.77	0.19		
	NWI	0.71	0.69	0.83	0.90	0.92	0.71	0.50	0.42
4	Sw_core	0.12	0.12	0.46	0.86	0.86	0.14		
	Sw_NMR	0.11	0.10	0.43	0.87	0.87	0.16		
	NWI	0.72	0.72	0.86	0.95	0.95	0.76	0.46	0.43
5	Sw_core	0.15	0.10	0.43	0.74	0.74	0.15		
	Sw_NMR	0.14	0.13	0.46	0.71	0.71	0.15		
	NWI	0.82	0.82	0.88	0.90	0.90	0.84	0.53	0.30
6	Sw_core	0.13	0.13	0.44	0.76	0.76	0.19		
	Sw_NMR	0.15	0.14	0.49	0.73	0.73	0.17		
	NWI	0.84	0.85	0.84	0.78	0.78	0.76	0.50	0.24

Table 1   Saturation and Wettability Index by NMR

As explained in the previous sections, the NMR-derived saturations of steps 4 - 9 are very robust because the water and oil peak are well separated. The agreement with the independent Sw_core from SCAL volumetrics is excellent, see Figure 7. The largest exceptions are with sample 1 for which the Sw_core values are somewhat questionable because of significant observed grain losses.
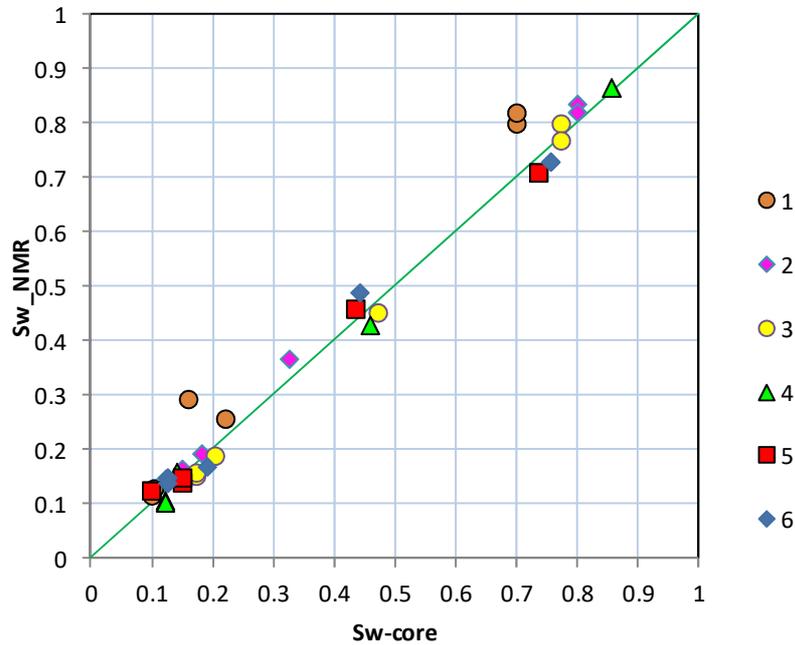
Figure 7   NMR-derived saturation versus SCAL-derived saturation for samples 1 to 6

The NMR Wettability Index correlates well with the Amott (and USBM) index, see Figure 8. As mentioned in the Introduction, there is no one-to-one relationship between these indices, but rather a positive trend between the common endpoints [-1,-1] and [+1,+1]. The observed trend implies that a given NMR Wettability Index corresponds to a lower Amott value, at least for positive index values.

There appears to be a slight trend between the NMR Wettability Index and Sw, see Figure 9. When analyzed against step number, Figure 10, it appears that the samples become more water-wet with every subsequent step; the most water-wet values are seen at steps 7 and 8, which have the lowest oil saturation. Part of this residual oil is present in the form of snapped-off droplets that have no contact with the surface; this is not properly incorporated in the model, and will result in a too high index. The interpretations of steps 7 and 8 thus have the largest uncertainty.

If this trend were true, it would mean that flooding mineral oil has some effect on the wetting condition of the samples. However, the evidence is not strong enough to support this concern. Suijkerbuijk et al [6] reported a study in which Berea samples were aged with various crudes, and subsequently flooded with mineral oil. They did not observe a change in wetting.
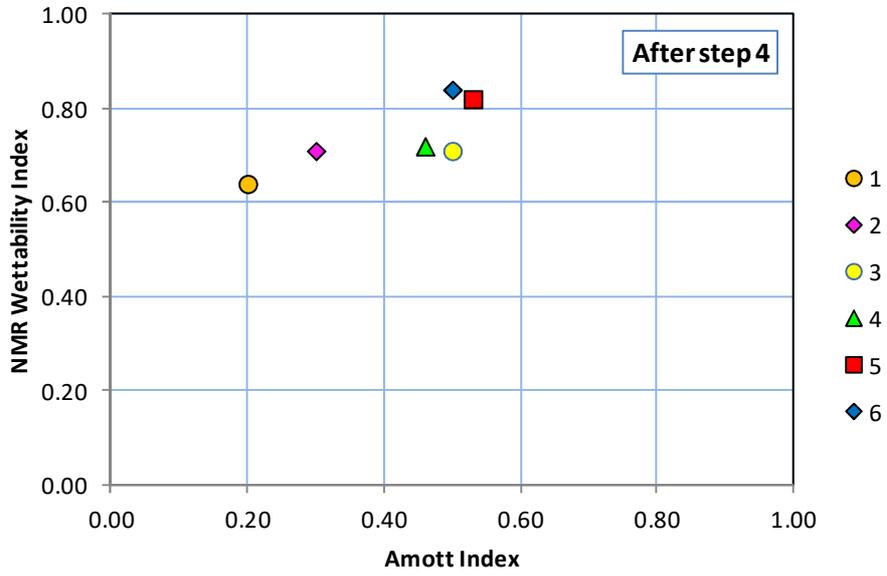
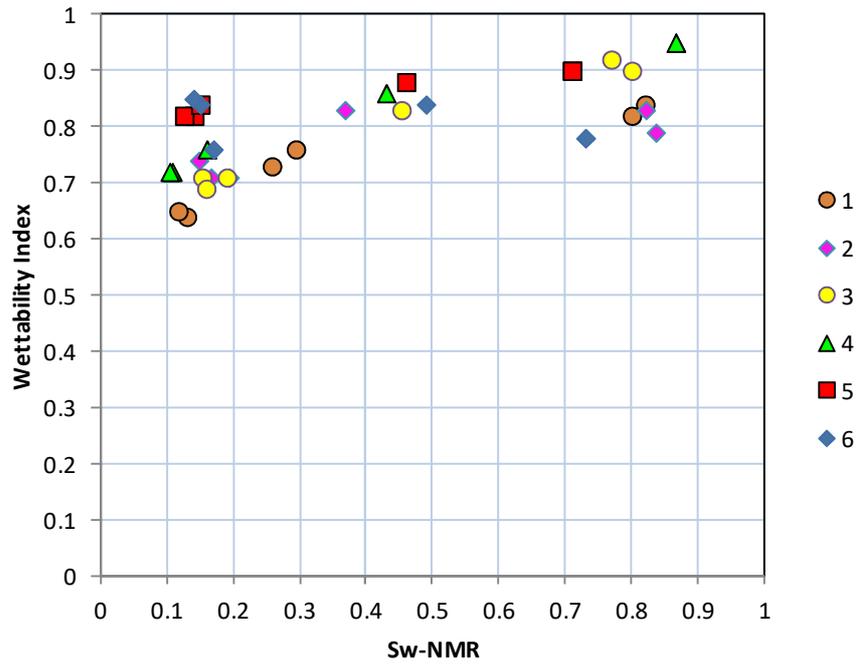Figure 8   NMR Wettability Index (after step 4) versus Amott Index

Figure 9   NMR-derived Wettability against water saturation at the various preparation steps 4-9.
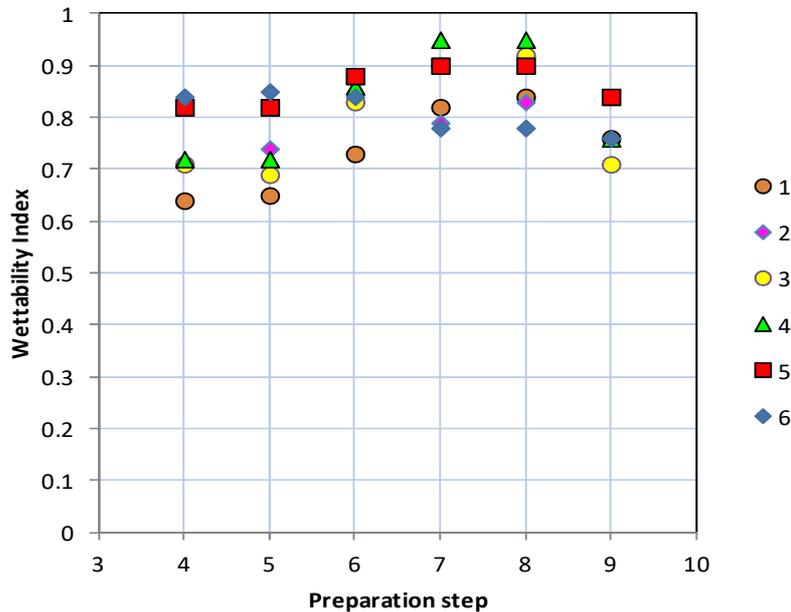
Figure 10   NMR Wettability Index at subsequent preparation steps

Wettability interpretation of the NMR log

The same method was applied to the NMR log run in the same well. The additional challenge is now that the Sw=1 response is unknown. However, from the core data it appears that the shape of this response is rather constant, and the position on the T2-axis shifts with permeability. A first estimate of permeability could be obtained from the k-phi correlation. Furthermore, the water saturation could be estimated from the Rxo log which measures the resistivity at about the same depth of investigation as the NMR log. In the process of matching the actual response with the modeled response both permeability and saturation may be adjusted, in addition to the wetting profile. Details of this approach can be found in previous publications [5,7].

An example of the interpretation in the oil zone is shown in Figure 11. Contrary to the situation in the core analysis, the live crude has a much longer relaxation time, which results in a good sensitivity to wettability. The wetting index in the oil zone was found to be 0.5 $\pm$ 0.2; this is slightly less waterwet than found in the core analysis. The most likely reason for this difference is the value of the surface relaxivity; we assumed the same value for mineral oil and crude oil as these have not yet been measured. The interpretation of the continuous NMR log, Figure 12, shows that the wetting index gradually changes to fully water-wet over the transition zone towards the OWC; this is expected because in the transition zone a larger portion of the rock remains fully water bearing, and thus has no chance to develop any oil-wetness [8]. This observation is important because, even if transition zone SCAL is lacking, it allows the use of more waterwet flow properties in the transition zone.
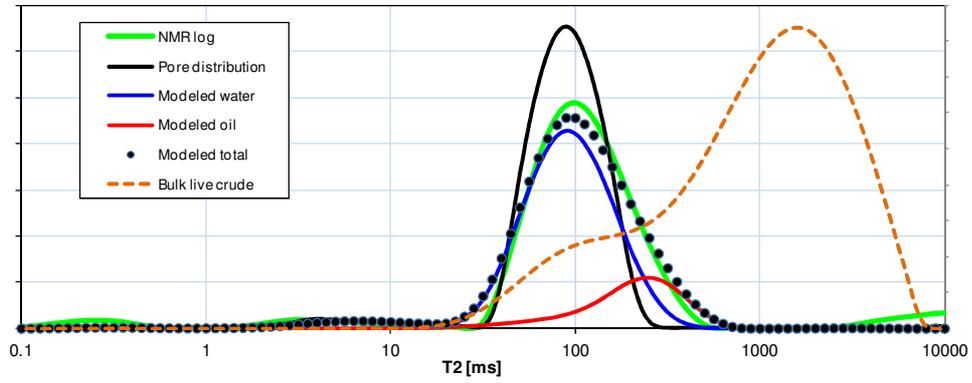
Figure 11   Observed and modeled response from the NMR log in the oil zone.
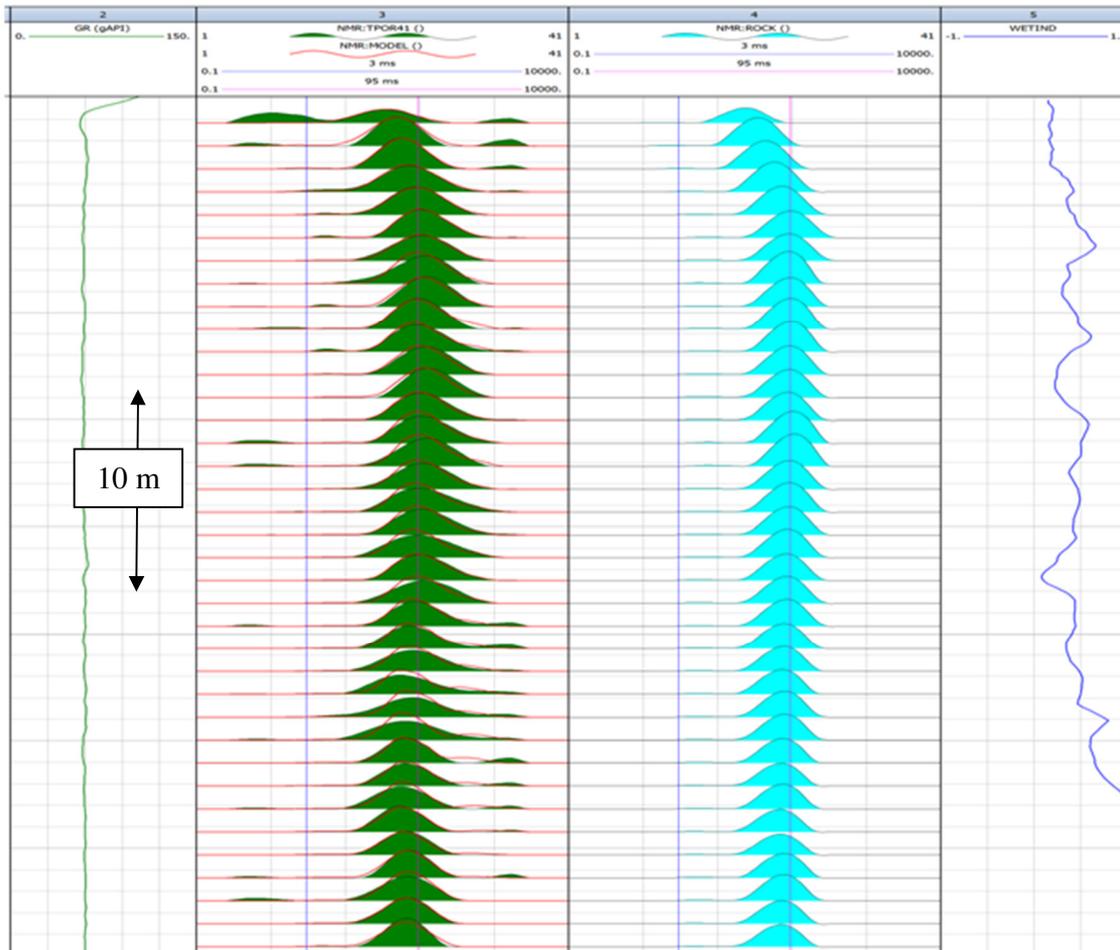

Figure 12   Overlay of the measured NMR log (TPOR) with the modeled result (MODEL), and the modeled water-filled response (ROCK); the derived NMR wettability index (WETIND).

CONCLUSIONS

NMR measurements performed at various stages of Amott and USBM wettability determination show a consistent fairly water-wet wettability (NWI ≈ 0.75 $\pm$ 0.15) for the chalk samples in this study.

Water and oil responses can be precisely modelled for the situations with refined oil.

NMR measurements on samples with crude oil could not be interpreted because the water and oil responses completely overlap.

The NMR Wettability Index correlates well with the Amott and USBM index, but is numerically different because it has a different definition.

NMR-derived saturations are in excellent agreement with independently derived Sw_core values.

Since NMR measurements are non-destructive, they may provide a relatively inexpensive indication of the wettability of samples at any stage of SCAL analyses.

Analysis of the continuous NMR log shows an in-situ wettability of NWI ≈ 0.5 $\pm$ 0.2 in the oil zone, trending to fully water-wet over the transition zone to the OWC.

ACKNOWLEDGEMENTS

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