SCA2003-05: VARIATION OF SPECIAL CORE ANALYSIS PROPERTIES FOR INTERMEDIATE WET SANDSTONE MATERIAL

Arne Skauge[1,2], Bartek Vik[1], and Bård Ottesen[1,2]
(1) CIPR, University of Bergen, and (2) ResLab

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ABSTRACT

Wettability is known to influence fluid flow processes in porous media. Most North Sea sandstone reservoirs fall into the large group of intermediate wet state. However, special core analysis of intermediate wet rock shows a wide variation in properties like; end point saturation, capillary pressure and relative permeability.

In this study, we find an improved understanding of the intermediate wet state by dividing the intermediate wet group into three sub-classes. Fractionally-wet (FW), where oil and water wet sites are random with respect to pore size, and mixed wet defined by water and oil wet pores that are sorted by pore size. We assume two classes of mixed wet state, where the oil wet sites are either in the large or the small pores. MWL (mixed-wet large) is defined by oil wet large pores, while MWS (mixed-wet small) refers to the smaller pores are oil wet.

The USBM and Amott-Harvey wettability indices are used to group reservoir data into reservoirs with FW, MWS, and MWL behavior. Some of the main results were that the fractional-wet rock has a more robust wettability. Cleaned cores maintain a non-water-wet state, indicating that the wetting sites may be coupled to mineralogy in addition to adsorption/deposition of oil components changing the surface properties of the rock. Also MWS maintains wettability after cleaning, while the mixed wet (MWL) cores become more water wet after solvent cleaning. The average waterflood remaining oil saturation (Sorw) is lowest for MWL cores. The remaining oil saturation for the MWL rocks also show a reduced Sorw with increasing permeability, but the FW and MWS reservoirs indicate a constant Sorw independent of permeability. The type of intermediate wettability has impact on data structure needed to build representative reservoir models. In addition, the type of wettability influences the shape of relative permeability curves and also the capillary pressure relations for different classes of intermediate wettability.

INTRODUCTION

The rock wettability is a main factor in determining the oil recovery efficiency of water displacement processes in oil reservoirs. Measurements of remaining oil saturation as a function of wettability have often detected a minimum in remaining oil saturation at intermediate wettability, or a corresponding maximum in oil recovery [1]. Even in a summary of waterflood from a large group of reservoir core data [2], the same type of relation was observed from the trend curve. However, the spread in the data was very large especially around a wettability index equal to zero. The experimental results indicate that the standard wettability indices can not resolve the variation in oil recovery or there must be other parameters than wettability that also strongly influence oil recovery.

Wettability of a rock sample has traditionally been measured by displacement (Amott-Harvey index [3,4], I_{AH}) or by integration of the area under the capillary pressure curve (USBM index [3,5], I_{USBM}). These tests represent experimental indicators of wettability, but are not necessarily correlated. In a recent paper Dixit et al [6] have questioned if I_{USBM} should be equal to I_{AH}. The USBM method gives a quantification of the average core wettability by measurement of the areas under the positive (forced secondary drainage) and negative capillary pressure (forced imbibition) curves. The ratio of the areas under the two capillary pressure curves represent the ratio of work necessary for the fluids to displace each other. The USBM method has the advantage over the Amott method of quantifying wettability near neutral wetting properties. But still, the USBM can not distinguish between different types of intermediate wettability like fraction wet and mixed wettability. Therefore there has been a search for better methods to distinguish the different states of intermediate wettability [7].

The network model studies by Dixit et al [8] are the background for the concept used in this paper. They applied several assumptions relating to the underlying pore-scale displacement mechanisms in order to achieve analytical relationships between I_{AH} and I_{USBM} for mixed-wet and fractionally-wet rock. This simple approach provides some guidelines regarding the influence of the distribution of oil-wet surfaces within the porous medium on I_{AH} and I_{USBM}. More detailed insight into the relationship between I_{AH} and I_{USBM} is provided by modeling the pore-scale displacement processes in a network of interconnected pores. The effects of pore size distribution, interconnectivity, displacement mechanisms, distribution of volume and of oil-wet pores within the pore space have all been investigated by means of the network model. [8]

In this work we use the approach by Dixit et al [8] to investigate relationships for cores from North Sea sandstone reservoirs grouped by USBM – A-H relations as either mixed wet or fractional wet.

RESULTS AND DISCUSSION

There is a need to resolve the large variation in the properties for the group of intermediate wet reservoirs. Intermediate wetting can be divided into three sub-classes. Fractionally-wet (FW) where oil and water wet sites are random with respect to pore size, and mixed wet defined by water and oil wet pores that are sorted by pore size. There are at least two classes of mixed wet state. MWL (mixed-wet large) is defined by oil wet large pores, and MWS (mixed-wet small) refers to a situation where the smaller pores are oil wet. Some possible physical explanation for fractional wet (FW) are that the spot like oil wet sites on the surface could be explained by surface precipitation or variation in mineralogy changing the affinity between oil and the mineral surface. Conventional mixed wet refers to mixed wet large (MWL). In this case, the reservoir is assumed initially waterwet, and oil migrates through a primary drainage process into the reservoir. Further, over geological time oil components may adsorb on the surface, and as a consequence the oil wet fraction should be in the larger pores that were invaded during the primary drainage. A more unconventional mixed wet state is the mixed wet small (MWS) where the oil wet sites are in the smaller pores. The argument behind this wetting situation has been discussed earlier [9,10]. If oil enters smaller pores, the oil phase pressure must be much higher than the water phase pressure ($P_o >> P_w$), and the interface curvature is higher at high capillary pressure P_c (small pores). This situation is unstable and water films may rupture and oil will then be in contact with the solid surface.

But still the question remains as to do the existence of fractional wet, mixed wet large, mixed wet small state in oil reservoirs? Our recent paper [2], analyzed wettability data from many North Sea oil fields. We found 13 reservoirs to have enough USBM and Amott-Harvey data to determine the state of intermediate wettability. Of these reservoirs, five could be grouped as MWL, four as FW, and four as MWS. Another question is then, can this classification explain the wide variation seem on intermediate wet reservoirs? This is the main topic in the further discussion. One reservoir typical for each of the three groups has been selected for further analysis.

The indication of FW, MWL, and MWS was based on comparing I_{USBM} to I_{AH}. The analysis of Dixit at al [8] led to the following differentiation of intermediate wet cores.

When $I_{USBM} = 0$ at $I_{AH} = 0$ it indicates FW
When $I_{USBM} > 0$ at $I_{AH} = 0$ it indicates MWL
When $I_{USBM} < 0$ at $I_{AH} = 0$ it indicates MWS

If the larger pores are more oil-wet (MWL), the USBM index indicates more water wet conditions than does the I_{AH}. Snap-off in the water-wet pores is expected to shift USBM to more water-wet values without affecting the Amott-Harvey results. Fractional wet core, here, oil and water wet sites are random with respect to pore size, and should have equal I_{USBM} and I_{AH}. For MWS cores snap-off is suppressed and the smaller pores are the more oil-wet fraction of the porous media, and $I_{USBM} < I_{AH}$.

The I_{AH} number has a range from -1 to +1, and positive values refer to water wet state. The I_{USBM} scale is also positive for more water-wet samples and negative for those that are more oil-wet. In principle, it can range from $+\infty$ (strongly water-wet) to $-\infty$ (strongly oil-wet). However, for practical purposes, the range $-1 < I_{USBM} < +1$ covers most data. Since I_{AH} reflects spontaneous imbibition, whereas I_{USBM} is derived from capillary pressure curves, it is not immediately evident what the relationship between these two measures should be. The relation between I_{AH} and I_{USBM} is often linear in a range around zero wettability indices. Dixit et al [8] found this linear range to extend from -0,5 to +0,5 for fraction wet core data. We have used linear trend curves to describe the relation between I_{USBM} and I_{AH}. This is a fair approximation as the data usually are from -0,6 to +0,6. Data from the three selected reservoirs are plotted in Figure 1.

Core cleaning

The rock types that are showing a mixed-wet-small (MWS) behavior are characterized by a more robust wettability with respect to core cleaning. Figure 2 illustrates the effect of more or less standard core cleaning procedure on this rock type category. The core samples used have first been tested in fresh state, and thereafter cleaned and restored before repeating the wettability measurements. Core cleaning was done by flooding mixtures of toluene and methanol at a temperature of 70 ^oC. A couple of the core plugs are somewhat affected by the cleaning process, but as expected from the overall picture of the results, there is no clear tendency towards more water wet material after cleaning. This is believed to be due to the limited access the solvents have to the small oil-wet pores, and hence the cleaning efficiency of these pores is very limited.

A similar picture is seen from the fractional-wet (FW) rock types even though the amount of samples in the test is very limited. There is no clear trend towards more water-wet material after cleaning and restoring. Cleaned cores maintain a non-water-wet state, indicating that the wetting sites may be coupled to mineralogy in addition to adsorption/deposition of oil components changing the surface properties of the rock.

On the other hand the mixed-wet-large (MWL) rock material is clearly shifted towards more water-wet behavior after cleaning and restoring. In this case the oil-wet sites, which have become oil-wet from oil invasion and further deposition of hydrocarbon components on the pore walls, are easily displaced or accessed by the solvents during a cleaning process. Hence, the cleaning process is able to remove hydrocarbon depositions and transform these large pores to water-wet after cleaning.

Initial water saturation and wettability

The relation between initial water saturation and wettability is expected to be complex and influenced by among other the pore structure and thereby parameters like porosity and permeability. However, the variation of wettability with initial water saturation is towards more waterwet at high initial water saturation for the classes of intermediate wettability, FW, MWS, and MWL. The trend also holds for both Amott-Harvey index and USBM index versus initial water saturation. Similar trends have been observed in summaries of field variations of wettability [2,11,12].

Initial water saturation and remaining oil after waterflooding

The remaining oil saturation after waterflooding may be related to the initial water saturation or initial oil saturation. If the initial oil saturation is higher usual more oil is trapped, that is, at higher initial oil saturation (Soi) one expects a higher residual oil saturation (Sor). This relation is often correlated as a Land type relation [13]. Mixed wet rock, both MWS and MWL, show a typical Land type relation for residual oil saturation as a function of initial saturation. The MWL reservoirs show an stronger increase in Sorw with decrease in Swi than the MWS type of cores. Fractional wet, FW, does not show correlation between Sorw and Soi, and in fact, some cases show a reduced Sorw at higher Soi.

Waterflood remaining oil saturation

The average waterflood remaining oil saturation is found to lowest for mixed wet large cores (MWL). The highest remaining oil saturation is seen for mixed wet small. The results are not surprising as oil located in small pores would require high capillary number to mobilize. Figure 3, shows the average remaining oil saturation after waterflooding for cores from the three different classes of intermediate wet rock. The end-effect is not corrected in the data presented. However, little end-effects should conventionally be expected for intermediate wet cores. Though, in an earlier study we found strong capillary dependence even at high rate for an intermediate wet core[14].

Permeability

The influence of permeability on SCAL properties like; initial water saturation, wettability, relative permeability, imbibition capillary pressure, or residual oil saturation are complex relations, that are highly coupled. In this paper, the effect of permeability on variation of the SCAL parameters is analysed as simple 1-D relations. We find difference in the relation of permeability versus initial water saturation and also relative permeability as mentioned earlier. Higher permeability shows a shift towards less water-wet behaviour is a general trend for all intermediate wettability classes.

In addition residual oil saturation is reduced at higher permeability for mixed wet large (MWL) cores, while the trend of permeability and residual oil saturation is much weaker for MWS and FW core material.

Relative permeability

It is well established that the water-oil relative permeability is a function of wettability [15]. However, the effect of different intermediate wet states on relative permeability has not yet been reported. Using field data the influence of wettability is often obscured by other parameters like permeability, initial saturations, pore structure, etc. In order to be able to compare the three classes of intermediate wetting states, we have compared the endpoint water relative permeability. The endpoint relative permeability is not directly comparable as krwe is a function of the endpoint saturation. A scaled parameter is therefore used. The parameter is a product of the endpoint water relative permeability and the corresponding water saturation. Figure 4, shows the average scaled endpoint water relative permeability for the different wettability classes. Mixed wet large cores show higher endpoint water relative permeability. The oil wet nature of the larger pores is expected to give low resistance to water flow compared to situations with waterwet large pores (MWS). Indeed, the experimental results confirm such a variation in the endpoint relative permeability data. We find that the mixed wet small cores had more curved relative permeability data, that is higher Corey exponents for both water and oil relative permeability. The fraction wet cores showed larger variation in the scaled endpoint water permeability, but the average value is in the order of MWS cores.

The MWL cores also had a weak shift in the scaled endpoint water permeability (increasing) with increase in permeability. While there were no systematic variation with permeability for MWS and FW core material.

Capillary pressure

It is difficult to find capillary pressure data that could be compared for the different wetting states. We found samples representing MWS and MWL having same reservoir quality and total wettability index. The permeability was 100 mD with a porosity of 0.25. Figure 5 show that the area under the forced water imbibition is different for the two cases. The MWL core has a larger area under the Pc curve than the MWS core. This is indicating that more work may be required to extract oil from the core when the larger pores are oil wet.

CONCLUSIONS

The concept of dividing intermediate wettability into three classes from measurements of USBM and Amott-Harvey wettability indices has to some degree explained the large scatter in special core analysis data observed in summary of waterflood data.

Experimental wettability indices indicate that some reservoirs have USBM indices systematically different than Amott-Harvey indices corresponding to expected behaviour of both fractional wet and mixed wet with either the large or the small pores being oil wet.

Cores from reservoirs with mixed wet large (MWL) type wettability (oil wet large pores) appear to have very different core analysis behavior than other intermediate wet material.

MWL cores seems to be more difficult to restore after cleaning, and care should be taken in using data for restored cores when the wettability indicates mixed wet large behavior.

MWL cores show lower residual oil saturation, and higher scaled endpoint water relative permeability than the other classes of intermediate wettability.

The concept of defining classes of intermediate wet state leads to important results that have impact on SCAL input description in reservoir simulation models. Examples are trends with permeability and initial water saturation.

More data is needed to confirm the very interesting trends observed

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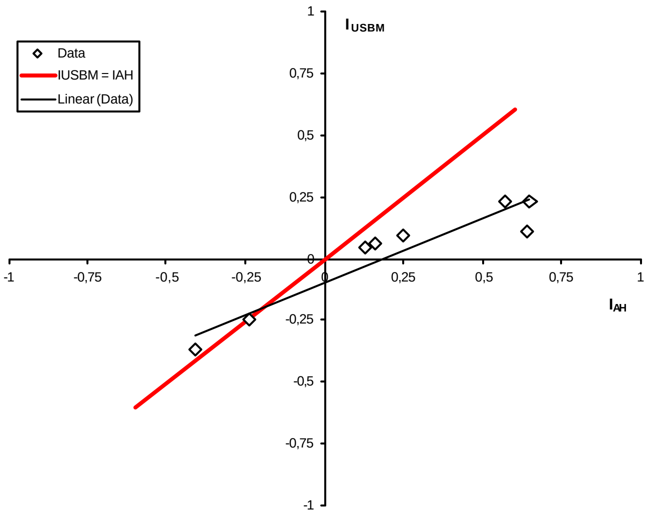
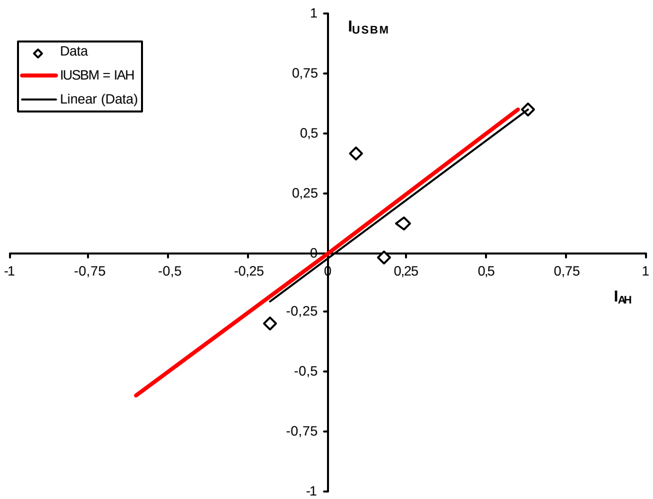
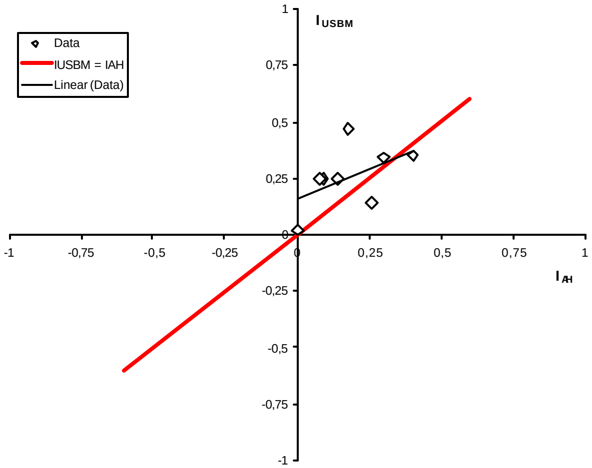


MWS



FW



MWL

Figure 1. Wettability data for three oil fields having MWS, FW, and MWL type wettability

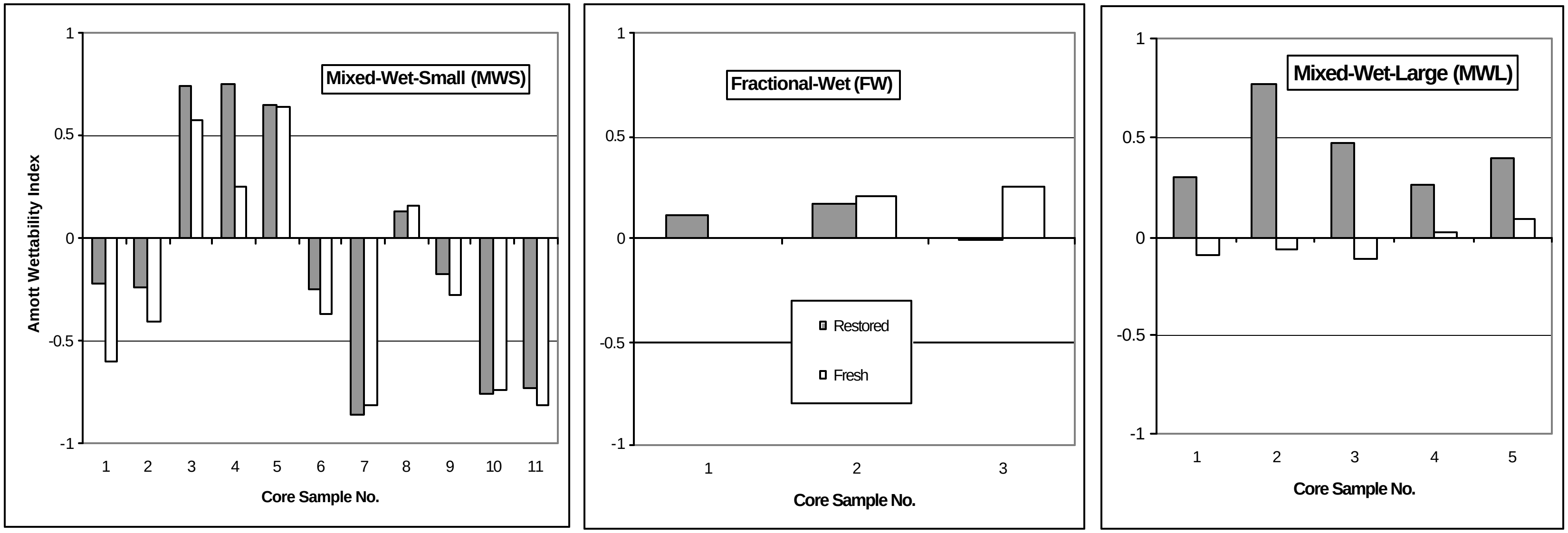


Figure 2: Amott wettability indices for the three selected reservoirs for both fresh and cleaned (and restored) rock mat

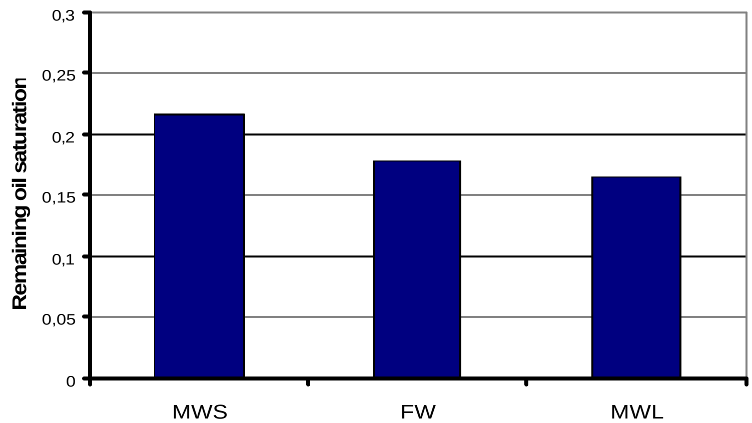


Figure 3: Average remaining oil saturation for the classes of intermediate wet cores.

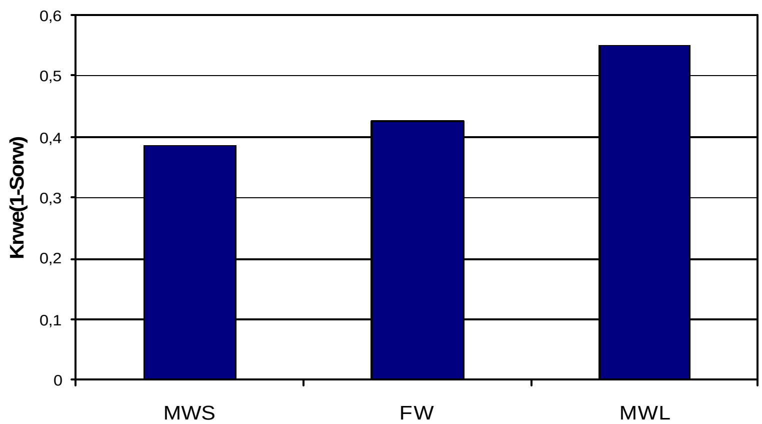


Figure 4: Average endpoint relative permeability scaled with end point water saturation for the three groups of intermediate wet states

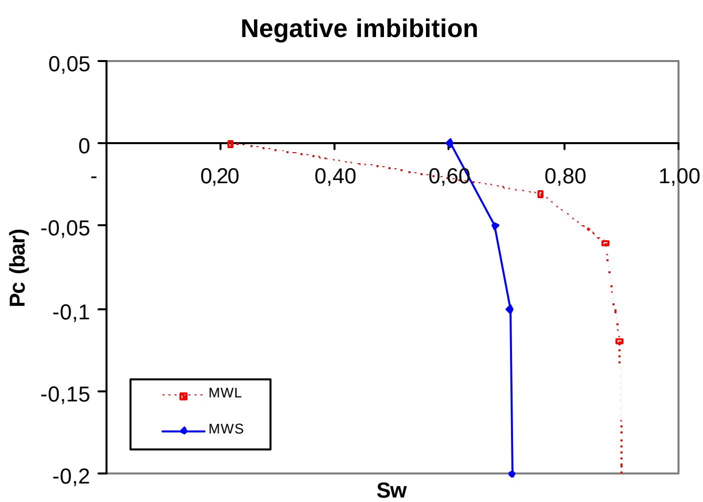


Figure 5: Capillary pressure (forced water imbibition) for MWL and MWS cores with 100 mD permeability and porosity of 0.25.