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Two-Phase Oil-Water Empirical Correlation Models for SCAL and Petrophysical Properties in Intermediate Wet Sandstone Reservoirs

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Abstract. A consensus has long been established that the best secondary oil recovery through waterflood is attained in intermediate wet reservoir systems. In the absence of special core analysis (SCAL) data during the initial stages of field evaluation, experimentally-derived correlations are generated in this study for preliminary evaluation purposes. Currently, it is identified that ambiguity exists between petrophysical relationships in intermediate wet reservoirs. Clarifying these relationships provides us with further understanding into maximizing oil recovery in such systems. Hence, the main objective of this study is to analyse and provide further insights into the relationships between petrophysical properties, which are ultimately vital for reservoir simulations. The correlations are generated through linear regression analysis from experimental core measurements. It has been proven that the most reliable correlations are essentially empirical rather than theoretical, especially with the case of relative permeability. The variation of SCAL parameters and correlations generated are studied as a function of wettability, permeability, porosity, initial water saturation and rock type. It is observed that residual oil saturation is moderately correlated to Amott-Harvey wettability in an upward curvilinear relationship while scaled endpoint relative permeability in two-phase oil-water system is strongly and linearly correlated to wettability. When investigating the effects of permeability, one must take into account that having too low or too high value might present anomalies in the correlations. The general trend for intermediate wettability reservoir is that a higher permeability shows a shift towards less water-wet behaviour (shift to oil-wet). Moreover, for initial water saturation and wettability, the trend is towards more water-wet at higher initial water saturation. Meanwhile, porosity is not strongly correlated to any of the parameters except permeability.

1. Introduction

Today, majority of the reservoir systems are observed to have wettabilities intermediate between the typical extremes of strongly water-wet and strongly oil-wet. Furthermore, it has been heavily investigated that the most optimum secondary oil recovery is found in sandstone reservoirs with initial intermediate wettability [1,2,3,4]. The efficiency of oil recovery depends on innumerable interacting mechanisms, properties and factors at both pore level and macroscopic scale. Hence, an in-depth understanding of these interacting forces is required for an economical and systematic oil recovery.

Previous researchers have conducted investigations of core plugs from various regions for intermediate wet reservoir systems. However, most of them have concentrated in one field [5,6] or a collection of selected homogeneous fields [7,3]. This study focuses on cores from various regions with different properties to each other to examine the influence of heterogeneity and whether previously established trends still hold the same in heterogeneous samples. There is still ambiguity regarding relationships between petrophysical properties especially residual oil saturation and end-point relative permeability. Although some trends have been confirmed, variations still exist [8,2]. As many sandstone reservoirs are intermediate wet and coupled with the finding that the most optimum waterflood is in intermediate wet reservoirs lead us to a greater need for an improved understanding and characterization of fluid flow behaviour and forces that govern such systems. In addition, only very limited data is attainable in the early stages of field evaluation, hence, there is a necessity to predict Special Core Analysis (SCAL) properties. Consequently, the aim of this work is to achieve improved understanding of the multiphase flow behaviour in intermediate wet sandstone reservoirs. Secondly, correlations are derived, based on actual experimental data, through linear regression analysis. The basis of the correlations is to deliver a starting point for SCAL petrophysical properties in the absence of real measured data in early field evaluations. The correlations are intended to provide general trends instead of exact numbers and are anticipated to have an impact on SCAL input description in reservoir simulation models for reservoir characterization as presented in Table 1, Section 5.

2. Intermediate Wettability

In this study, all wettability behaviours between the two extremities of strongly oil-wet and water-wet are called intermediate wettability. Furthermore, intermediate wettability may be divided into homogeneous or heterogeneous classifications. Neutral wettability is categorized as homogeneous intermediate-wet where all pores possess a slight, but equal affinity for water or oil, in other words, all pores equally lacking any strong preference. In contrast, heterogeneous intermediate wettability is further classified as (1) mixed-wet system [9] and its subclasses namely Mixed-Wet Large (MWL) and Mixed-Wet Small (MWS) and (2) fractional wet system [10].

2.1. Mixed-Wet Large System

Mixed-wet system was first introduced as a general term by Salathiel [9] where the small, fine pores would be water-wet and has no oil, while larger pores are oil-wet. This would later be referred to as Mixed-Wet Large System by Skauge et al [2, 7]. In this system, oil-wet surfaces are continuous throughout the large pores resulting in low residual oil saturations. Since all the oil are situated in the oil-wet larger pores; a small, finite permeability to oil exists all the way to very small oil saturations. Subsequently, during waterflood, oil is continuously drained up until extremely low oil saturations are attained.

The origin of Mixed-Wet Large system (MWL) is theorized, assuming an initially water filled and water-wet reservoir, water is displaced by oil through primary drainage and enters the larger pores first with the smallest threshold capillary pressure. The process of water displacement from sequentially smaller pores persists till a maximum capillary pressure is established. Consequently, after primary drainage, water remains in the tiniest pores and coat pore walls as films. The mechanism of such origin could be theorized by taking into account pore geometry. Assuming circular pores by definition of Skauge et. al. [11], radii of larger pores are higher than smaller pores. Due to the bulk curvature interface, fluid and capillary pressures, the resultant disjoining pressure is greater in large pores than small pores. An increase in disjoining pressure means that water film thickness becomes thinner, hence, since the disjoining pressure is greatest in large pores, the films rupture [20] first there leading alterable wettability in larger pores, causing the formation of Mixed-Wet Large system. However, considering other pore geometries, there could be instances where wettability is altered first in the smaller pores giving rise to Mixed-Wet Small system.

2.2. Mixed-Wet Small System

Mixed-Wet Small wettability is a more unconventional mixed-wet system where larger pores are water-wet, while oil-wet condition is in the smallest pores. The origin of such system also depends upon pore geometry. Assuming the pore shapes are alike to a star, the films would be convex-shaped. Each pore-shape and its film would have different capillary pressure. Following the definition in literature [11], the water films curvature would be negative resulting in a higher disjoining pressure in small pore than the larger pore. Hence, the disjoining pressure would be at its highest in the small pore leading to Mixed-Wet Small wettability.

2.3. Fractional-Wet System

Fractional wettability refers to a wetting condition where oil and water positions are randomly situated in the rock matrix in accordance to pore size. The mechanism for this system is theorized when crude oil undergoes adsorption onto some pore walls but ignoring others due to surface chemistry differences of minerals present in the rock matrix. Furthermore, other mechanisms could be precipitation due to rock/oil/brine interactions and variations of pore shapes and curvatures.

The main difference between fractionally wet system and the mixed wet system is the randomness of the oil-wet or water-wet sites and that there are no continuous oil-wet paths in a fractional-wet system. Moreover, the theoretical explanations related to the disjoining pressure have been thoroughly investigated by Skauge et. al. [11]. They presented a flat surface theory where the pore shapes are triangular and would therefore, exhibit planar films. Such flat pore walls would present zero pore curvature and the disjoining pressure in the large and small pores are equal, hence, reaching maximum value concurrently. Therefore, wettability would not be related to pore size for this system. Agbalaka et. al. [12] further described the behaviour of this system is very much alike to uniformly-wetting conditions.

3. Data Summary and Experimental Procedures

A total of 14 samples of sandstone cores from different regional fields have been collected and analysed. This study focused on reservoir characterisation of intermediate-wet and heterogeneous nature of 3 regional areas in Libya (5 samples), Canada (8 sample) and North Sea (1 sample). Laboratory experiments were conducted on the 5 core samples from Libya in order to obtain data while core data from Canada [13] and North Sea [14] reservoirs were obtained from published literature. Realistically, not all fields are as homogeneous as previous conceptual studies like the Berea sandstone [23]. By incorporating data from different areas, the aim of this study is to replicate realistic heterogeneous conditions and observe fluid flow in intermediate-wet reservoirs.

The core tests used are primarily unsteady state, waterflood displacement tests conducted to obtain relative permeability data and residual oil saturation. The Amott-Harvey test was used as a measurement for wettability. The core samples used in this study were relatively clean sandstones of a well consolidated nature. The clay content, kaolinite, was between 8% - 20%. The cores were stable and did not experience irreversible changes when exposed to solvents required in the preparation operations and procedures.

The Canadian core data obtained from literature [13] contain highly viscous oil, or what is known as heavy oil. Usually, such heavy oils with low API (<20) display characteristics of non-Darcy behavior with high compressibility, thus resulting in a highly nonlinear system [21].

4. Results And Discussion

The Canadian dataset possess both USBM and Amott-Harvey Wettability indices which enable us to identify those samples as Mixed-Wet Small system based on Dixit et. al.'s model [15]. The other samples could not be classified as only the Amott-Wettability test was conducted.

4.1. Variations of Wettability

4.1.1. Wettability as a function of Initial Water Saturation (Swi)

It could be observed that at lower initial water saturation, the wettability index becomes more oil-wet as could be seen in Figure 1 below which is also consistent with literature in Figure 2. Physically, this may be explained that if there is lower initial water saturation, the area of the porous medium that is coated by stable, thick water films also decreases. This may lead to greater exposure of rock to crude oil (increase in oil saturation) and therefore, adsorption of polar components which may change rock wettability preference to more oil-wet.

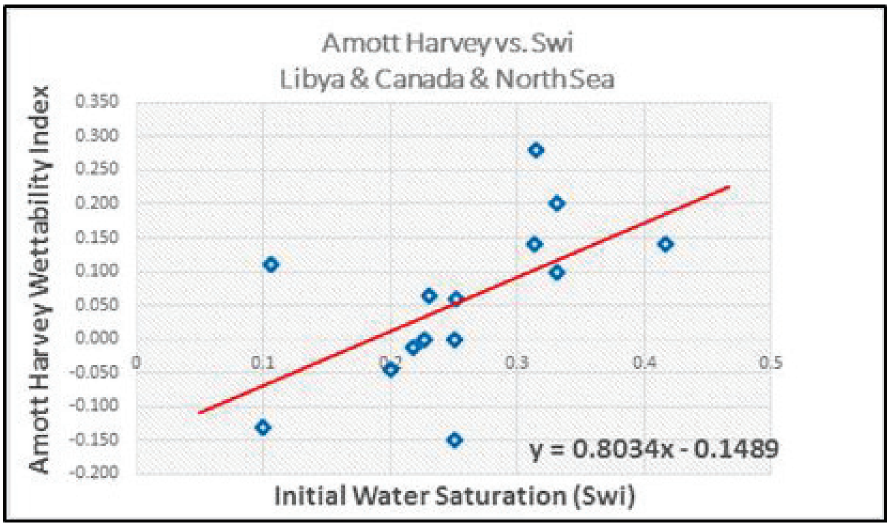


Figure 1. Wettability Index as a function of Swi for all regional fields

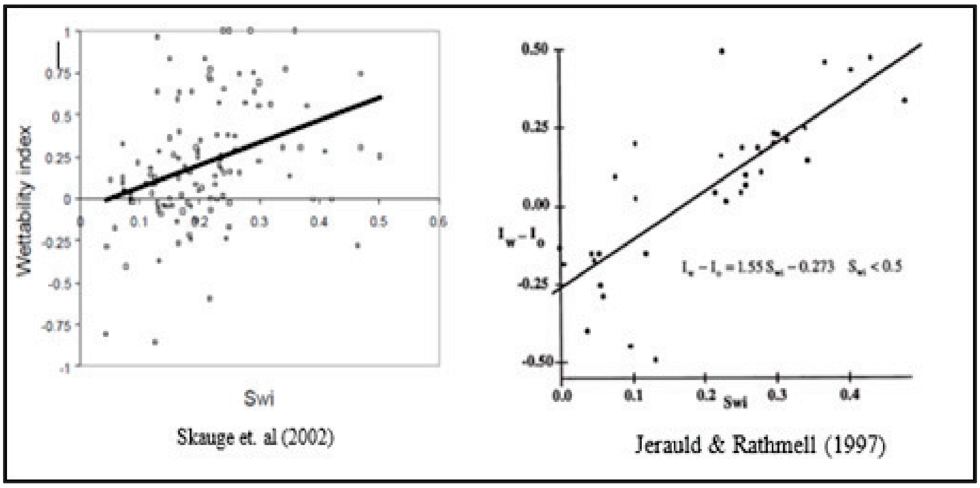


Figure 2. Comparison with literature,
Wettability vs. Initial Water Saturation [2,5]

4.1.2. Wettability as a function of Permeability

It is observed at higher permeability that there is a wettability alteration towards more oil-wet behavior (negative correlation) for all classes of intermediate wettability [2]. This phenomenon may be explained physically because at higher permeability, there are usually, larger channels (and larger pores) available to flow through and this, in turn, makes it easier for more oil to move and imbibe into the pores with the least capillary pressure forces, i.e. small threshold capillary pressures. The increase in oil saturation contacting the rock mineral surface could alter wettability to more oil-wet through adsorption of polar components or film rupture.

If we combine all data, an opposing positive correlation is identified. If investigated further to individual locations, the Canadian dataset is the one causing the discrepancy while the Libyan dataset agrees with literature. The discrepancy in the Canadian dataset could be due to some minerals, such as sulphides, located in high permeability pores that are more hydrophilic in nature. This may lead to more-water wet trend at higher permeability specific to this Canadian region.

4.2. Variations of Residual Oil Saturation

4.2.1. Residual Oil Saturation as a function of Amott-Harvey Wettability Index

The dataset in Figure 3 indicates an upward quadratic function with the minimal position of residual oil saturation at Amott-wettability indices of intermediate wettability. Physically, this may be explained through the capillary pressure forces being the least in wettability systems near the neutral indices and that the fluids are inclined to flow concurrently leading to a decrease in oil saturation with increase in pore-volume throughput [3]. Thus, residual oil saturation may be expected to be lower at intermediate-wetting conditions. This quadratic upward function is consistent with literature findings [16, 2] and as shown in Figure 4.

For intermediate wet class of Mixed-Wet Large (MWL), low residual oil saturation is due to the presence of continuous oil-wet surface in the larger pores throughout the rock which bridges walls adjoining to the pore corners [17] and caused a finite, tiny oil permeability to last down to even extremely low oil saturation. Therefore, the MWL system blends together the best qualities of both oil and water-wet systems. In comparison with a water-wet system, trapping of oil is decreased in the oil-wet large pores while if compared with the oil-wetting system, the trapping of oil is less due to the small pores being filled by water in the mixed-wettability system.

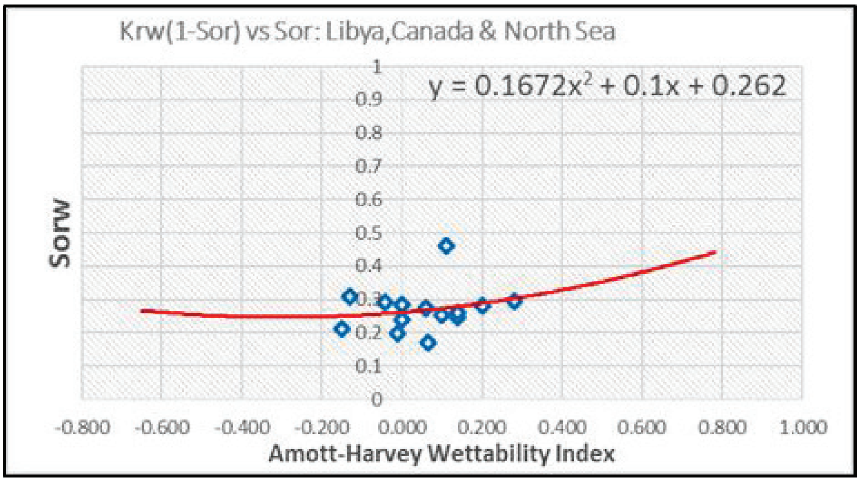


Figure 3. Residual Oil Saturation vs. Wettability

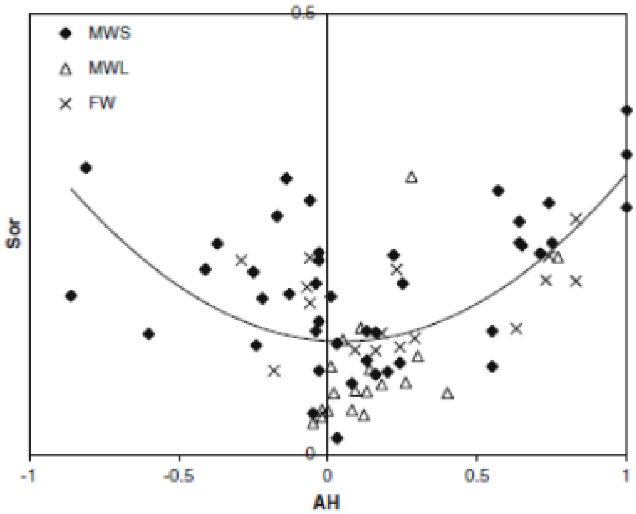


Figure 4. Residual Oil Saturation vs. Wettability, Comparison with Literature, Adapted from [2]

4.2.2. Residual Oil Saturation (Sorw) as a function of Initial Water Saturation (Swi)

When residual oil saturation (Sorw) is plotted against initial water saturation (Figure 5) for all regional cores in the dataset, it is identified that at higher initial water saturation, residual oil saturation decreases. This relationship is in agreement with Hazlett et al. [18] and is typically known as Land type correlation as shown in Figure 6. Furthermore, Skauge et al. [2] specified that the intermediate wettability classes of both MWL and MWS also displayed a Land type relationship, with the MWS reservoirs indicating a weaker increase in Sorw with decreasing Swi.

The relationship identified between Swi and Sorw for the dataset investigated could be physically interpreted through the reversible and irreversible flow of the oil/water interface. At low initial water saturation, interfacial movements/energy throughout imbibition (in this case, oil is being displaced by water) includes mainly the interfaces relaxing as they adapt to the pore/grain curvature. There is no phase trapping during this period due to the absence of the pore-filling occurrences. Subsequently, at high capillary pressure, residual oil saturation is non-responsive to small variations in initial water saturation. When the initial water saturation is high, water occupies the pores where interfacial oil-water movements are irreversible with the potential of oil trapping if pores were originally filled with oil during imbibition.

The residual oil saturation could also be correlated to initial oil saturation. Usually, higher initial oil saturation yields greater amount of trapped oil, therefore, at higher initial oil saturation, it is anticipated that residual oil saturation is also higher.

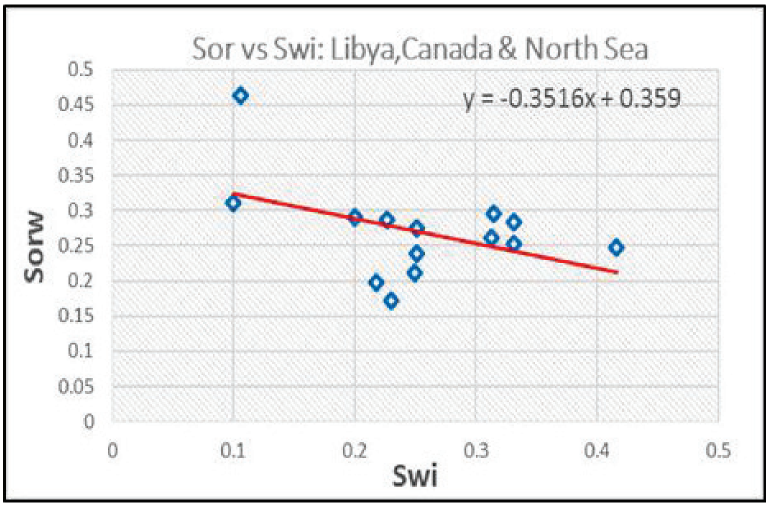
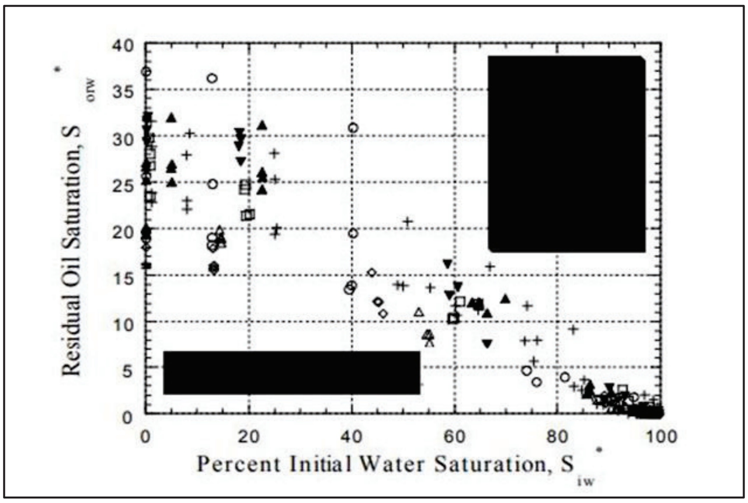


Figure 5. Residual Oil Saturation vs. Initial Water Saturation



[redacted]

[redacted]

Figure 6. Comparison with Literature, Adapted from [18]:
Residual Oil Saturation vs. Initial Water Saturation

4.2.3. Residual Oil Saturation (Sorw) as a function of Permeability

For Mixed-Wet Large cores, it is observed that as permeability increased, residual oil saturation decreased (negative correlation); though trend is substantially weaker for Mixed-Wet Small and Fractionally-Wet cores. Higher permeability would mean larger interconnecting channels to flow and should tend to result in lower Sorw.

In the cores investigated within this study, if all regional cores are combined, a very weak opposing trend (positive correlation) is identified as shown in Figure 7. This discrepancy could be attributed to different mineralogies and pore/grain curvatures of the cores. Unfortunately, the Libyan cores (5 samples) are limited in nature to be analysed alone. However, as for the Canadian dataset, if inspected further, it is recognized that the highly permeable rocks in the Canadian formation investigated contain highly viscous oils, inclusive of bitumen. The highly viscous nature of the oil may contribute to snap-off effects and/or bypassing of the oil (unfavourable mobility ratio), resulting in a tendency for more oil to be trapped, hence, higher residual oil saturation and opposing trend.

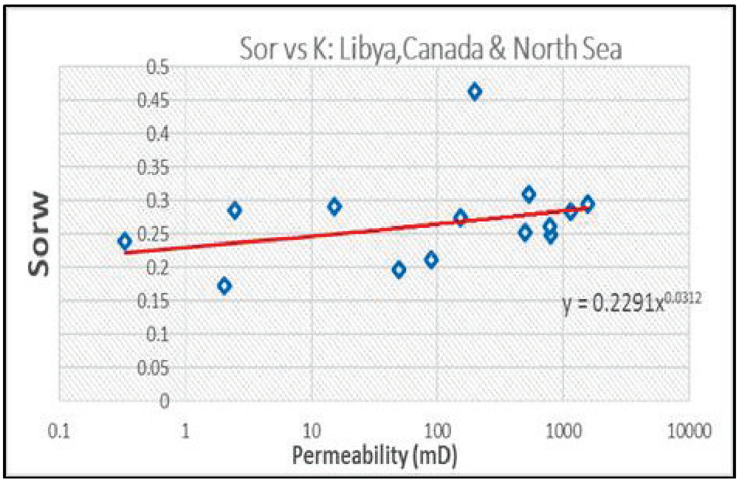


Figure 7. Residual Oil Saturation vs. Permeability: All regions

4.3. *Variations of Endpoint Water Relative Permeability, Krw(e)*

The endpoint water relative permeability at residual oil saturation, Krw(1-Sor), is a function of endpoint saturation and since residual oil saturation differs with each experiment, a scaled parameter was used. The scaled parameter is calculated by multiplying endpoint water relative permeability by the water saturation at which it was acquired (1-Sor), hence, the scaled parameter symbolized as: Krw(e)*(1-Sor) [2, 8].

4.3.1. *Endpoint Krw(e) as a function of Wettability*

If all dataset are combined in Figure 8 below, it is detected that more water-wet behaviour leads to lower endpoint relative permeability to water which are consistent with literature findings as illustrated in Figure 9 [2, 8].

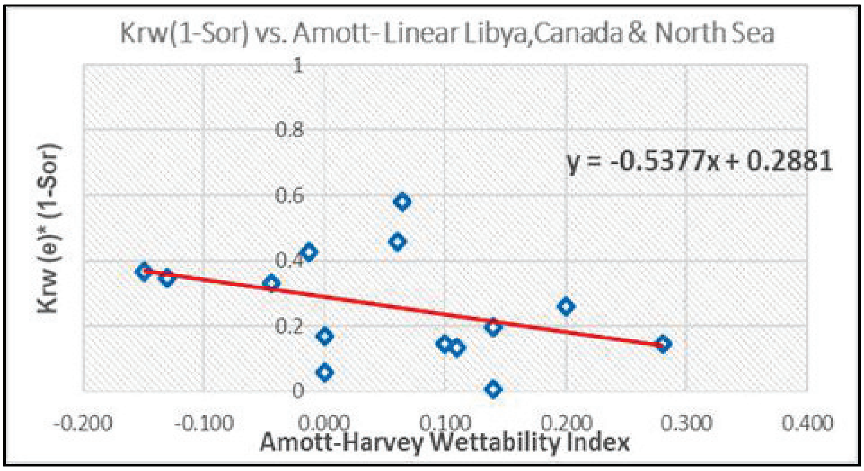
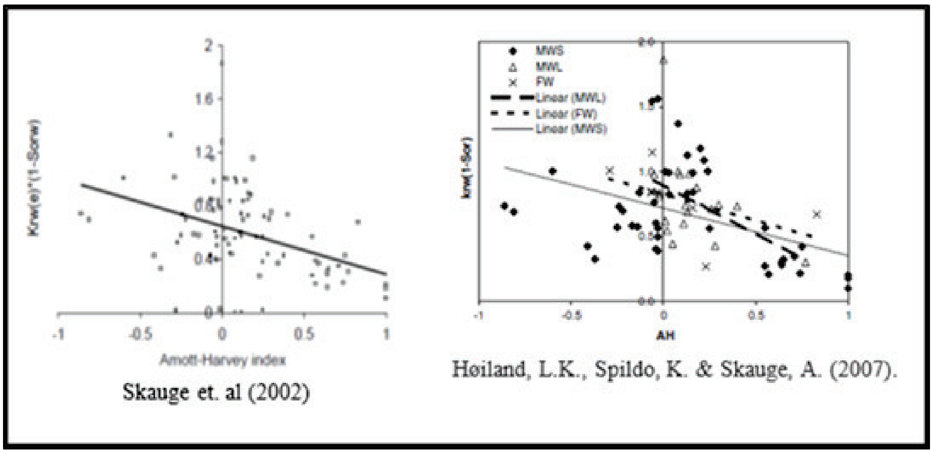


Figure 8. Scaled Endpoint Relative Permeability to Water vs. Wettability

In mixed-wettability system such as the MWS cores where the larger pores are water-wet, there is an in inclination for residual oil saturation to form and mould into trapped droplets resulting in blocked pore throats and lowering effective water permeability.



Skauge et. al (2002)

Høiland, L.K., Spildo, K. & Skauge, A. (2007).

Figure 9. Comparison with literature findings: Krw (e) vs. Wettability, Adapted from literature [2], [8]

4.3.2. Endpoint Krw(e) as a function of Initial Water Saturation (Swi)

The relations between initial water saturation (Swi) and wettability would form the foundation for the trend linking the end-point relative permeability to water [Krw(e)] to initial water saturation, Swi. Wettability and relative permeability are correlated. Higher initial water saturation results in greater water-wet behaviour and yields to lower relative permeability to water as shown in Figure. 10.

The correlation between endpoint relative permeability to water and initial water saturation is interrelated to the correlation between residual oil saturation (Sorw) and initial water saturation (Swi) as displayed in Figure 11. Initially, low Swi equals to small Sorw, and subsequently, the [Krw(e)] is high. At higher Swi likewise leads to lower Sorw, resulting in more water-wet behaviour and successively, the [Krw(e)] is low.

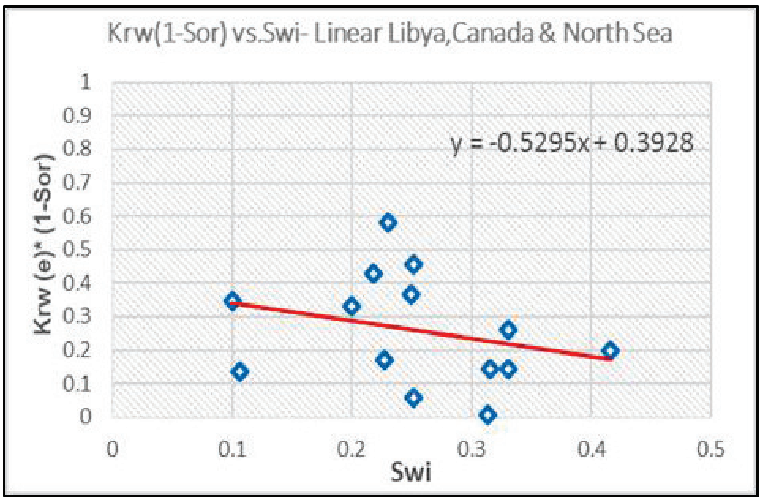


Figure 10. Scaled Endpoint Relative Permeability to Water vs. Initial Water Saturation

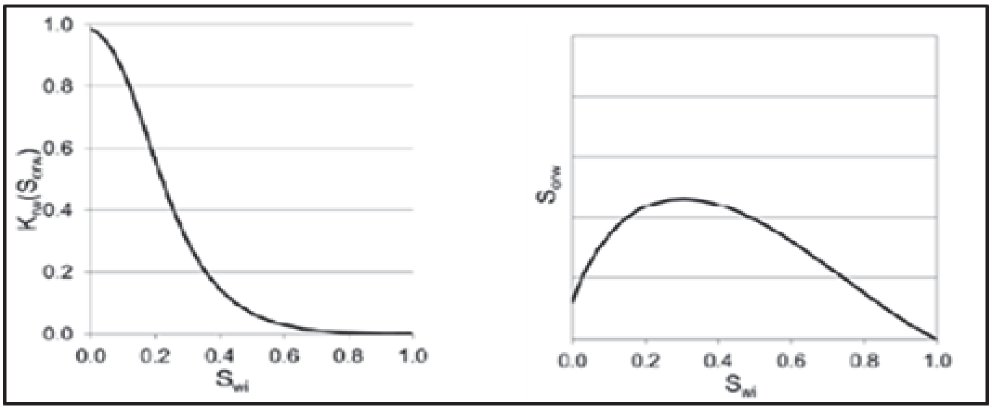


Figure 11. Comparison from literature: (1) Krw(e) vs. Swi (2) Sorw vs. Swi, Adapted from [18]

4.3.3. *Endpoint Krw(e) as a function of Permeability*

It is stated in literature that Mixed-Wet Large cores have a weak positive correlation when scaled endpoint water relative permeability is plotted as a function of permeability. However, there are no clear correlations for Mixed-Wet Small and Fractional Wet cores [2, 7]. Higher permeability means more area and thus, larger interconnecting channels for fluid flow.

If all regional fields are combined in the dataset currently investigated (Figure 12), an opposing weak negative trend is observed. This discrepancy may be due to the heterogeneous nature of the fields from different areas with their various morphologies, lithology, depositional environment and minerals. The discrepancy could also be due to limited data. However, if both fields are further scrutinised separately, the Canadian dataset (Figure 13) displayed a weak positive trend in agreement with literature. The Libyan dataset (5 samples) are limited in nature to draw a conclusive result.

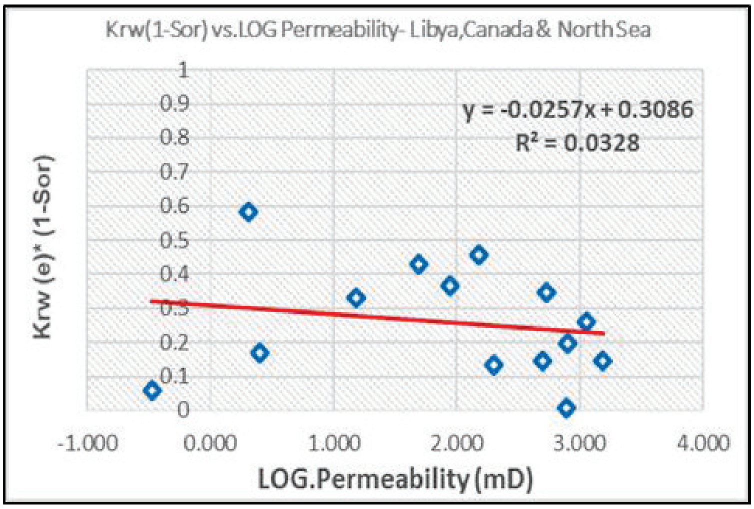


Figure 12. Scaled Endpoint Relative Permeability to Water vs. Log Permeability

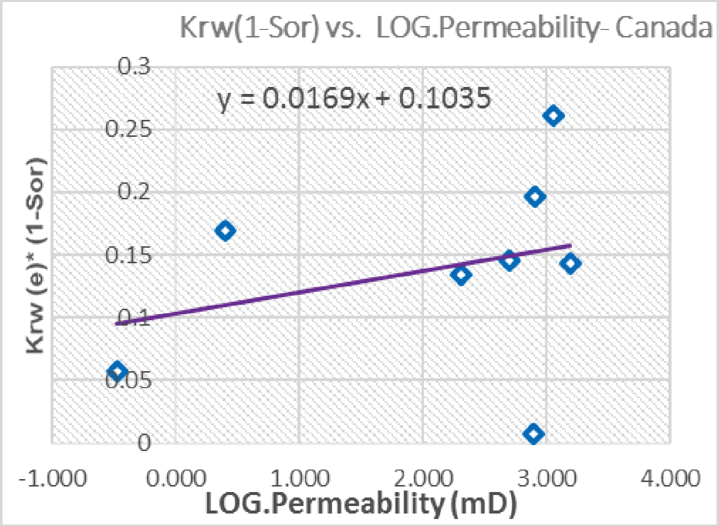


Figure 13. Scaled Endpoint Relative Permeability to Water vs. Log.Permeability, Canadian dataset

5. Conclusions

This study focused on the regional-wide reservoir characterization of intermediate-wet and heterogeneous nature of 3 regional areas in Libya (5 samples), Canada (8 sample) and North Sea (1 sample). By incorporating data from different areas, the aim of this study is to replicate realistic heterogeneous conditions and observe fluid flow and petrophysical trends in intermediate-wet reservoirs. It is concluded that:

- Most of the petrophysical trends agree with literature findings, despite being combined from 3 different regional areas. This is true for all correlations such as endpoint relative permeability studied as a function of wettability, initial water saturation and rock type. Additionally, trends for residual oil saturation as a function of wettability and initial water saturation are also consistent with literature.
- All of the opposing trends to literature were the ones correlated as a function of permeability. Heterogeneity plays a central role in this discrepancy and the various differing mineralogy, pore geometries, crude oil properties and oil/brine/rock interactions in each region contribute further.
- The pore-scale physics of multi-phase flow and petrophysical trends in intermediate wet reservoirs have been thoroughly discussed and would be useful for SCAL input in simulation models.

Table 1. Correlations

CORRELATIONS
1. Wettability Index as a function of Initial Water Saturation (Swi) Amott-Harvey Wettability Index = 0.8034*Swi - 0.1489 *Range of Validity: 0.15 – 0.4 % of Swi*
2. Wettability as a function of Permeability Amott-Harvey Wettability Index = -0.0422*K(abs) + 0.0455 *Range of Validity: 0.3 – 2,000 mD*

3. **Residual Oil Saturation (Sorw) as a function of Amott-Harvey Wettability Index (AH)**
   $Sorw = 0.1672(AH)^2 + 0.1*AH + 0.262$
   Range of Validity: Amott Wettability Index -0.5 to 0.5

4. **Residual Oil Saturation (Sorw) as a function of Initial Water Saturation (Swi)**
   $\mathbf{Sorw = -0.3516*Swi + 0.359}$
   Range of Validity: 0.15 – 0.4 % of Swi

5. ***Endpoint Water Relative Permeability [*****Krw(e)]** ***as a function of Amott-Harvey Wettability Index (AH)***
   $Krw(e) = -0.5377*AH + 0.2881$
   Range of Validity: Amott Wettability Index -0.5 to 0.5

6. ***Endpoint Water Relative Permeability [*****Krw(e)]** ***as a function of Initial Water Saturation (Swi)***
   $Krw(e) = -0.5295*Swi + 0.3928$
   Range of Validity: 0.15 – 0.4 % of Swi

7. ***Endpoint [*****Krw(e)]** ***as a function of Permeability, K (abs)***
   $Krw(e) = \mathbf{0.0169*K(abs) + 0.1035}$
   Range of Validity: 0.3 – 2,000 mD

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