IRREDUCIBLE WATER SATURATION AND ITS GOVERNING FACTORS: CHARACTERISTICS OF SOME SANDSTONES IN WESTERN INDONESIA

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ABSTRACT

Irreducible water saturation (S_{wirr}) plays a very significant role in the estimation of hydrocarbon in place and reserves. Inaccurate S_{wirr} and lack of knowledge for judging its accuracy may result in erroneous and misleading reserve estimates along with its consequences. This study is basically aimed at understanding of S_{wirr} characteristics of reservoir sandstones in some fields in western Indonesia. For the study, data obtained from 1,334 core samples – taken from 78 fields in 10 sedimentary basins – is used. Observations and investigations are made in sedimentary basin, field, and formation scales. The main finding is that rock wettability plays a very significant factor in determining S_{wirr} characteristics, in a manner more than what rock pore types and configuration do. Its variation – be it contrasting or difference in strength – influences the S_{wirr} characteristics in its relation to rock permeability. It is also found that geological similarity and geographical proximity do not have effects on S_{wirr} characteristics unless they directly affect the rock's overall wettability. This occurs not only at higher scale of sedimentary basin but also at lower levels of field and rock formations. The study also produces permeability - S_{wirr} correlations for both sedimentary basins and rock formations levels. The overall results of this study is an understanding that gross simplification in assuming reservoir general wettability has to avoided in order to prevent erroneous picture over a field's most representative S_{wirr} characteristics.

Keywords: *irreducible water saturation, reserves, wettability, sandstone*

I. INTRODUCTION

Irreducible water saturation is loosely defined as the minimum level of water saturation – for a certain type of reservoir rock with its intrinsic properties – that can be established using mechanically forced fluid displacement. Irreducible water saturation – often interchanged with connate water saturation or interstitial water saturation – plays a significant role in the determination of hydrocarbon in place and reserves. No known hydrocarbon-bearing reservoir rocks are in existence without presence of water, be it deposited either during diagenesis process or later. This is also the case even for very high permeability reservoirs such as reservoirs with natural fractures.

In the estimation of underground hydrocarbon volume, accurate and reliable irreducible water saturation (S_{wirr}) data is needed. Inaccurate and unrepresentative S_{wirr} values certainly result in misleading oil or gas original in place (OOIP/OGIP) with all of its consequences. Widarsono (2008) in his study over the error of connate water saturation estimation on OGIP put that an error by merely ten water saturation unit (i.e. percent of pore space) may result in approximately 20% error in OGIP estimation – for relatively small reservoir bulk volumes (< 5 million reservoir barrel) – and gets even more pronounced for larger reservoirs.

Irreducible water saturation is also proved to have effects on reservoir production performance. For instance, connate water saturation tends to reduce effective gas permeability in gas condensate reservoirs. Calhoun (1953) in a series of laboratory investigations – as quoted in Amyx (1960) – showed that higher S_{wirr} values reduce ratio of gas-to-oil permeability (K_g/K_o) significantly, from a maximum value of 60 at S_{wirr} = 20% to 1.5 at S_{wirr} = 40%. This reduction in gas effective permeability has the potential to provide a set back for any recovery scenarios from a gas field. Information regarding irreducible water saturation is therefore crucial.

At lower scale, knowledge over irreducible water saturation is also important for standard open-hole log interpretation. Validity over water saturation estimates are often judged from consistency between permeability, porosity, water cut from well fluid sampling, and known representative S_{wirr} values usually obtained from core analysis. The vital role of information regarding irreducible water saturation in the determination of water saturation will in turn influence the reliability of OOIP/OGIP estimates.

The most reliable and representative S_{wirr} for an oil or gas field is best established through direct sampling or measurements made in the field of concern. However, not all fields or reservoirs have such data, even in the mature western Indonesia's sedimentary basins. Moreover, understanding characteristics of S_{wirr} in the region's sandstone reservoirs are imperative and is certainly needed to be enhanced further through any existing data for better reservoir characterization and modeling in the future. The understanding over the region's S_{wirr} characteristics – the objective of the study – was made through investigating the S_{wirr} variation in relation to other rock properties such as permeability and wettability, as well as to geographical aspects such as different fields, rock formations, and sedimentary basins.

There are at least three methods known for obtaining connate water saturation; well log interpretation, fluid saturation measurement on core samples drilled using oil-base mud, and capillary pressure data. Well log interpretation has limitation that the estimated water saturation may not necessarily S_{wirr} while the use of oil-base mud is not much and is increasingly limited. On the contrary, due to its nature as part of special core analysis laboratory (SCAL) tests capillary pressure data is usually readily available in sufficient quantity. For this study, data from 760 sandstone core samples taken from 78 oil and gas fields situated in 10 sedimentary basins in western Indonesia was used. In addition, water-oil relative permeability from 574 sandstone core samples from the same fields was also used as auxiliary data (Table 1). All data was obtained from LEMIGAS Core Laboratory archive. No original laboratory data is presented, and all data shown in this article is processing and interpretation results by nature.

Table 1
List of data available to the study

Sedimentary basin	Number of field(s)	Data		
		Capillary press(*)	W-O relative permeability	Porosity - permeability
Central Sumatra	21	181	164	345
South Sumatra	21	161	160	321
Northwest Java	8	86	51	137
Kutei	7	130	70	200
Sunda	7	63	46	109
West Natuna	5	68	29	97
North Sumatra	5	48	31	79
Tarakan	2	10	10	20
Barito	1	9	7	16
Northeast Java	1	4	6	10
Total	**78**	**760**	**574**	**1334**

(*) from porous plate (static) technique

II. IRREDUCIBLE WATER SATURATION: A BRIEF REVIEW

After formation, hydrocarbons were compacted, concentrated, and squeezed out of its source rocks, from which it then migrated upward following buoyancy and hydrodynamic flow mechanisms (Chapman, 1986; Tissot and Welte, 1978). In their path, following continuous phase in long filaments the hydrocarbons encountered various pore and pore-throat sizes, permeability, rock-forming minerals, and formation water with their different affinity tendencies toward the migrating fluids. As the hydrocarbon reached suitable rock structural and/or stratigraphic traps they finally rested after displacing as much as possible the pre-existing formation water – depending on capillary forces and pressure gradient – with leaving specific levels of irreducible water saturation (S_{wirr}) within the traps. Provided that later geological events permitted these hydrocarbons may migrate further to find more suitable traps.

Irreducible water saturation has causative interrelations with at least two other very well-acknowledged petrophysical properties; permeability and capillary pressure. Intrinsic rock permeability (K) is very dependent on the complexity of the rock's pore structure and pore-throat size distributions. Higher complexity usually means lower rock permeability. This higher complexity also means higher capillary force. Capillary force (   ) is easilly represented with the basic equation of

$$P_c = \frac{\sigma \cos\theta}{r} \qquad \text{......... (1)}$$

with σ,   , and   are interfacial tension between wetting and non-wetting phases, contact angle between wetting phase and rock surface, and rock average pore radius, respectively. Higher rock pore complexity effectively reduces r resulting in higher   . This P_c is heightened further when interfacial tension (σ) between the pre-existing formation water and the migrating hydrocarbons is high and the rock tends to be water-wet (i.e. low   values).

The migration of hydrocarbons as droplets in water-saturated rocks – during migration or within final traps – was opposed by the capillary forces. This implies that rocks – under the same wettability tendency – tend to increase in S_{wirr} with decrease in permeability, and vice versa. On the other hand, rocks with similar permeability tend to have higher S_{wirr} for those with water-wettability than ones with more oil-wetness tendencies. In the both cases mentioned above, higher   values conceptually have led to higher *capillary-bound* water hence higher S_{wirr}.

Experimentally, the K – S_{wirr} relationship had been reported as early as in 1947 by Welge and Bruce (as quoted in Amyx *et al,* 1960). They showed that all of the tested 13 sandstone types tend to have their connate water saturation increases with decrease in permeability. They also showed that there is not a single general trend exhibited by the tested samples. Instead, individual sandstone type shows distinctive K – S_{wirr} trend even though some of them show similarities. No mentions, however, had been presented with regard to any possible relation between the trends and the samples' wettability.

The causative or mutual interaction between S_{wirr}, K, and P_c are further exhibited by the reverse relationship, in which levels of S_{wirr} influence effective permeability of hydrocarbons that move through them. Upon realizing this relationship, several investigators had studied the phenomenon and produced some empirical models. For instance, Wyllie and Rose (1950) proposed

$$K = \left(\frac{C\phi^3}{S_{wirr}}\right)^2 \text{, mD} \qquad \text{......... (2)}$$

with C is a constant that depends on hydrocarbon density (e.g. $C = 250$ for medium gravity oil and $C = 79$ for dry gas) and ϕ is porosity (in fraction). Note that S_{wirr} is also in fraction. Later, Timur (1968) proposed a more general – i.e. independent of hydrocarbon types – form of

$$K = 0.136\frac{\phi^{4.4}}{S_{wirr}^{\ 2}} \text{, mD} \qquad \text{......... (3)}$$

with ϕ and S_{wirr} are both in percentages.

Equations 2 and 3 show that with increase in S_{wirr} the permeability decreases. Physically, this is understood as reduction in flow path cross-sectional radius as S_{wirr} increases hence reducing effective permeability to hydrocarbon moving through it. Being empirical in nature – as well as directly related to porosity and irreducible water saturation – these two equations are often used for estimating absolute permeability from standard open-hole log analysis.

III. LABORATORY DATA

The capillary pressure data used in this study was exclusively derived following drainage process (i.e. non-wetting phase displacing wetting phase) of which about 81% (615 samples) was obtained using porous plate semi-permeable technique. The technique is primarily performed through placing brine-saturated samples on a porous disk itself is also saturated with brine. The semi-permeable disk is much less permeable than the samples to prevent the displacing fluid to penetrate the disk before the water saturation in the samples has reached its irreducible level.

The displacing fluid – could be either air or oil with special disk arrangement – is pressurized in a series of fine increments to allow very slow displacement process. In this near static displacement condition the displaced brine is recorded upon reaching static equilibrium. The assigned capillary pressure levels are then plotted with the recorded water saturation values (initial pore volume minus the displaced brine recorded upon reaching equilibrium at each displacement pressure). Figure 1 illustrates a couple of capillary pressure curves obtained from two samples with different permeability values. The irreducible water saturation is represented by water saturation levels through which vertical lines (dotted lines) meet asymptotically with the capillary pressure curves.

The drainage approach, under very small pressure increments, is designed and recorded in order to simulate the process of hydrocarbon displacement as it enters its trap. The length of equilibrium time needed after each pressure increment is very much dependent of sample's permeability and may take very long for low permeability samples. For this reason, some of the samples – especially the low permeability samples – were tested using the dynamic centrifuge method. Through the exertion of centrifugal force – instead of relying on near pure capillary force – the drainage displacement process is forced and the desired equilibrium time is sped up. Around 19% of the data belongs to this technique. Readers can explore Amyx *et al.* (1960) or Tiab and Donaldson (2004) for information regarding basic principle of centrifuge technique.

Apart from the 760 samples tested for their capillary pressure data, as many as 574 samples were also utilized for their water-oil relative permeability data. Both sample sets for water-oil relative permeability and capillary pressure tests were derived from the same depths in the same well. The primary

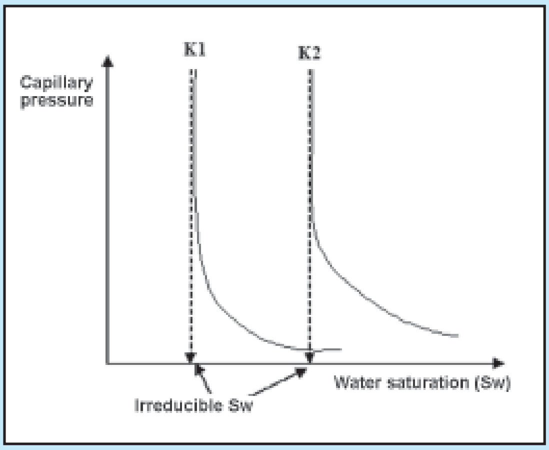

Figure 1
Irreducible water saturation (S_{wirr}) as indicated from capillary pressure curves. The two curves represent two rock samples with different permeability values (K1 > K2)

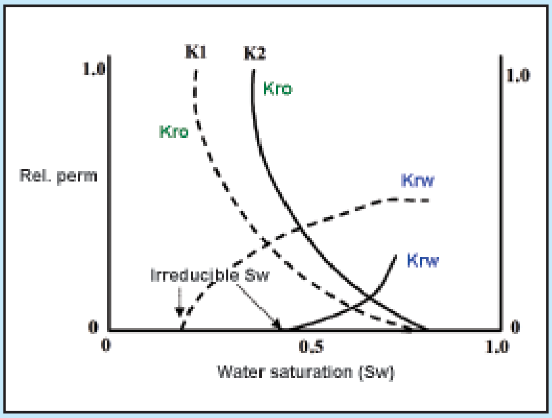

Figure 2
Wettability indication from water – oil relative permeability curves. When the Kro = Krw intersection falls at Sw < 0.5 the rock of concern tends to be oil-wet (dotted curves) while the reverse case indicates water-wettability (solid curves)

purpose of this data is to provide indication over the wettability of the samples used in capillary pressure tests. As discussed in Widarsono (2010), interception between relative permeability to oil (Kro) and relative permeability to water (Krw) curves indicates the wettability of the tested sample. Figure 2 illustrates two conditions in which one of the Kro = Krw point (i.e. intercept) falls at a water saturation value of lower than 50% whereas the other falls at a value higher than 50%. The two examples indicate oil-wetting and water-wetting tendencies, respectively.

Another auxiliary data is porosity – permeability data from the combined capillary pressure and relative permeability of 1334 samples. The use of the data is mainly to support in describing the nature of pore structure of the sample sets reflected in their porosity – permeability relationships.

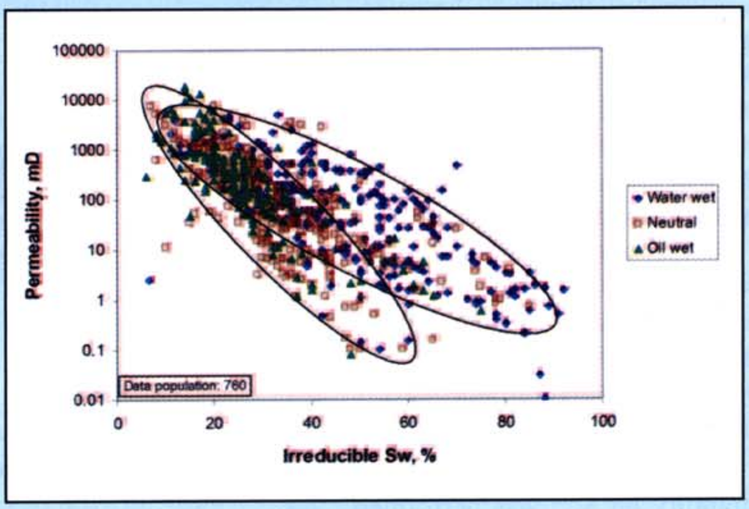

Figure 3
Plot showing increase in S_{wirr} with decrease in permeability. This trend is true for all sandstone samples with different wettability but with water-wet samples exhibiting stronger tendency for higher S_{wirr}. Interestingly, samples with neutral wettability tend to be less definitive even though a larger portion of them is more aligned to oil-wettability

IV. ANALYSIS OF DATA

In analyzing the data four grouping for analysis have been established. First grouping is designed to observe the influence of wettability – and permeability – on irreducible water saturation (S_{wirr}) characteristics. Second grouping is to study what different sedimentary basins may tend to show their S_{wirr} characteristics. The consideration that underlines this grouping is that different sedimentary basins are likely to have differences in geological setting and other related aspects hence influencing S_{wirr} characteristics. The remaining two groupings are analyses on lower geological scales, individual field and rock formations.

A. S_{wirr} vs. permeability and wettability

In this study, main indicator of wettability is the water-oil relative permeability data with wettability test data in auxiliary role only. The reason is that samples for both capillary pressure and water-oil relative permeability underwent core cleansing prior to test – in which alteration in wettability is most likely to occur – while wettability test always use native cores. However, as concluded in Widarsono (2010) hot core cleansing is not likely to change its wettability too considerably and is more likely to reduce the wetting tendency in strength. Therefore, any available wettability test data was used to support determination of general wettability of a core samples set whenever information from water-oil relative permeability tests is inconclusive.

In using the water-oil relative permeability data for wettability indicator, the criteria established for classification is; $S_w < 45\%$ for 'oil-wet', 45% $S_w \leq 55\%$ for 'neutral', and $S_w > 55\%$ for 'water-wet' (Figure 2). Following this criteria wettability of the 760 core samples, from which the capillary pressure and S_{wirr} data was obtained – was determined. Out of the 760 samples, 298 are classified as water-wet, 291 as neutral, and 171 as oil-wet.

Figure 3 exhibits plot between permeability and S_{wirr} of all samples. In general it is shown that S_{wirr} increases with decrease in permeability. This is in accordance with Equation 1 that implies lower permeability – i.e. smaller - results in larger capillary pressure and therefore higher S_{wirr}. The large capillary force provides large opposition to the displacement of wetting phase (usually assumed as brine) by non-wetting phase (i.e. air or oil) in a drainage process resulting in high S_{wirr}. This explains that even though all three wetting tendencies exhibit similar K – S_{wirr} characteristics samples with water-wettability tend to show stronger inclination towards higher S_{wirr}. The less definitive manner shown by neutral-wettability samples is certainly caused by the very absence of the wetting tendency itself (i.e. neutral) leaving less direct and more complicated factors – e.g. pore size distribution and clay presence – to determine the S_{wirr} characteristics.

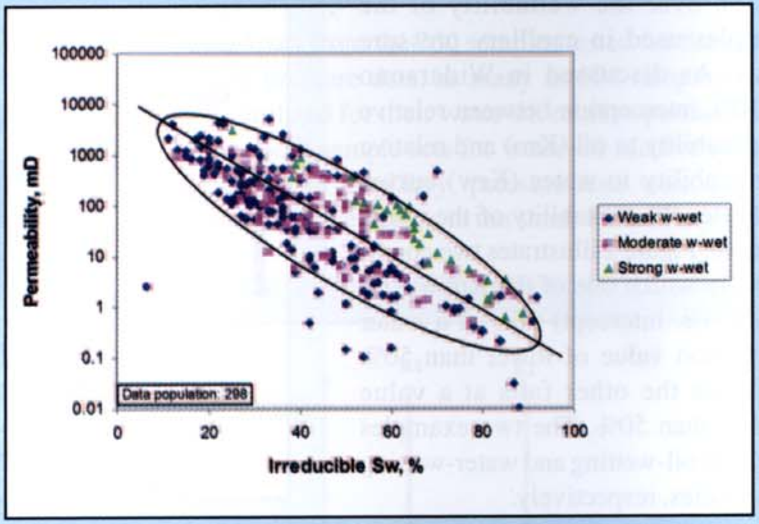

Figure 4
K - S_{wirr} plot for water-wet group samples. Despite overlapping separation between the three wettability sub-groups is obvious which indicates the strong influence of wettability strength on S_{wirr} characteristics

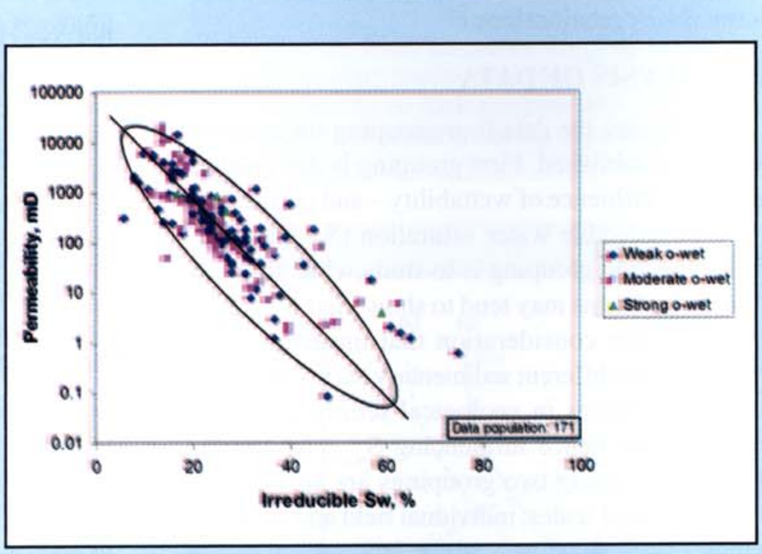

Figure 5
K - S_{wirr} plot for oil-wet group samples. No obvious separation is visible underlining the minimum influence of oil-wettability strength on S_{wirr} characteristics

Deeper analysis on the effect of wettability on S_{wirr} was performed through observation on each wettabiliy group. Figure 4 shows the plot for water-wet group, cluster analysis on which indicates correlation of

$$Log\ \ K = 18683\ \ e^{-0.125*Swirr} \ldots (4)$$

with permeability (K) in mD and S_{wirr} in percent (%). Although the group appears to be represented by a single general correlation the actual characteristics within the group are not necessarily uniform. As shown on Figure 4, significant difference is shown by strong water-wet and weak water-wet sub-groups with the strong water-wet samples tend to have significantly higher S_{wirr} values. This can be logically explained using Equation 1 in which stronger water-wetness results in lower θ and higher P_c hence higher S_{wirr}. It can therefore be conclusively observed that wetness strength plays a significant role in controlling S_{wirr} characteristics in water-wet sandstones.

Similarly, a more detailed observation was also made on the oil-wet group (Figure 5). The cluster enveloping of the data yields a general correlation of

$$Log\ \ K\ =\ 32952\ \ e^{-0.196\ *Swirr} \qquad (5)$$

In a manner different to the case of water-wet group, no significant division between different strength in oil-wetness is observed. Samples with weak, moderate, and strong oil-wetness behave intermingly and show similar K - S_{wirr} characteristics. Although data for the strong oil-wet is very limited for a decisive conclusion but a deviation from the weak and moderate oil-wettability is still noticeable. This can probably be taken as an indicator that the effect of oil-wettability on S_{wirr} is somewhat weaker than in the case of water-wettability.

More thorough examination on the wettability subgroups within the water-wet and oil-wet groups result in a set of $K – S_{wirr}$ correlations. The correlations are

$$Log \quad K = 15380 \quad e^{-0.136 \; * Swirr} \qquad \text{.........} \; (6)$$

for weak water-wet sandstones,

$$Log \quad K = 26250 \quad e^{-0.134 \; * Swirr} \qquad \text{.........} \; (7)$$

for moderate water-wet sandstones,

$$Log \quad K = 133795 \quad e^{-0.137 \; * Swirr} \qquad \text{.........} \; (8)$$

for strong water-wet sandstones,

$$Log \quad K = 33059 \quad e^{-0.197 \; * Swirr} \qquad \text{.........} \; (9)$$

for weak oil-wet sandstones,

$$Log \quad K = 32531 \quad e^{-0.195 \; * Swirr} \qquad \text{.........} \; 10)$$

for moderate oil-wet sandstones, and

$$Log \quad K = 11553 \quad e^{-0.131 \; * Swirr} \qquad \text{........} \; (11)$$

for strong oil-wet sandstones.

Validity of Equation 11 (strong oil-wet) is obviously questionable since the equation was derived using four data points only. The actual equation is likely to be of not very different from Equations 2, 6, and 7 based on the presumption that oil-wetness strength influences S_{wir} characteristics in a manner weaker than water-wetness. This can also be considered as applicable to neutral wettability sandstones based on the observation that most of its data points fall in fine alignment with those belonging to oil-wet sandstones.

B. S_{wirr} vs. sedimentary basin

Sedimentary basins as the basic earth structure required for the formation of oil and gas reservoirs may be different in general characteristics depending on a long array of factors including mineral resources, physical and chemical interaction mechanisms, transportation and sedimentation system, depth and extent, and petroleum system. For instance, the Northwest Java Basin is described as having been filled with fluvial deposits along with shale and marl in its more restricted environments such as Talang Akar Formation, from which most of the sandstone samples have been taken (Schlumberger, 1986). In comparison, the Tertiary sediments in the Kutei Basin are stratigraphically very complex with numerous facies changes and sedimentary strata that represent transgressive – regressive cycles in marine – deltaic environments. The transgressive sequence is mostly represented by coarse clastic and shales deposited in a paralic coastal plain to shallow marine environments while the regressive sequence mainly consists of thick deltaic to paralic clastics containing abundant coals and lignites (Schlumberger, 1986). These environmental differences in the sedimentary basin-related rock formations may have repercussion on the S_{wirr} characteristics.

In studying the effect of different sedimentary basins to S_{wirr} characteristics, data from seven main productive sedimentary basins are presented. Figure 6 presents the K - S_{wirr} plots for Central Sumatra, South Sumatra, and Northwest Java Basins while Figure 7 depicts the corresponding data for North

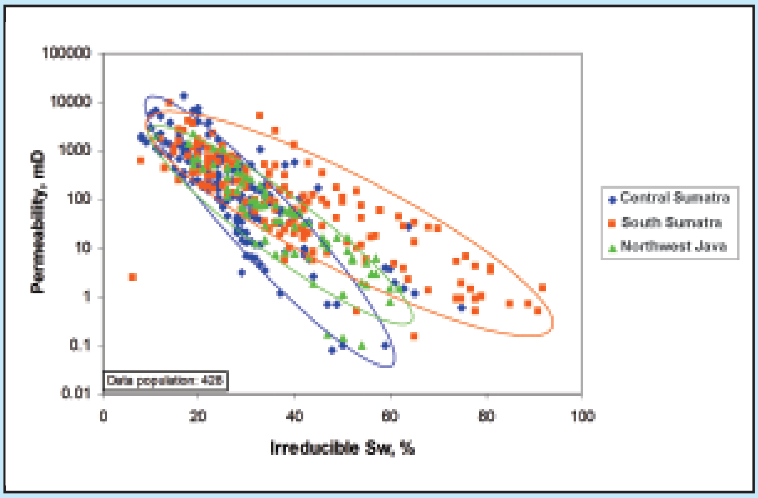

Figure 6
K - S_{wirr} plots for samples from Central Sumatra, South Sumatra, and Northwest Java Basins. The three show similar behavior but in varried degrees towards variation in permeability

Sumatra, Kutei, Sunda, and West Natuna Basins. All seven sedimentary basins exhibit the same S_{wirr} behavior with regard to permeability, the lower the permeability the higher the S_{wirr} values. What differs one sedimentary basin to the others in this matter is the differences in the general K - S_{wirr} correlations even though some of them exhibit sufficient similarity.

Presented on Figure 6, samples from South Sumatra Basin exhibit higher S_{wirr} characteristics than ones from the other two basins for the same permeability levels. Similarly on Figure 7, deviation from the ‘main stream’ formed by samples from three sedimentary basins (Kutei, North Sumatra, and Sunda) is shown by samples from West Natuna Basin. Despite the differences in general, similarities are also visible in the S_{wirr} characteristics. The scatter shown by samples from North Sumatra leads to its inclusion in the cluster of data from the Sunda Basin (Figure 7). Similar S_{wirr} occurrence is also demonstrated by the Kutei data relative to the combined North Sumatra – Sunda Basins’ data.

In general K - S_{wirr} correlations for the seven main sedimentary basins are

$$Log \quad K = 64606 \ e^{-0.236 * Swirr} \quad .. (12)$$

for Central Sumatra Basin (except for Pematang Formation),

$$Log \quad K = 13429 \, e^{-0.124 * Swirr} \quad .. (13)$$

for South Sumatra Basin,

$$Log \quad K = 46913 \ e^{-0.191 * Swirr} \quad .. (14)$$

for Northwest Java Basin,

$$Log \quad K = 68500 \ e^{-0.245 * Swirr} \quad .. (15)$$

for West Natuna Basin,

$$Log \quad K = 19715 e^{-0.138 * Swirr} \quad .. (16)$$

for Kutei Basin, and

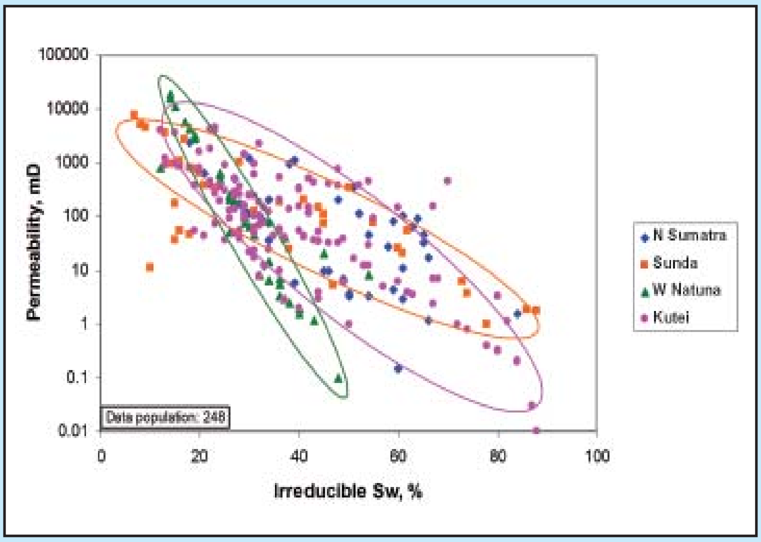

Figure 7
K - S_{wirr} plots for samples from North Sumatra, Sunda, West Natuna, and Kutei Basins. Different characteristics are visible except the scatter shown by North Sumatra data leaving it apparently included within the same cluster with data from Sunda Basin

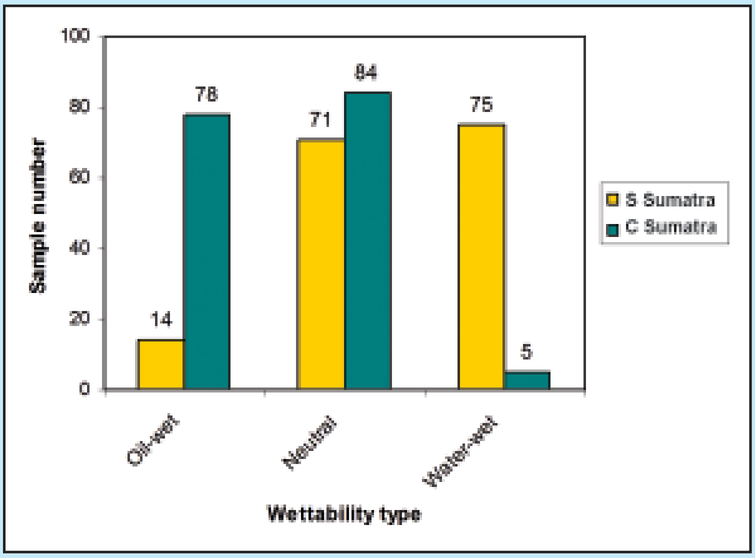

Figure 8
Wettabilitty composition of samples from South Sumatra and Central Sumatra Basins. The geographical proximity of the two sedimentary basins does not necessarily make them similar in wettability characteristics. (note: numbers on top of histogram represent number of samples)

$$Log \quad K = 6815\, e^{-0.104 * Swirr} \quad \ldots (17)$$

for the combined North Sumatra – Sunda Basins.

Differences in S_{wirr} characteristics are undoubtedly caused by the specific characteristics of the rocks of concern. Although the empirical expressions of Equations 2 and 3 describe the correlation between permeability and irreducible water saturation but they do not accommodate its potential variations in the light of different rock characteristics. The expression can indeed be considered as inadequate since it has been previously discussed that S_{wirr} characteristics is not only influenced by rock's permeability (i.e. pore throat configuration) but also by wettability. This is best illustrated by the plots on Figures 3 through 7 showing that if the vertical variation in S_{wirr} is clearly caused by variation in permeability then the horizontal S_{wirr} variation is therefore likely caused by the second factor – the rock wettability.

The effect of wettability is readily demonstrated when analysis is made on the wettability compositions of the samples plotted and presented on Figures 6 and 7. Histograms on Figures 8 and 9 depict wettability compositions of two clusters of samples with contrasting K - S_{wirr} trends as shown on Figures 6 and 7, respectively. Difference in K - S_{wirr} trends shown by Central Sumatra and South Sumatra samples (Figure 6) are accompanied by contrasting wettability compositions demonstrated by the two sets of samples (Figure 8). The lower S_{wirr} characteristics shown by the Central Sumatra samples are without doubt connected to their predominantly oil-wet tendency while the reverse is true for the South Sumatra samples' inclination towards more water-wettability.

Plots for the North Sumatra, Sunda,

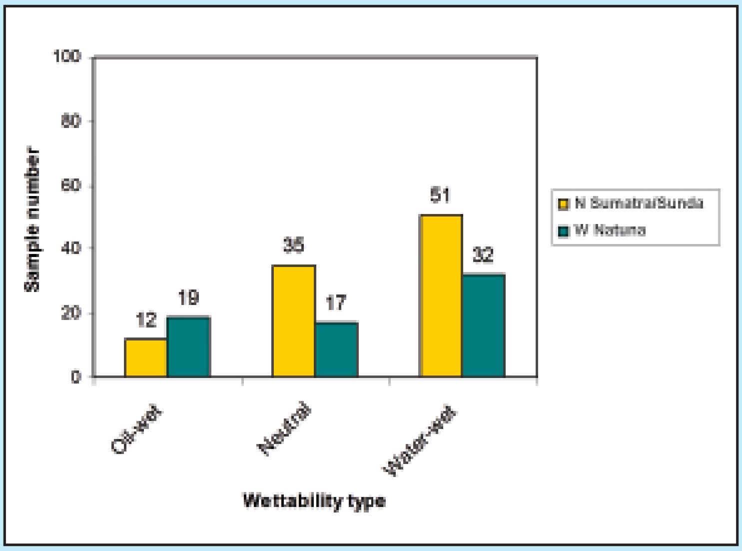

Figure 9
Wettabilitty composition of samples from West Natuna and combined North Sumatra - Sunda Basins. The three sedimentary basins tend to be predominantly water-wet but with different levels of strength and composition. (note: numbers on top of histogram represent number of samples)

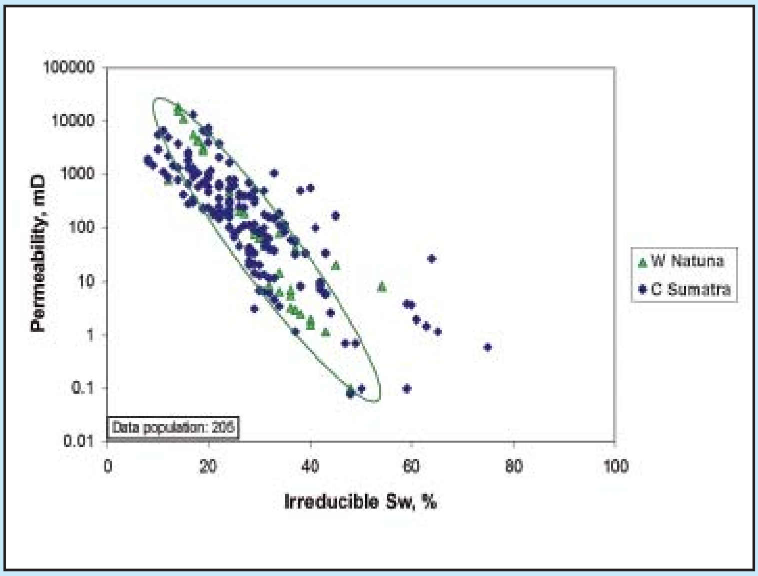

Figure 10
Comparison between the largely oil-wet Central Sumatra samples and the 'slightly' water-wet West Natuna samples. The similarity between the two sets may be taken as an evidence that oil-wettability hardly affect S_{wirr} characteristics

ference in the K - S_{wirr} slopes is most probably caused by different ‘strength’ in the water-wettability inclination. As clearly shown by the histogram on Figure 9, the North Sumatra/Sunda samples are ‘stronger’ in their water-wetness tendency when compared to the samples from the West Natuna Basin.

The conclusion drawn from Figures 6 through 9 is that S_{wirr} characteristics is much influenced by relative strength in water-wettability while somewhat less effectively influenced by strength difference in oil-wettability. Evidence over the lower effectivity of oil-wettability, compared to water-wettability, to govern K - S_{wirr} characteristics is demonstrated by data plot on Figure 10, in which the largely oil-wet Central Sumatra samples fall amicably within the same cluster with the ‘slightly’ water-wet West Natuna samples. This reveals further that even though sedimentary basins are complex geologically and may differ from one to another but wettability – as the manifestation of the complexity itself – plays an important factor in influencing S_{wirr} characteristics.

C. S_{wirr} vs. individual field

It has been shown that specific complexity and characteristics of individual sedimentary basin may result in different S_{wirr} characteristics apparently due to, among others, differences in rock wettability. This tendency towards specific K - S_{wirr} characteristics for most of individual sedimentary basins – some show similarity however – does actually not mask the fact that the fields contained within the basins may also behave in a non-uniform manner. This is demonstrated by the following graphs.

Figures 11 through 13 present examples of K - S_{wirr} trends for some fields in Central Sumatra, South Sumatra, and Kutei Basins. The slopes were actually created without taking into consideration the possibility of multi-slope situation similar to the case of sedimentary basin at

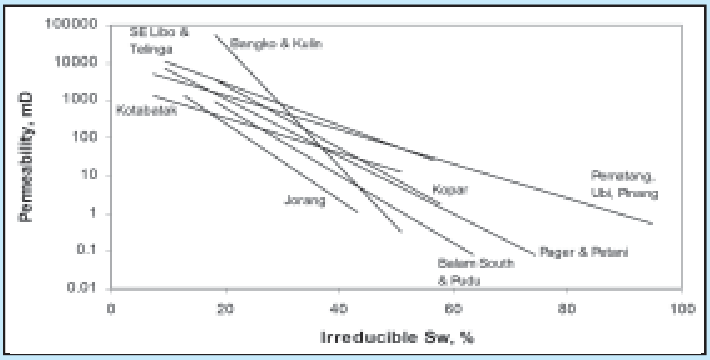

Figure 11
K - S_{wirr} gradients for some fields in Central Sumatra Basin. Bangko and Kulin fields’ samples appear to be more oil-wet than the others

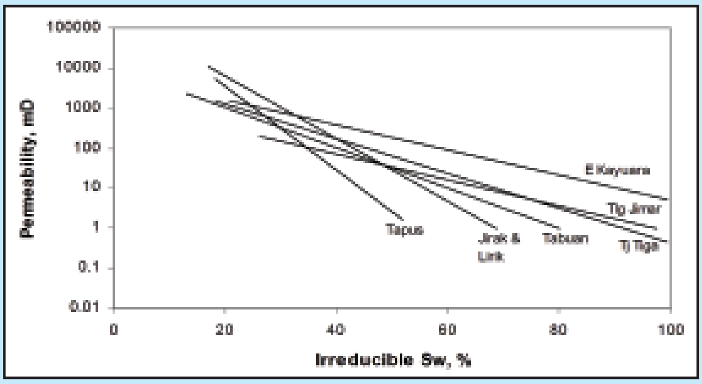

Figure 12
K - S_{wirr} gradients for some fields in South Sumatra Basin. Samples from Tapus, Jirak, and Lirik fields appear to be weaker in water-wettability in a sedimentary basin that is largely water-wet in characteristics

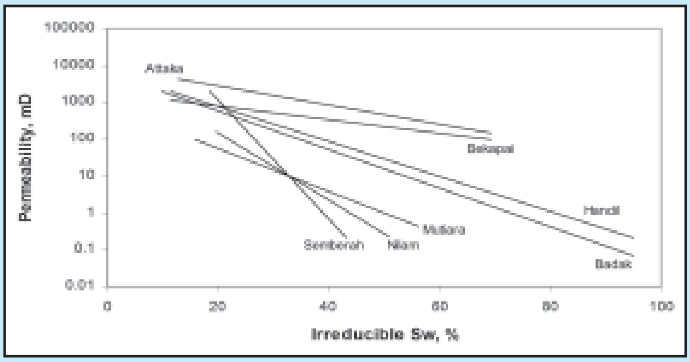

Figure 13
K - S_{wirr} gradients for some fields in Kutei Basin. Note that the characteristics of Semberah field is markedly different from other fields that were also deposited under delta plain and delta front environments such as Handil, Badak, and Nilam fields hence signifying complexities in sedimentary basin systems

larger scale (mega scale). The single slope representation for individual field is aimed at investigating level of S_{wirr} heterogeneity within a single sedimentary basin.

In general, heterogeneity in K - S_{wirr} characteristics is clearly observed in any sedimentary basin among the three presented on Figures 11 through 13. For instance, although reservoir rocks in Central Sumatra fields are oil-wet in general differences in the slopes are still palpably visible, with Bangko and Kulin samples apparently in the oddest deviation from the general trend (Figure 11). Despite the differences similarity in slopes is also indicated by some fields with one representing Pematang, Ubi, and Pinang fields as an example. The variation in the K - S_{wirr} gradients for some fields and the uniform ones for other fields in spite of the fact that those fields are not necessarily located in geographical proximity shows that heterogeneity is certainly a norm in Central Sumatra Basin. Similar states of heterogeneity also occur in the other two cases (Figures 12 and 13).

Heterogeneity may affect any rock physical property, but in a way similar to what occurs at sedimentary basin scale wettability can also play an important role in influencing the K - S_{wirr} characteristics at field scale within the basin. In order to observe the effect, comparisons in wettability composition have been made for each sedimentary basin between two of the most contrasting K - S_{wirr} gradients. For Central Sumatra samples the SE Libo/Telinga and Jorang fields are taken while for South Sumatra and Kutei Basins E Kayuara – Tapus and Attaka – Semberah comparisons were made, respectively. Figure 14 presents the wettability comparisons for the three cases.

Wettability comparisons for the three cases demonstrate that wettability is indeed a significant factor in swaying K - S_{wirr} characteristics. For Central Sumatra's largely oil-wet samples both sample sets that make SE Libo/Telinga and Jorang fields' K - S_{wirr} gradients are certainly oil-wet, yet different K - S_{wirr} characteristics between the two sets are obvious (Figure 11). Judging from the wettability comparison between the two sets (Figure 14a) different strength in wettability is likely to be the main cause, even though it is thought that different strength in oil-wettability is less effective – compared to water-wettability – in influencing the K - S_{wirr} trend.

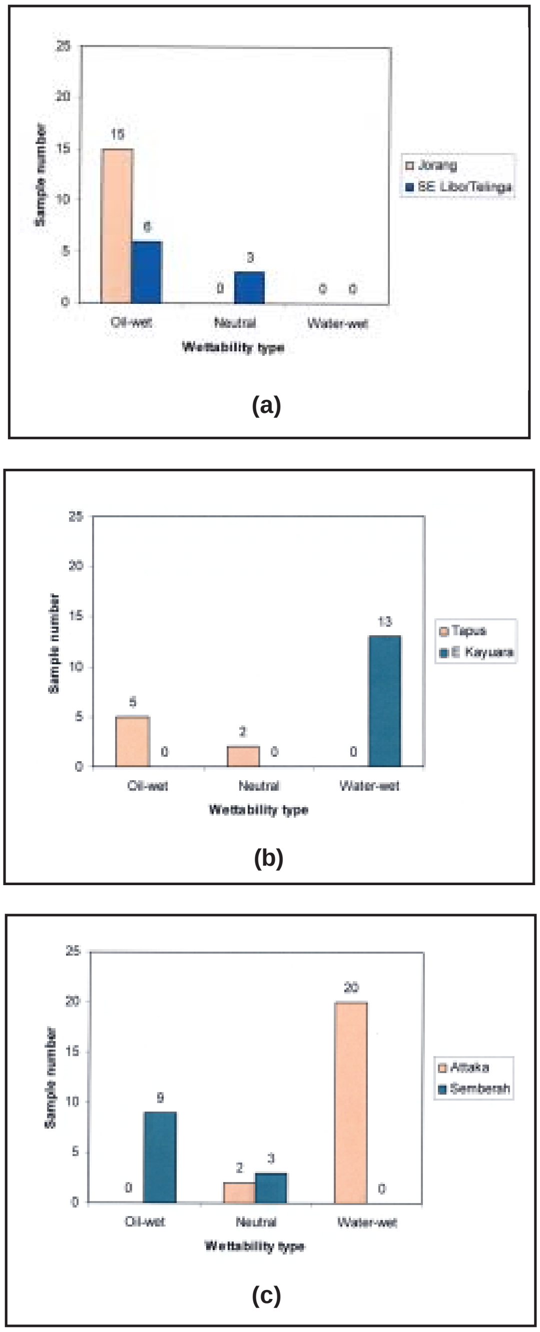

Figure 14
Wettability composisition of the two most contrasting K - S_{wirr} gradients;
(a) SE Libo/Telinga and Jorang for Central Sumatra Basin, (b) E Kayuara and Tapus for South Sumatra Basin, and (c) Attaka and Semberah for Kutei Basin.
Difference in wettability composition appears to play a pivotal role in shaping K - S_{wirr} characteristics. (note: numbers on top of histogram represent number of samples)

Comparisons on wettability composition for the other two cases are slightly different. For the two cases (Figures 14b and 14c) the two sets of samples are of opposite wettability. Tapus and Semberah samples are preferentially oil-wet whereas E Kayuara and Attaka samples are definitely water-wet. The three cases show that contrasting K - S_{wirr} trends is not only governed by opposing wetting tendencies but also – to somewhat lesser degrees – by different strength in oil-wettability.

At macro scale, as shown on Figures 11 through 13, all fields appear to have each of its K - S_{wirr} gradient uniform regardless of wettability. At lower scale, the meso scale, the picture could be different. To investigate this possibility a more meticulous investigation was made on the gradients for individual fields. Four sets of samples – having complete wettability types needed – are selected. Figures 15, 16, 17, and 18 present plots for Tanjung Tiga (South Sumatra Basin), Bajubang (Central Sumatra Basin), Handil (Kutei Basin), and E Kayuara (South Sumatra Basin) fields. The first two examples (Figures 15 and 16) show that separation is indicated between samples with opposing wettability, of which neutral and water-wettability samples are commonly represented by a single K - S_{wirr} gradient. This occurrence shows that in the case of Tanjung Tiga and Bajubang fields, neutral and water-wettabilities behave similarly leaving the oil-wet samples to yield K - S_{wirr} characteristics that are markedly lower in values. This explains that – despite its supposedly limited effect on K - S_{wirr} characteristics – samples with oil-wettability may differ from samples with either neutral or weak water-wettability.

The case is rather different for Handil field samples (Figure 17), which exhibit three apparent K - S_{wirr} gradients representing all three wettabilities. This case presents full influence of wettability K - S_{wirr} characteristics. In a case completely different, Figure 18 depicts a case – E

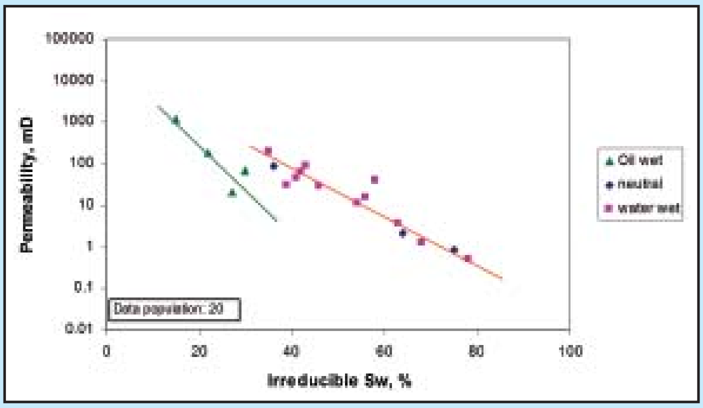

Figure 15
K - S_{wirr} data plot for Tanjung Tiga field, South Sumatra Basin. Combined neutral and water-wet samples are in certain deviation from the oil-wet samples

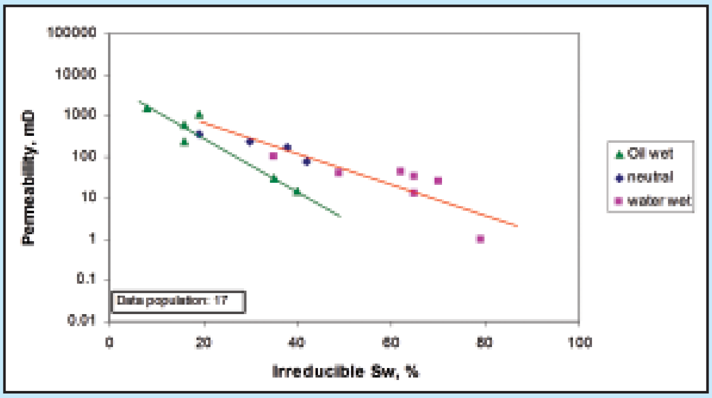

Figure 16
K - S_{wirr} data plot for Bajubang field, Central Sumatra Basin. Oil-wet samples tend to have lower S_{wirr} values than ones belong to neutral and water-wet samples

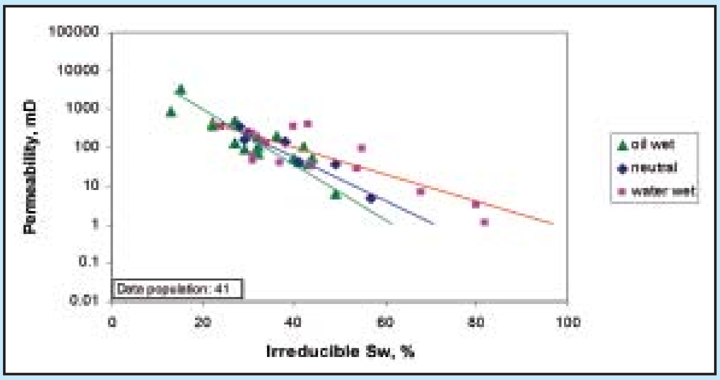

Figure 17
K - S_{wirr} data plot for Handil field, Kutei Basin. Three slopes belonging to oil-wet, neutral, and water-wet characteristics are visible

Kayuara field, South Sumatra Basin – in which all samples with the three wettabilities are represented by a common single gradient. This appears that there is no effect of wettability on K - S_{wirr} tendency. However, a more thorough investigation had revealed that the oil-wet and water-wet samples are of weak in nature hence leading to no noticeable difference when compared to neutral-wettability. Observation over the four cases put above suggests that variation in the K - S_{wirr} characteristics of a reservoir is very much influenced by the level of wettability variation and heterogeneity.

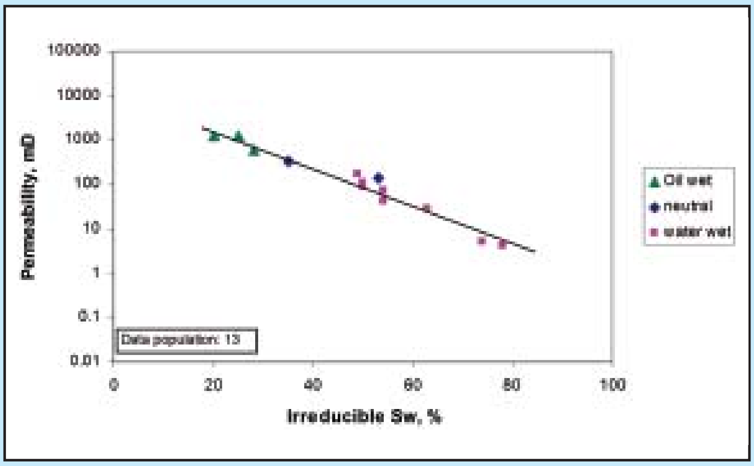

Figure 18
K - S_{wirr} data plot for E Kayuara field, South Sumatra Basin.
All samples with three different wettabilities are in one slope.
A closer investigation shows that the oil and water wettability
are classified as 'very weak' (i.e. close to neutral numerically)
leading to minimum effect on S_{wirr} characteristics

D. S_{wirr} vs. individual rock formation

In any petrophysical evaluation, division and classification of properties are often based on geological rock formations due to the presumption that they represent distinctive geological uniqueness caused by specific factors such as depositional environment, source rocks, diagenetic events, and age. Rock formations in the Central Sumatra sedimentary basin are taken as an example due to its detailed data available to the study. Manifestation of heterogeneity is often illustrated using correlation between porosity and permeablity. Figure 19 presents the correlations for some of the rock formations in the Central Sumatra Basin.

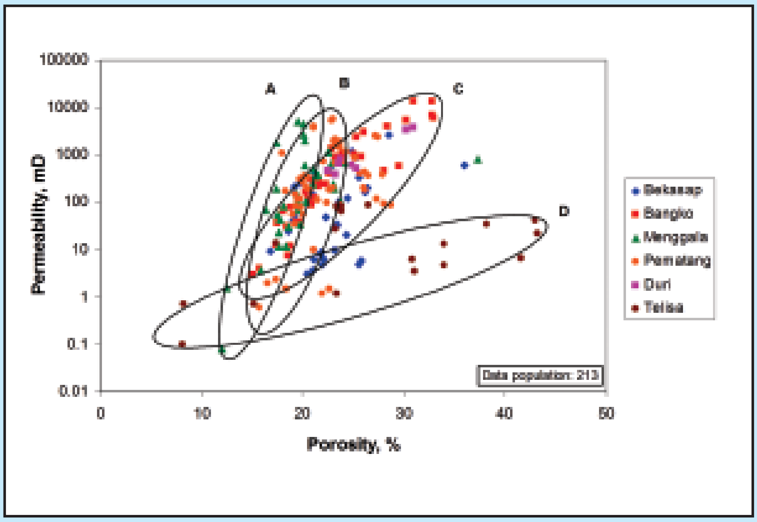

Figure 19
Porosity – permeability correlations for some rock formations
in Central Sumatra Basin. Clustres A represents Menggala
Formation, B for Pematang Formation, C for Bekasap – Bangko –
Duri Formations, and D for Telisa Formation

The K - S_{wirr} plot for the Central Sumatra rock formations are presented on Figure 20. The plot exhibits two big clusters which trends are shaped by Bangko and Pematang samples (Group A) and by Bekasap, Menggala, and Telisa samples (Group B). Duri samples (only 4 samples) are included in Group A for no specific reason. Note that the data used for the plot is only data that is specifically known to belong to certain rock formations. Having no identity regarding their rock formations, the other Central Sumatra data is not included in the plot.

When K - S_{wirr} plots presented on Figure 20 are coincided with the hydraulic heterogeneity indicators presented on Figure 19 it has become noticeable that the rock formation's heterogeneity, represented by porosity – permeability characteristics, is not the governing factor for the formation's K - S_{wirr} characteristics. There are at least four clusters indicated; A (Menggala Formation), B (Pematang Formation), C (Bekasap, Bangko, and Duri Formations), and D (Telisa Formation). This grouping is certainly not in agreement with the grouping on Figure 20. Bangko and Bekasap samples fall in the same porosity – permeability cluster even though having different K - S_{wirr} characteristics while the opposite is the case for samples from Menggala and Telisa Formations.

Upon observing the disagreement between the rock formations' rock hydraulic heterogeneity and their corresponding K - S_{wirr} characteristics observation was made on the wettability composition of the two clusters shown on Figure 20 (i.e. Clusters A and B). Figure 21 presents the result, in which it is obvious that Cluster A is characterized by stronger oil-wettability tendency than the one exhibited by Cluster B. This occurrence, again, explains that wettability plays a predominant factor in influencing S_{wirr} characteristics of reservoir rocks.

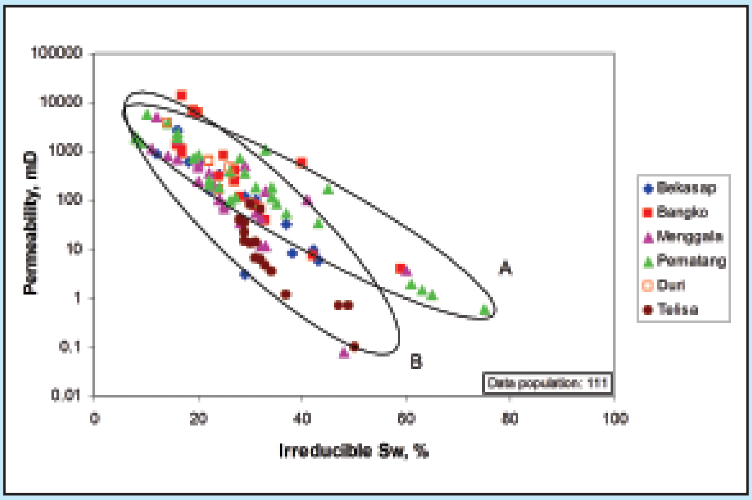

Figure 20
K - S_{wirr} plots for six rock formations in Central Sumatra Basin. Samples from Bangko and Pematang Formations (cluster A) are apparently different in characteristics from the rest of the data population (cluster B), except Duri samples that are too few for cluster inclusion

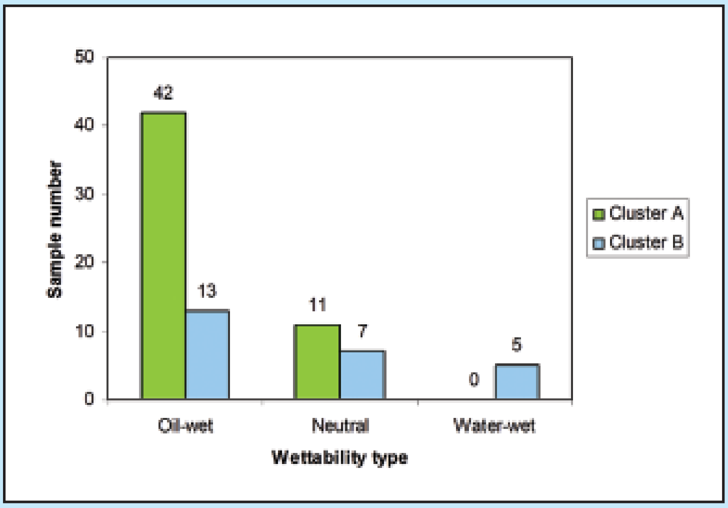

Figure 21
Wettability composition of some samples representing rock formations in Central Sumatra Basin. Cluster A includes samples from Bangko, Pematang, and Duri Formations whereas Cluster B covers Bekasap, Menggala, and Telisa samples

V. FURTHER DISCUSSION

As in the case of all empirical studies, quantity of data used in the study determines the validity of any conclusion drawn. The data quantity used in this study varries significantly among the sedimentary basins investigated. The data quantity for three top sedimentary basins – Central Sumatra, South Sumatra, and Northwest Java Basins – is far larger than the others like Sunda and West Natuna Basins (Table 1). This is not to mention that – considering the large number of fields in those three sedimentary basins – the data quantity available for the three basins is probably insufficient for a credible representation. This is even worse for the other seven sedimentary basins with their more limited data quantity. However, since the primary objective of this study is to investigate the factor(s) that govern S_{wirr} characteristics then it is thoughtfully considered that geological representativeness should not be of a major concern. Sedimentary basins merely represent places of origin for the samples, which data is used in the study. Consequently, any mathematical correlations presented in this article have to be viewed and used with some caution.

Characteristics of irreducible water saturation in reservoir rocks are certainly not determined by geological similarity, let alone geographical proximity. For instance, Central Sumatra and South Sumatra Basins are located nearby geographically and similar geologically (Schlumberger, 1986). Nonetheless, this study has clearly revealed that the Central Sumatra samples used in this study are predominantly oil-wet whereas the South Sumatra samples are largely water-wet. The factors affecting S_{wirr} that matter and wettability appears to be the most crucial one. Other factors – including porosity and permeability characteristics – are likely to influence in more minor fashion.

From all K - S_{wirr} plots made in this study one rather uniform occurrence that is readily visible is that rock wettability does not affect S_{wirr} much at high permeability levels. For rocks with differing wettability this occurs at permeability higher than roughly 100 mD. Over this permeability value the S_{wirr} values converge into a single big cluster. From physical point view, this occurrence is indeed logical. High permeability rocks have larger pore throats and usually also larger pore chambers. In this condition the pore radius element in the capillary force (Equation 1) is lessened hence reducing difference in total capillary forces between differing wettabilities. Moreover, in large pore chambers and throats any irreducible water volumes are likey to be less distinctive relative to the large volume of the pore chambers/throats themselves.

VI. CONCLUSIONS

Through the findings that mark this study, a set of main conclusions have been taken:

1. Irreducible water saturation tends to increase with decrease in permeability. This occurs for all sandstones used in this study.
2. Rock wettability appears to be a major factor in determining irreducible water saturation.
3. Variation in wettability strongly influences variation in irreducible water saturation characteristics, whereas variation in rock porosity – permeability relationship does not have specific influence.
4. Irreducible water saturation tends to be higher for rocks with water-wettability compared to ones for rocks with oil-wettability. However, this difference is not only exhibited in rocks with opposing wettabilities but also in rocks with different strength of wettability even though both are belonging to the same wettability type (i.e. water-wet or oil-wet).
5. The effect of wettability on irreducible water saturation is considerably less in rocks with high permeabilitty values. A more thorough analysis is required nonetheless for better knowing the most representative range of values.
6. Geological similarity and geographical proximity do not necessarily result in similar wettability type/strength and similar irreducible water saturation characteristics.
7. The influence of wettability on irreducible water saturation takes place in all scales of observation; sedimentary basin, field, and rock formation.

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