SINGLE OR MULTIPLE POROSITY CUT-OFF? A NEW RELEVANCE PROVIDED BY APPLICATION OF A NEW APPROACH

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ABSTRACT

Porosity cut-off is one of the most important parameter normally used to differentiate between reservoir and non-reservoir rocks. Quantity of the parameter certainly dictates reservoir volumes, hence directly influences economics and commerciality of a given oil/gas field. An ever critical issue in relation to this parameter is whether the use of porosity cut-off has to be established through a single or multiple values especially for heterogeneous formation rocks. This certainly may lead to different reservoir sizes along with the technical *and* economical *consequences. The study presented in this article is meant to further investigate this question. The thrust of this study lies on the application of a newly proposed method for determining porosity cut-off. It is put that with this new and reliable method – compared to the traditionally used method – a more conclusive answer can be achieved. For the purpose, a heterogeneous limestone reservoir in West Java – Indonesia is used. Evaluation, analysis, and application of the new method on data from the field's eight wells have shown that multiple porosity cut-off values are needed for better definitions of reservoirs. Application of a single value for these reservoirs can still be regarded as unrepresentative. The fact underlines that – despite the new approach's reliability – heterogeneity governs more over the use of either single or multiple cut-off values rather than limitations of method. The study also proves that the new method for determining porosity cut-off works well for highly heterogeneous reservoir rocks.*

Key words: *Porosity cut-off, heterogeneous reservoir, multiple porosity cut-off values, new method for porosity cut-off determination.*

I. INTRODUCTION

As universally acknowledged cut-off parameter is used to define a limit of acceptance over a certain parameter or measured entity. Dependent upon the nature of parameter of interest cut-off values are set to distinguish parts of the parameter that are to be 'included' or 'excluded' from consideration. In case of rock porosity, cut-off value is normally used to distinguish parts of the rock formation that can be regarded as 'reservoir' from the rest of formation rocks.

It is also well acknowledged that application of porosity cut-off values is much dependent on the level of heterogeneity of reservoir rocks under concern. Relatively homogeneous reservoir rocks may need only a single cut-off value whereas the reverse is true for reservoirs with high level of rock heterogeneity. However, as clearly put by Worthington (2005), there are no fully satisfactory methods for determining reservoir cut-off parameters and the case is also true for porosity cut-off value. In his comprehensive review over the variously known methods he truthfully underlined that porosity cut-off value is a difficult parameter to establish due to its indirect relation to permeability cut-off, the parameter that directly separate reservoirs from non-reservoir rocks.

Combination of rock heterogeneity and lack of satisfactory method for determining parameter cut-

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off may raise a question over whether the need for multiple porosity cut-off in reservoir evaluation – as common wisdom dictates – is really caused by the rock heterogeneity itself or simply by the lack of satisfactory methods (and measuring equipment). Recent works by Widarsono (2009, 2010) have shown satisfactory results in application of a new approach for determining porosity cut-off on several sandstone and limestone reservoirs. With the existence of this supposedly more reliable method than the traditional ones it has become relevant to seek an answer to the above-mentioned question.

The study presented in this article was mainly carried out by applying the recently proposed approach on mercury injection for capillary pressure (MICP) data from several wells in WJ field. Results of the method's application were compared with results from the traditional porosity – permeability plot leading to conclusions over the need of whether single or multiple cut-off values.

II. A BRIEF OVERVIEW OVER THE METHOD

The method for determining porosity cut-off proposed in Widarsono (2009) is basically a further development of a technique presented by some workers, Pittman (1992) among others. In his paper he showed that there is an excellent correlation between permeability, pore throat radius, and porosity, using which permeability can be accurately predicted. This approach was then utilized by Jaya et al. (2005) to attempt the establishment of a set of correlations for permeability prediction that are valid for reservoirs in Indonesia. In the work they used a huge set of MICP data taken from measurements on core samples retrieved from various fields in Indonesia. Despite the vast amount of data used, however, during the study in Widarsono (2009) – as well as in Widarsono (2010) – it was found that the correlations are too general to be accurately used for individual and specific reservoirs. It was the approach that was then adopted and used for determination of porosity cut-off. See Tiab and Donaldson (2004), for a discussion related to MICP measurements.

In Widarsono (2009), the adopted approach was used and modified not for permeability prediction but for determination of porosity cut-off. In the work all fundamental aspects such as relation between permeability and pore throat radius/capillary pressure, factors that influence rock pore throat sizes, correlation with porosity, and relation between mercury saturation and permeability were discussed. Summarily, the method consists of two main steps. First, establishment of permeability – pore throat size (K – R) correlation, and second, multiple regression that correlates the correlation established in first step with porosity. The final permeability – pore throat size – porosity (K – R – ϕ) relation is then used to determine porosity cut-off using the most suitable permeability cut-off.

As shown in Widarsono (2009, 2010), the method has worked satisfactorily on seven sandstone and five limestone reservoirs from which the MICP data was obtained. The results upon applying the method show considerable reduction in uncertainty in the produced porosity cut-off values when compared to ones resulted by the traditional permeability – porosity (K – ϕ) transforms. This is certainly due to far better correlations exhibited by permeability – pore throat size compared to porosity – permeability, so that attaching porosity into the finely correlated permeability – pore throat size through multiple regressions has improved correlation between permeability and porosity. Using this largely reliable method the study on the question over WJ field's porosity cut-off was carried out.

III. CASE STUDY: WJ FIELD

WJ field is located in West Java province and its hydrocarbon accumulation is primarily contained in Baturaja Formation (BRF). The formation is mainly made of bio-clastic carbonate rocks and carbonate reef overlying conformably on top of Talang Akar Formation (TAF). The BRF was deposited in the Early Miocene with obvious signs of open marine development environment. Core description supported by integrated petrographic studies (Lemigas, 2002) reveals presence of grainstones, packstones, and wackestones with skeletal framework typicaly composed by larger forams, red algae, and in lesser compositions, echinoid, bryozoans, brachiopods, small benthonic forams, planktonic forams, and indeterminate bioclast. Pore types of the rocks range from integranular to vuggy, mouldic, and intraganular. Presence of natural fractures and stylolites are also indicated. Table 1 presents a brief summary over porosity, permeability, and visual description of the reservoir rocks.

Table 1
Summary of basic petrophysical properties and visual description of samples taken from the eight wells in WJ field.

Well	Porosity (frac.)	Permeability (mD)	Visual description
WJ-5	0.079 – 0.287	0.5 – 92.5	Packstone wth minor boundstone, lt gy – lt brn, L.foram, coral, micro x-lin, vugs (5 – 8 mm), sli stylolite
WJ-6	0.13 – 0.295	11.8 – 475	Grainstone - packstone, lt gy – crm – lt brn, L.foram, algae, vugs (5 – 10 mm), loc intraparticle, nat frac wth xln
WJ-7	0.087 – 0.166	0.03 – 43.2	Packstone , wth algae, lt gy, L.foram, pp-mott vugs, sli stylolite
WJ-8	0.057 – 0.238	1.07 – 34.9	Packstone wth minor grainstone, lt brn, L.foram, foss fragm, vugs, loc xln, loc frac
WJ-10	0.112 – 0.225	1.27 – 14.1	Wackestone – packstone, wth sli algae, wht – lt gy, L.foram, vugs, loc intraparticles, med – med coarse grn
WJ-18	0.031 – 0.33	0.05 – 34	Packstone – wackstone, wht – lt gy, algae, L.foram, micro stylolite, vugs wth calcite xln
WJ-31	0.013 – 0.188	0.01 – 17	Packstone – wackstone – wth minor mudstone, wht – lt gy, crystal'n of bioturb structure, mold cast, fine to med grn
WJ-33	0.043 – 0.244	47.7 – 66.1	Packstone – wackstone – grainstone, wht – lt brn, bioturb, stylolite, minor grapestone, fine to med grn

The MICP data is available to some of the existing wells in WJ field, out of which data from eight wells was considered suitable – having at least two core samples with MICP measurement – for the purpose of the study. Figures 1 and 2 present two sets of MICP curves obtained from WJ – 7 (depth: xx41.35 meters) and WJ – 31(depth: xx35.88 meters) wells. Notice the different in shape of cumulative curves for the two samples, even though both of them are low in porosity (0.112 and 0.173, respectively) and permeability (1.98 mD and 3.67 mD, respectively). The difference reflects more of difference in pore configuration, with WJ – 7 sample represented by a spectrum of pore throat sizes whereas the WJ – 31 sample is more by a single predominant pore throat size, as indicated by the incremental curves. This kind of difference in pore configuration is likely to provide a scatter when one attempts to construct a porosity – permeability transform, but this difficulty has been proved lessened with the introduction of permeability – pore throat size relationship as demonstrated in Widarsono (2009, 2010) and to be presented in this work.

Following the established procedure, processing and analysis were carried out on the data for the eight WJ wells. Not all tables and graphs are to be presented in this article due to their rather large numbers. Tabulated data is limited to correlation factors and resulted cut-off porosity values only, whereas graphical data is limited to plots with 'worst' and 'best' correlation factors for individual wells and plots for combined all well data. Readers are advised to analyze the tabulated data and compared it with the presented graphical data to have illustration over results for all individual wells.

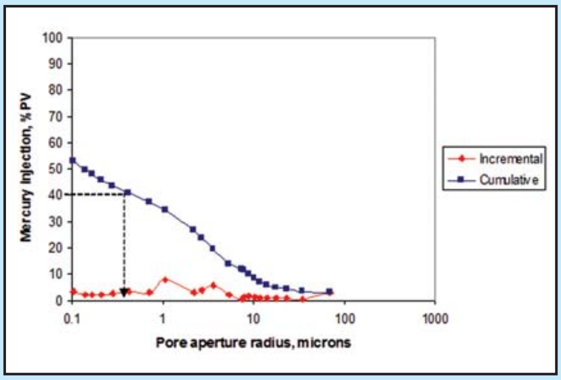

Figure 1
Mercury injection for capillary pressure (MICP) for a WJ-7 well's sample (depth:xx41.35 m, porosity: 0.112, permeability: 1.98mD). Dashed lines represent an example of pore throat radius at a certain percent pore volume of mercury injected (example: R_{40})

Plots between porosity and permeability for carbonate rocks such as in the case in WJ field are not difficult to guess; difficult correlations. Figures 3, 4, and 5 are plots representing WJ – 31, WJ – 18, and all wells combined. The plot in Figure 3 is often regarded as a rule rather than an exception for carbonate rocks, for which pore structures typically vary considerably. For this well this is not reflected by the K – R plot (Table 2) showing good correlation except for lower levels mercury saturation. For WJ – 18 plot in Figure 4 the correlation is the best (R^2 =

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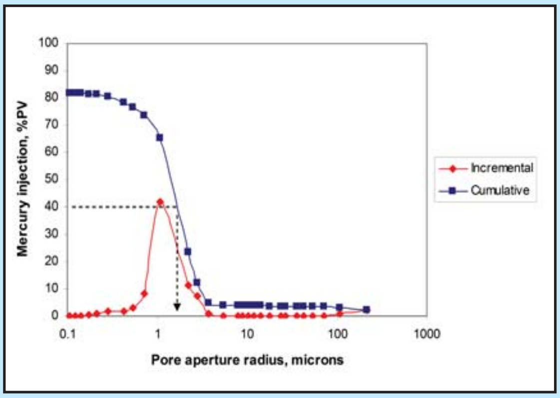

Figure 2
Mercury injection for capillary pressure (MICP) for a WJ-31 well's sample (depth: xx35.88 m, porosity: 0.173, permeability: 3.67mD). Dashed lines represent an example of pore throat radius at a certain percent pore volume of mercury injected (example: R_{40})

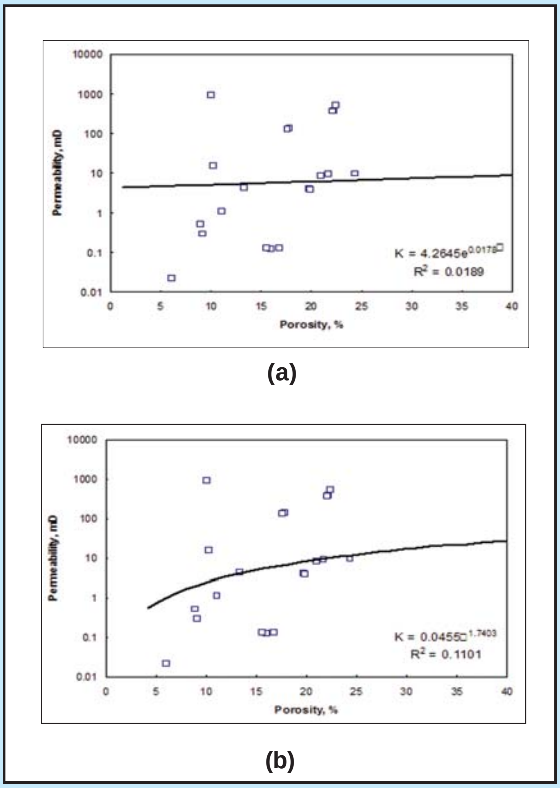

FIgure 3
Permeability-porosity plots for samples from WJ-31 well. The correlation coefficients of 0.00189 (a, exponential correlation) and 0.1101 (b, power correlation) indicate very scattered data points and the most "uncorrelated" among eight wells.

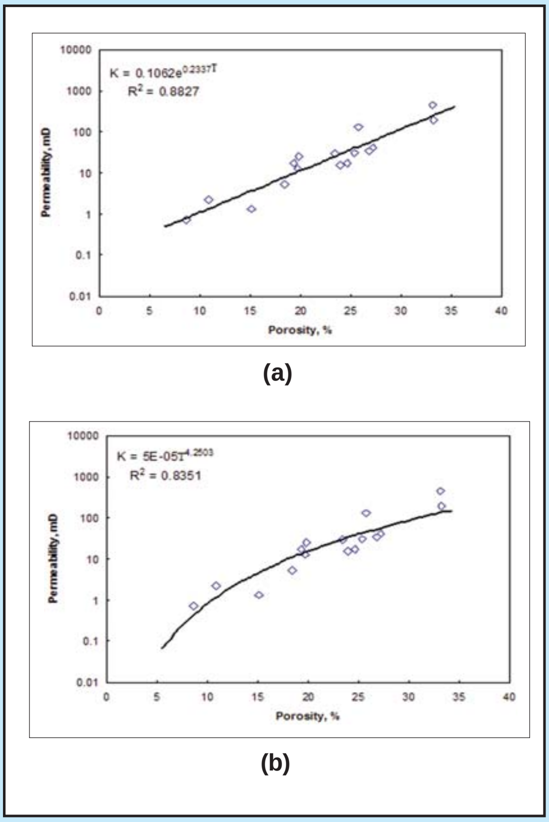

Figure 4
Permeability-porosity plots of simples from WJ-18 well. The correlation coefficients of 0.8827 (a, exponential correlation) and 0.8351 (b, power correlation) represent a fine correlation and the best K-ϕ plot for individual well

0.827, Table 2) and with an even better K – R plots (R^2 = 0.8912 – 0.9924, Table 2). The all data plot also prove to be scattered for the K – ϕ data (Figure 5).

From the K – ϕ plots it is not hard to see that estimating porosity cut-off solely from the relationships is difficult. Although similar occurrence could take place in K – R relationship but the state of K – ϕ plots normally contains much higher uncertainty levels in porosity cut-off values leading to presence of wide value ranges, both for permeability cut-off values of 1 mD and 0.1 mD. Tables 3 and 4 present the overall results for the individual wells and average values for the data from the eight wells used in this study through the use of exponential regression and power regression, respectively. Despite the estimated values obtained from the regression, value

Table 2
Correlation degree (R^2) values for porosity – permeability (ϕ – K) and permeability – pore trota radii (effective) (K – R) plots at various mercury saturation levels. Shaded R^2 values are the highest values representing the best correlation hence taken for further calcucations and evaluations

Well	R2							
	$K-\phi$	$K-R_{15}$	$K-R_{20}$	$K-R_{25}$	$K-R_{30}$	$K-R_{35}$	$K-R_{40}$	$K-R_{50}$
WJ-5	0.397	0.9793	0.9732	0.9983	0.9974	0.9931	0.9996	0.9988
WJ-6	0.6973	0.96	0.9058	0.9415	0.9382	0.9921	0.9988	0.9878
WJ-7	0.8295	0.9633	0.9696	0.9425	0.9531	0.9671	0.9981	0.9938
WJ-8	0.4302	0.9856	0.9772	0.9826	0.9829	0.9966	0.9814	0.9928
WJ-10	0.3387	0.4556	0.351	0.2764	0.1387	0.2551	0.1073	4556
WJ-18	0.8351	0.8912	0.9299	0.9678	0.984	0.9865	0.9924	0.9659
WJ-31	0.7674	0.176	0.217	0.2324	0.9567	0.9701	0.9954	0.9943
WJ-33	0.1101	0.9737	0.9911	0.9914	0.9998	0.9911	0.9414	0.375
All wells	0.4203	0.4535	0.5841	0.6852	0.6854	0.6762	0.7148	0.5657

Table 3
Comparison over porosity cut-off values (ϕ_c) resulted from ϕ – K and K – R – ϕ relations. Exponential ϕ – K relationship yields the porosity cut-off values through extrapolation using the regressed line to 0.1 mD and 1 mD.

Well	K - ϕ Relationship				K – R – ϕ Relationship			
	K_c = 1 mD		K_c = 0.1 mD		K_c = 1 mD		K_c = 0.1 mD	
	ϕ_c (frac.)	ϕ_c range (frac.)	ϕ_c (frac.)	ϕ_c range (frac.)	R_c (mD)	ϕ_c (frac.)	R_c (mD)	ϕ_c (frac.)
WJ – 5	NA(*)	0 – 0.22	NA	0 – 0.11	0.96	0.125	0.125	0.104
WJ – 6	0.01	0 – 0.06	NA	NA	0.1143	0.059	0.0182	0.012
WJ – 7	0.09	0.07 – 0.12	0.05	0.03 – 0.08	0.39	0.105	0.0031	0.061
WJ – 8	NA	0 – 0.05	NA	NA	0.858	0.094	0.487	0.029
WJ – 10	0.05	0.04 – 0.08	NA	NA	0.537	0.112	0.00166	NA
WJ – 18	0.09	0.06 – 0.11	NA	NA	0.537	0.114	0.207	0.047
WJ – 31	0.09	0.04 – 0.11	NA	0 – 0.04	0.934	0.093	0.357	NA
WJ – 33	NA	NA	NA	NA	0.84	0.127	0.174	0.081
Average	(**)		(**)			0.104		0.055
All Wells	NA	0 – 0.25	NA	0 – 0.17	0.651	0.124	0.1165	0.072

(*) Not available because interception of K – ϕ regression line yields negative values
(**) Not averaged due to insufficient data point

Table 4
Comparison over porosity cut-off values (ϕ_c) resulted from ϕ – K and K – R – ϕ relations. Power ϕ – K relationship yields the porosity cut-off values through extrapolation using the regressed line to 0.1 mD and 1 mD

Well	K – ϕ Relationship				K – R – ϕ Relationship			
	K_c = 1 mD		K_c = 0.1 mD		K_c = 1 mD		K_c = 0.1 mD	
	ϕc (fraksi)	ϕ_c range (fract)	ϕ_c (fract)	ϕ_c range (fract)	Rc (mD)	ϕ_c (frac.)	R_c (mD)	ϕ_c (frac.)
WJ – 5	0.05	0.02 – 0.12	0.01	0 – 0.05	0.96	0.125	0.125	0.104
WJ – 6	0.08	0.05 – 0.12	0.05	0.03 – 0.09	0.1143	0.059	0.0182	0.012
WJ – 7	0.08	0.06 – 0.10	0.05	0.03 – 0.08	0.39	0.105	0.0031	0.061
WJ – 8	0.05	0.04 – 0.07	0.01	0 – 0.05	0.858	0.094	0.487	0.029
WJ – 10	0.05	0.04 – 0.13	0.02	0 – 0.05	0.537	0.112	0.00166	NA
WJ – 18	0.10	0.08 – 0.12	0.06	0.05 – 0.08	0.537	0.114	0.207	0.047
WJ – 31	0.07	0.06 – 0.14	0.03	0.01 – 0.04	0.934	0.093	0.357	0.051
WJ – 33	0.05	0 – 0.17	0.01	0 – 0.15	0.84	0.127	0.174	0.081
Average	0.066		0.032			0.104		0.055
All Wells	0.04	0 – 0.17	0.02	0 – 0.11	0.651	0.124	0.1165	0.072

NA: Not available because estimation falls out of range

ranges are always the case due to scatters normally seen in the K – ϕ plots.

Nevertheless, averaged values of porosity cut-off estimates show that average porosity values of 0.066 (K_c = 1 mD) and 0.032 (K_c = 0.1 mD) through the use of power relationship are different from the ‘all wells’ plot result of 0.04 and 0.02 (Table 4). The results from using exponential relationships shown in Table 3 exhibit worse conclusions, though. This comparison shows the need to have different porosity cut-off values for individual well, or group of wells, in the WJ field dependent on the heterogeneity of the field’s reservoir rocks.

For K – R plots two examples are presented in Figures 6 and 7 representing the ‘worst’ and the ‘best’ plots. Similarly then, the plots for K – R – ϕ relationship, after multiple regression, show average values (Table 4) of 0.104 (K_c = 1 mD) and 0.055 (K_c = 0.1 mD) that are different from the average values of 0.124 and 0.072 obtained from ‘all wells’ plots (Figure 8). Although better than the K – ϕ plots it is obvious that the far better K – R – ϕ relationships (as shown before, this is true because R^2 values for K – R data plots are much higher than R^2 for K – ϕ data plots) show that there are still differences in porosity cut-off values between individual wells and average

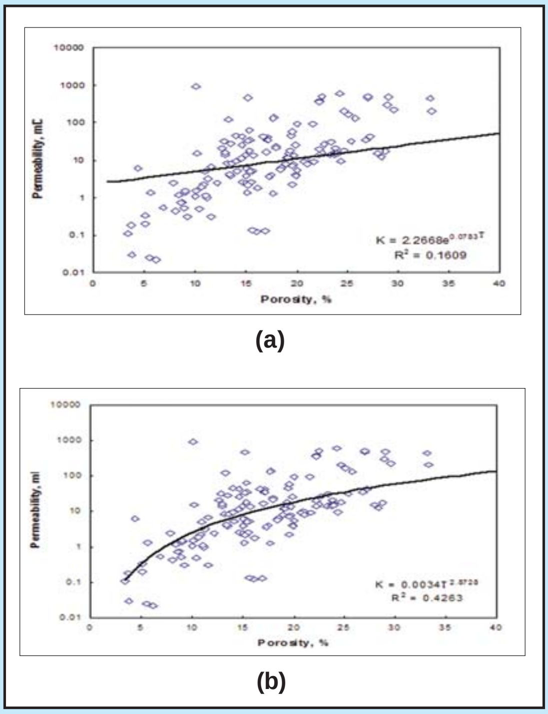

Figure 5
Permeability-porosity plots for data from all wells. The correlation coefficients of 0.1609 (a, exponential correlation) and 0.4263 (b, power correlation) indicate a lack of K-ϕ correlation as also clearly shown by the scatter in the graphs

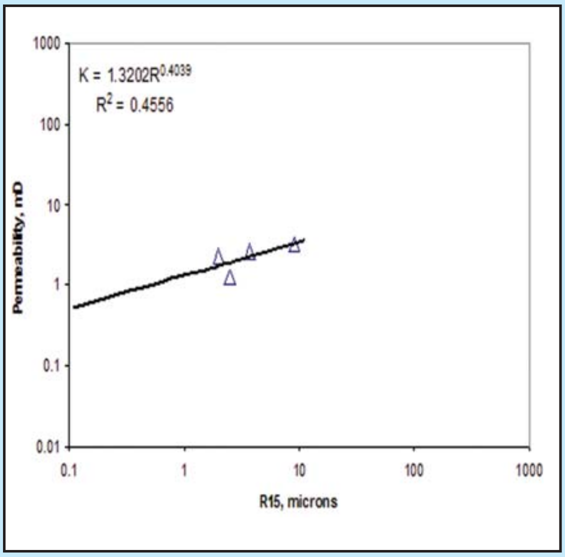

Figure 6
Permeability-pore throat size (R_{15}) plot for WJ-10 well. The correlation coefficients of 0.4556 is the "worst" best K-R plot among the eight wells used in the study

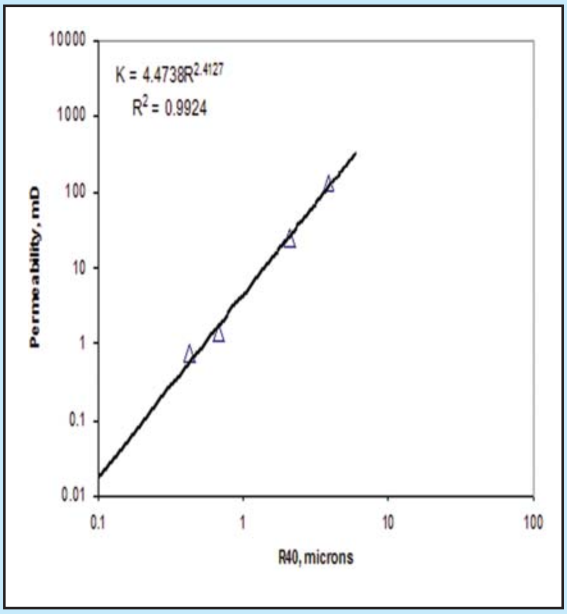

FIgure 7
Permeability-pore throat size (R_{40}) plot for WJ-18 well. The correlation coefficient of 0.9924 is among the "best" of the best K-R plot among the eight wells used in the study

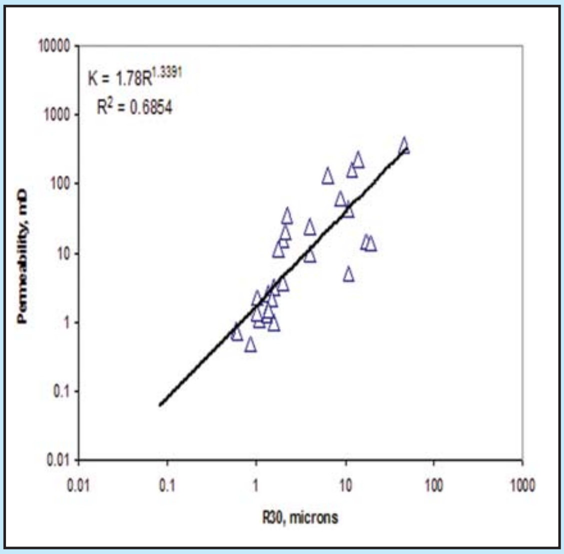

Figure 8
Permeability-pore throat size (R_{30}) plot for all wells. The correlation coefficient of 0.6854 is better than its corresponding K-ϕ plost but not as good as the best plots for individual wells

'all wells'. In a manner similar to the results shown by the K – ϕ plots it can then be concluded that there is a need to observe different porosity cut-off values for different parts of the rock formation in WJ field.

IV. DISCUSSION

Porosity cut-off as a means for differentiating hydrocarbon reservoirs from non reservoirs appears to be dependent strongly on rock heterogeneity in rock formation. From the study, both the less reliable K – ϕ relationship and the more reliable K – R – ϕ relationship have shown that the cut-off parameter cannot be taken as a single value for the entire formation rocks, especially for the WJ field upon which the study was conducted. Application of a single porosity cut-off and multiple porosity cut-off values will nevertheless result in different volumes of reservoir, which in effect may result in different strategies for exploiting the hydrocarbon accumulation.

As shown by this study, as well as by works in Widarsono (2009, 2010), the newly proposed method has shown that it works better to yield porosity cut-off values compared to the traditional K – ϕ transform. Considering the more reliable K – R – ϕ relationship, this method provides reliable porosity cut-

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off values. However, results of this study has shown that through the use of this reliable method it is obvious that - in a manner of reinforcing the statement above - a single porosity cut-off value cannot be applied reliably, especially for limestone reservoir like the one which data was used in this study.

The limestone reservoir rocks in WJ field appear to range from wackestones to grainstones with minor boundstones presence. No obvious trends between the visual lithology and petrophysics such as permeability and porosity are observed. Classification and grouping based on well locations has led to no clear distinction. Heterogeneity of the limestone reservoir rocks in WJ field certainly influences the correlation between permeability and porosity, but it is also clearly shown that relationship between permeability and pore throat size prevail in a more direct manner. This underlines the applicability of the method on any reservoir rock types.

V. CONCLUSIONS

Application of the newly proposed method on WJ field has resulted on four main conclusions:

- Single value of porosity cut-off value cannot be used for a desired and reliable result, especially for heterogeneous reservoirs such as the limestone reservoir in WJ field. Multiple values are likely therefore to provide a better definition of reservoir volumes.
- In spite of the high level of heterogeneity shown by the WJ field the newly proposed method of permeability – pore throat size – porosity relationship has shown that it is more reliable than the traditionally used permeability – porosity transform method. Other auxiliary methods such as usage of shale volumes and pore types may provide further beneficial contributions.
- In case of scattered, hence dubious, correlation between permeability and porosity the newly proposed method appears still to work well in determining porosity cut-off parameters.
- Through comparing cut-off porosity values obtained from application of both exponential and power relationships, it has been shown that in spite of scatters exhibited from permeability - porosity plots, better conclusions can be obtained through the use of appropriate mathematical relationship.

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