THE IMPACT OF HETEROGENEITY AND MULTI-SCALE MEASUREMENTS ON RESERVOIR CHARACTERIZATION AND STOOIP ESTIMATIONS

Moustafa Dernaika[1], Samy Serag[2] and M. Zubair Kalam[2]
[1]Ingrain Inc., Abu Dhabi and [2]ADCO, Abu Dhabi

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ABSTRACT
Reservoir heterogeneity is dependent upon depositional environments and subsequent events in the history of the reservoir. From a previous work, we reported variations in poroperms and cementation factor “m” as a function of different scale measurements and emphasized the importance of whole cores in better capturing reservoir heterogeneity. In the present work, we have extended our investigation on the effect of the multi-scale measurements on hundreds of samples from four different wells in a giant carbonate field in Abu Dhabi. Laboratory measurements were conducted on four different scale samples, ranging from full diameter 4 inch whole cores down to 1 inch plug samples. The smaller size samples were taken from the same bigger volume samples for direct comparisons. The multi-scale effect was studied on the variations of reservoir properties including porosity, permeability, capillary pressure and saturation exponent “n”. The multi-scale analyses confirmed the variations in rock properties and the influence of heterogeneity on reservoir performance. Whole core porosities tend to be lower than plug porosities. Permeability variations between different sample sizes appear to be governed by the degree of heterogeneity. Different capillary pressure and “n” curves were obtained from whole core and plug samples. The changes in rock properties as a function of sample scale (size) improve the understanding of reservoir heterogeneity and minimize the uncertainty in STOOIP calculations.

INTRODUCTION
Serag and co-workers [1] investigated the effect of multi scale measurements (whole cores down to small trims) on poroperm and cementation factor “m”. The samples came from single well “E” in the field, and the trims were taken from the plugs but the plug samples were cut adjacent to the whole cores. The main findings were that whole core porosity matched very well log data, and the plug porosities as compared to the whole core data were systematically higher. We found out that the degree of heterogeneity played a major role in comparing whole core to plug permeability. “m” was systematically reported lower in the measured whole core samples. The investigation has been extended to include hundreds of samples taken from 4 different wells in the same field. Laboratory measurements were conducted on full diameter four inch whole cores down to one inch diameter core plug samples. The smaller samples were taken from the same bigger volume samples for direct comparisons. The multi-scale effect was studied

on the variations of reservoir properties including porosity, permeability, capillary pressure and saturation exponent “n”.

EXPERIMENTAL MEASUREMENTS

Over 200 (4 inch diameter) whole cores were cut from four wells (i.e. A, B, C & D), and cleaned in Soxhlet extractors for poroperm measurements. Some of the samples were later cut smaller in diameter and were measured for whole core vertical permeability only. Vertical and horizontal plugs (1.5” diameter) were then cut from the whole cores and underwent poroperm analyses. Smaller samples (1” diameter) were also cut from the horizontal plugs and were measured for poroperm and MICP. Previous study focused on well E in the same field and examined the multi-scale effect from poroperm and cementation factor “m” only [1]. This is now extended to compare capillary pressure and resistivity index by porous plate between whole cores and adjacent plugs.

EXPERIMENTAL RESULTS AND INTERPRETATIONS

Helium Porosity

Figure 1 compares 4” whole core to 1.5” plug porosities from four wells. The majority of the measurements (almost 70%) give lower porosity values from whole cores (WC) by an average of 2 porosity unit (p.u.) and maximum of 9 p.u. In our previous investigation from well E we reported lower WC porosities by an average difference of 2.5 p.u. and maximum difference of 5.9 p.u. [1]. Ehrenberg [2] did a comparison study on coarsely bioclastic carbonate samples and obtained lower WC porosities by an average of 1.4 p.u. Ehrenberg referred the reason (probably) to lower surface/volume ratio for the WC samples. However, such a possibility is unlikely if we compare the effect of scale on porosity in figure 2. Figure 2 compares the WC porosities with 1” plug porosities taken from the same 1.5” samples. Almost 40% of the measurements show higher porosities from WC, suggesting this porosity scale phenomenon might be more related to sample heterogeneity than surface/volume ratio. The percentage of higher WC porosity as compared with 1.5” plug porosity varied between 10% (for well B) to 50% (for well C), with 18% for well A and 39% for well D. This indicates that the variation between WC and plug porosities could be related to rock nature and topology. Further investigation on this porosity scale issue may be needed perhaps through X-ray CT scanning and Digital Rock Physics to better understand the influencing factors. Sample grain volume was determined directly by measuring with a Helium gas expansion porosimeter. Bulk volume of whole core was measured by sample length and diameter calculation, while plug bulk volume was measured by immersion in mercury.

Gas Permeability

Figures 3 and 4 show WC versus 1.5” plug permeabilities for vertical and horizontal directions, respectively. There is a large variation in the permeability differences from sample to sample but there seems an overall tendency towards higher permeability values from whole core data. There is more scatter in the horizontal data, and one may see tendency towards higher plug permeability in the high permeability range in figure 4. This is further confirmed in figure 5 and figure 6 for WC versus plug permeabilities from 1.5” and 1” samples, respectively. In order to have direct comparison on the effect of decreasing sample size on permeability, figure 5 re-plots figure 4 data, but with measurements corresponding to the available 1” samples. The overall tendency of higher permeabilities from bigger size samples discussed in figure 4 is more evident in figure 5 and figure 6. There are different explanations for the permeability variations with scale. Small sample sizes (e.g. plugs) could overestimate permeability measurements by short-circuiting flow through porosity channels (e.g. vugs) with dimensions similar to plug length. On the other hand, 3D connectivity and flow paths are probably better captured in the larger whole core volumes which could exploit optimal connection pathways that tend to be unavailable within smaller subsets of the total rock volume. Both of these explanations seem reasonable and one would expect local heterogeneity to play a key role in defining the actual physical phenomenon responsible for the permeability variations. In our previous investigation on well E we observed higher WC permeabilities in low permeability range (i.e. <10 mD) where bigger rock volumes could enhance 3D connection pathways and yield higher permeability values. In higher permeability range, however, we obtained higher plug permeabilities which could be overestimated in plugs through relatively larger porosity channels [1].

Anisotropy

Figures 7 and figure 8 show differences in vertical and horizontal permeabilities from plugs and whole cores, respectively. Plug data in figure 7 shows a tendency towards slightly higher vertical permeability for cores below 100 mD. As for cores higher than 100 mD, the plug data shows higher horizontal permeability than vertical data. Such a variation or scatter in permeability is absent from the whole core data in figure 8. The whole cores give an overall tendency towards slightly higher horizontal permeabilities than vertical data over the entire permeability range. Whole core data seems to average the high and the low permeability zones into the overall volume, showing less scatter between Kv and Kh, and thus more representative permeability variations.

Capillary Pressure and Electrical Properties

Whole cores from well E were shown to produce lower cementation factor “m” values than adjacent plugs. Composite “m” value for the whole cores was 1.94 compared to the composite plug value of 2.12 (see figure 11) [1]. This was shown to have a significant impact on STOOIP calculations. Figure 9 shows initial (preliminary) primary drainage capillary pressure (Pc) curve from whole core sample #2 together with Pc curves from two adjacent 1.5” plugs (sample #3 and #4). The figure also compares mercury injection derived scaled Pc curves measured on corresponding trims from the plug samples. There is a reasonable match between the plug porous plate curves and the mercury injection Pc curves. Whole core Pc data shows an overall good match with the plug data in the available early part of the curve. However, plugs went down to lower water saturations at the same Pc step, suggesting differences in the pore sizes and perhaps pore throat size distributions between whole cores and plugs which can influence the desaturation path. Whole core Pc measurements by porous plate take exceedingly long time to establish equilibrium conditions at each Pc step. The whole core measurements are still ongoing, but it is interesting to notice the overall similarity between the whole core and plug Pc data. A full picture on the multi-scale behavior will be possible after the complete primary drainage test on that particular sample, and the other whole core samples from different reservoir rock types. Figure 10 gives corresponding resistivity index curves for the two plugs and the whole core sample (initial measurements only) which are acquired simultaneously with the Pc measurements in the porous plate setup. The plugs and the whole core were chosen from the same petrophysical rock type for effective comparisons. The available early part of the RI-Sw curve from the whole core shows similar behavior to the plug data, but there is a marginal increase in the calculated saturation exponent “n” from the whole core subject to the higher Pc steps. Such results from whole cores and plugs are important and may have large impact on STOOIP calculations and reservoir core characterizations.

CONCLUSIONS

1. Whole core measurements in heterogeneous systems tend to average rock poroperm properties better and give more representative data.
2. Whole core porosity tends to be lower than porosity from 1.5” diameter core plugs. The porosity variation cannot be attributed to surface/volume variation between big and small samples (when comparing WC to 1” diameter samples). Local heterogeneity may be the key element in this variation but further investigation may be needed to confirm other possible influencing factors.
3. The variations and scatter between whole core and plug permeabilities (both Kv and Kh) are significantly less compared with the measured porosities. Overall, the whole core permeabilities tend to be marginally higher than the core plug data.
4. Permeabilities from 1” plugs are generally lower than whole core data which suggests 3D connectivity and flow paths are probably better captured in the larger whole core volumes which could exploit optimal connection pathways.
5. Small plugs can also yield higher permeabilities than corresponding whole cores by short-circuiting flow through porosity channels. The main controlling factor is local heterogeneity.
6. Anisotropy in core plugs gave wider scatter in the Kv - Kh data, compared with whole core measurements. Core plug data showed higher vertical permeabilities than horizontal data, not evident from whole cores. The whole core Kv – Kh data averages the permeability measurements better (and hence less scatter), and thus probably show more representative carbonate reservoir behavior.
7. Although cementation factors ‘m’ measured on whole cores were found lower than corresponding core plug samples, the primary drainage capillary pressure and resistivity index, and hence saturation exponents ‘n’ may show different behavior in multi-scale measurements.
8. Initial data from whole cores show similarities in Pc and RI curves with core plug data. However, there are other differences which need to be addressed in more details once the ongoing tests are complete.

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2. Ehrenberg, S.N., 2007, Whole core versus plugs: Scale dependence of porosity and permeability measurements in platform carbonates: AAPG Bulletin, V. 91, NO. 6 (June 2007), pp. 835 – 846.

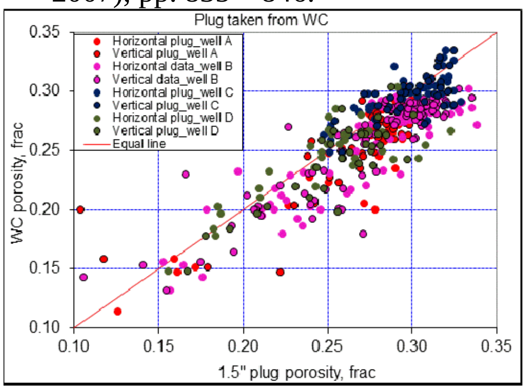

Figure 1 WC vs 1.5” plug porosity – all wells

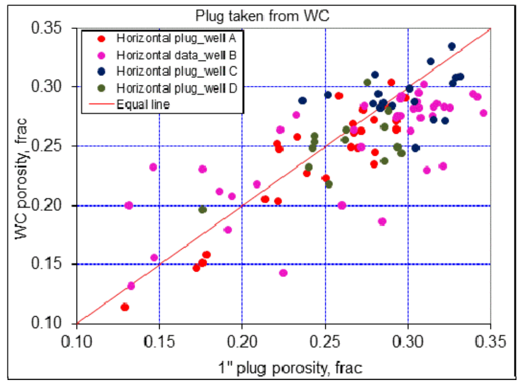

Figure 2 WC vs 1” plug porosity – all wells

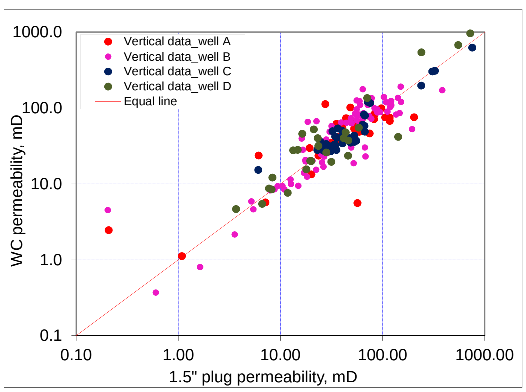

Figure 3 WC vs 1.5” plug Kv – all wells

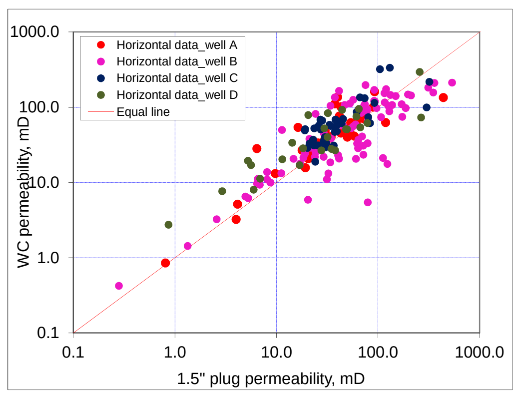

Figure 4 WC vs 1.5” plug Kh – all wells

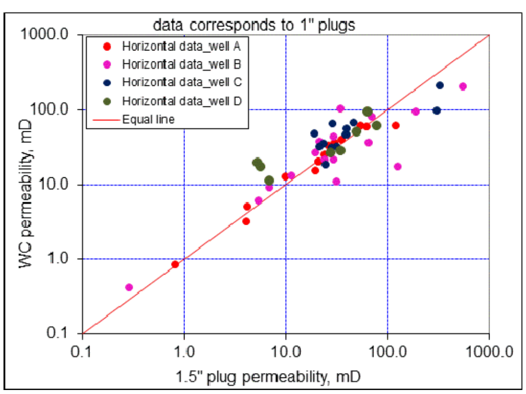

Figure 5 WC vs 1.5” plug Kh (corresponds to 1” plugs)

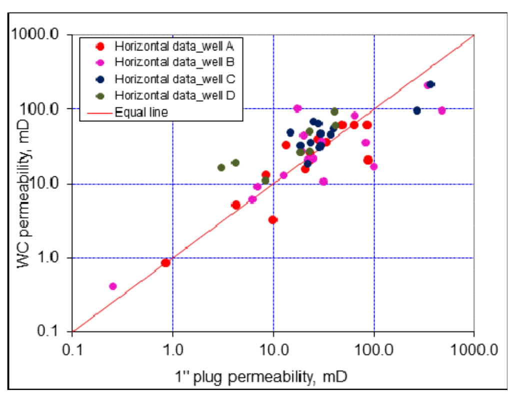

Figure 6 WC vs 1” plug Kh – all wells

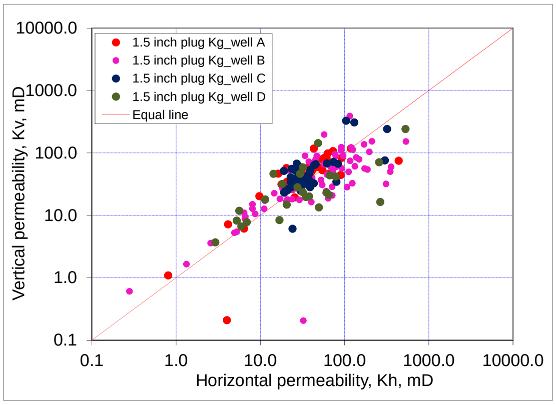

Figure 7 Kv vs Kh – plugs (Anisotropy)

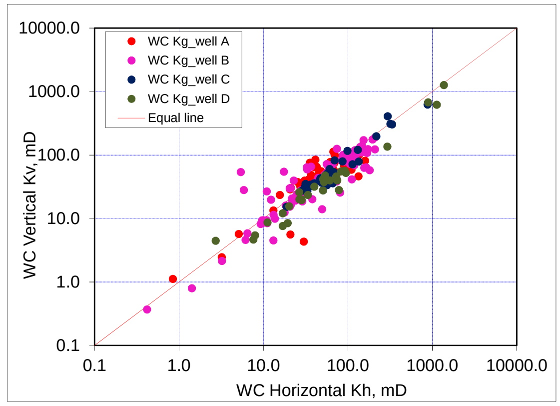

Figure 8 Kv vs Kh – WC's (Anisotropy)

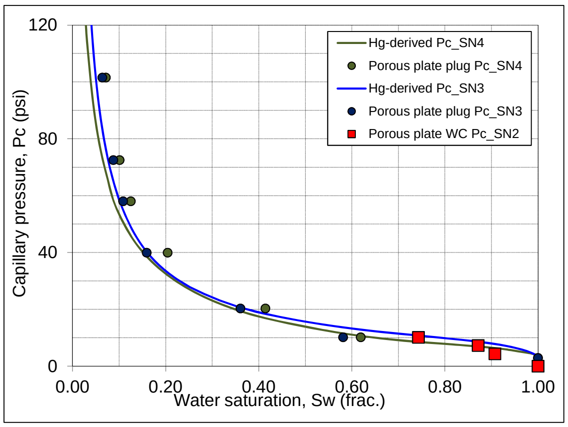

Figure 9 WC, adjacent plugs and Hg Pc curves (well E)

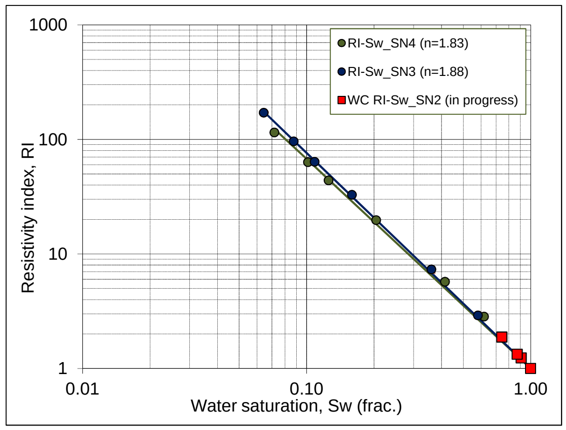

Figure 10 WC and adjacent plug RI-Sw curves (well E)

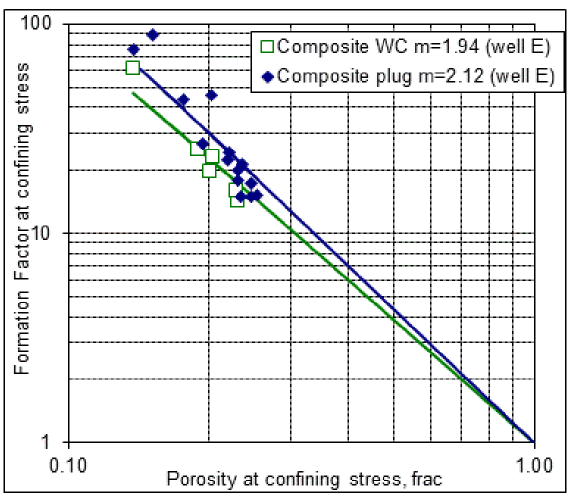

Figure 11 FF vs porosity for WC and plugs (well E) [1]