CAPILLARY PRESSURE AND RELATIVE PERMEABILITY ASSESSMENT ON WHOLE CORE SAMPLES FROM A GIANT MIDDLE EASTERN CARBONATE RESERVOIR UTILIZING DIGITAL ROCK PHYSICS

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ABSTRACT

Digital Rock Physics (DRP) has significantly evolved in the last few years and added invaluable contributions in improving core characterization and in providing high quality advanced SCAL measurements, emphasized through various studies/papers (SCA-2012-03 Kalam et al). This paper represents a unique DRP SCAL study that includes primary drainage capillary pressure (Pc) as part of Swi establishment and relative permeability (Kr) measurements done on four whole core (WC) samples from two different carbonate formations with a stylolite layer in between. The aim of the study was to evaluate how DRP results would compare with physical SCAL measurements done – on the same WC samples as a composite, as well as on plug samples from the same formations/layers – in a leading international core analysis lab in USA. The DRP results were up-scaled to the individual WC level and compared with the SCAL results from the corresponding layers. The DRP technology in this study also provided the capability of up-scaling the results to the WC composite which was used by the lab to assess the effect of the stylolite layer on the water flood. The comparison showed excellent matches between the physical and DRP-derived Pc and Kr data. The paper outlines the DRP methods used to determine the SCAL properties of the three formations. The laboratory measurements of SCAL properties took six years while the DRP work that followed blindly (without any knowledge of the laboratory results) was completed in six months. This demonstrates the effectiveness of the DRP technology in providing high quality SCAL data in a timely fashion regardless of sample size. Impact of possible wettability changes and sensitivities on one of the WC composite constituent component was also easily established unlike the high risk laboratory tests. This is the first water-oil displacement validation study results on reservoir whole cores of four inch diameter at full reservoir conditions using DRP.

INTRODUCTION

The DRP SCAL was initiated on four carbonate WC samples from Middle East. The work included computations of primary drainage Pc to insure that pore geometry (pore throat size distribution) has been properly captured for representative initial water saturation (Swi) establishment; in addition to Kr measurements (imbibition and secondary drainage). All data were up-scaled to the individual WC scale as well as to the composite WC scale. The WC composite included the four WC samples and was designed to resemble the vertical geological structure of the reservoir (WC1 came from top carbonate formation, WC2 came from the stylolite layer, WC3 & WC4 came from the bottom carbonate formation). Figure 1 shows schematic illustration of the WC composite. The DRP program followed a previous conventional SCAL study that included Pc and Kr measurements on individual plugs and plug composites from the same reservoir layers in addition to a WC water flood on the same WC composite.

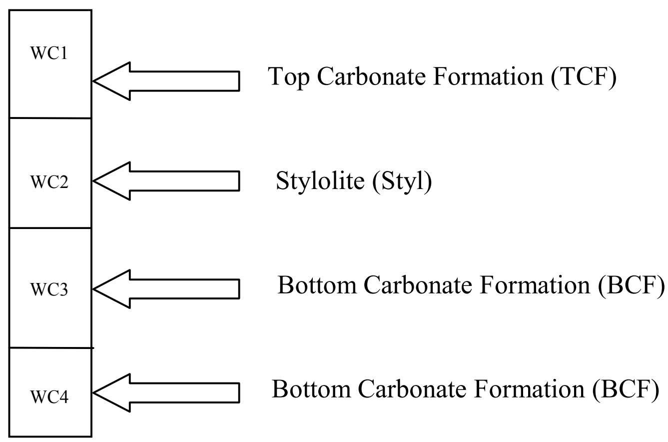

Figure 1 Schematic illustration of the whole core composite

METHODOLOGY

The workflow that was followed to generate the DRP results started with whole core dual energy CT scanning which in turn was used to identify the main flow unites followed by extraction of sub-samples at increasing resolution to describe the pore structure. When the needed pore structure was defined and properties computed; the individual sub-sample results were up-scaled to the required volume. In this case, the up-scaling was made to the individual WC sections as well as to the WC composite.

Plug selection and scanning: whole core CT scanning was the first step in selecting proper plugs. Upon plug acquisition, the samples were CT scanned at much higher resolution than the whole cores to assess their suitability.

Sub-sample selection: The 3D images of the selected plugs (for the DRP work) were segmented to identify different flow units. This segmentation identifies the macro-pore systems and the large scale connectivity of the flow units in the plug. Each segmented region was a target for sub-sampling.

Multi scale micro and nano imaging: The rock pore system was resolved using multi-scale micro-CT data at voxel resolutions down to 0.5microns. Micro-porosity structures such as micrite required nano-CT data at 0.05microns. The multi-scale imaging process provided registration of image volumes and therefore the direct association of computed properties with the spatial location of the sub-samples used in up-scaling.

CAPILLARY PRESSURE AND RELATIVE PERMEABILITY

Primary drainage Pc curves were computed using Lattice Boltzmann method at all scales that have directly detectable porosity. The up-scaling model accounts for the presence of detectible porosity at all scales and honors the spatial distribution of all scales within the up-scaled volume. This method allowed computations of primary drainage Pc curves at WC scale. Figure 2 shows the DRP computed Pc for each WC sample with the corresponding experimental Pc curve (by centrifuge) on plugs from the same formation layer.

For relative permeability simulations, **t**he DRP process used in this program is based on steady state fractional flow method. Wetting conditions "mixed to oil wet" were established based on previous experience and knowledge of the reservoir properties and wettability characteristics; this knowledge was developed through several previous SCAL programs that included extensive relative permeability and Amott-USBM measurements. The Kr measurements in his study included imbibition and secondary drainage cycles. The Kr data was up-scaled to the individual WC level as well as to the WC composite. The composite DRP Kr computations assumed two scenarios. Scenario 1, where the stylolite layer had similar wettability conditions to the other WC samples in the composite (mixed- to oil-wet). Scenario 2, where the stylolite layer had more affinity to water (assuming the tight stylolitic pores remained water wet) compared to the other whole cores. Figure 3 shows the DRP computed imbibition Kr curves for each WC with the corresponding measured lab Kr on plugs and plug composites from the same formation layer. Figure 4 shows similar comparison in secondary drainage mode. Figure 5 shows the DRP computed imbibition Kr on the WC composite in both scenarios. The DRP Kr test on the WC composite represented a vertical core flood through the stylolite layer which dominated the flow but did not block it.

SUMMARY AND DISCUSSION

<u>Capillary pressure:</u>

Whole core DRP primary drainage Pc curves show reasonable match with the lab Pc data given that it was measured on plugs (from the same formation layers); in another word, the observed minor differences between both measurements could be attributed to the difference in samples and to the difference in scale (DRP was done on whole cores while lab measurements were done on plug samples from the same formation layers). Saturation end points (Swi) from DRP are very close or within the same range reported by the lab measurements. Figure 2 shows comparison between the DRP and the lab derived drainage Pc for each WC sample. This confirms that the pore geometry has been properly characterized by DRP.

<u>Relative permeability:</u>

1. The imbibition Kr data (both Kro & Krw) show reasonable match between DRP and lab, except the stylolitic layer where the lab data shows much higher Krw compared to DRP (middle plot in figure 3). The lab imbibition Krw trend and end point (Krw = 0.68) indicate strong oil wetness (or high permeability sample). The reason for this behaviour should be further investigated by the lab taking into consideration the tight nature of the stylolitic zone. On the other hand, the DRP Krw trend and end point (Krw = 0.26) seem to be more compatible with the simulated mixed wettability and with the tight nature of the stylolitic zones that could remain water wet.

2. Secondary drainage Kr shows good match between DRP and lab data in the upper and lower layers in the reservoir. Secondary drainage Kr was not measured in the lab on the stylolitic layer sample (figure 4).

Whole core composite:

3. The imbibition (upscaled) WC composite Kr was simulated assuming two scenarios. Scenario 1: where the stylolitic layer had similar wettability conditions (mixed- to oil-wet, contact angle = 130 deg) to the remaining composite components. Scenario 2: where the stylolitic zone only remained water-wet (contact angle = 30 deg), which traps oil during water injection and reduces Krw; figure 5 shows both simulated scenarios.
4. The same WC composite was previously subjected to laboratory unsteady state water flood experiment at full reservoir conditions to investigate if the stylolitic layer was permeable to fluid flow; however there was no steady state measurement done in the lab on this composite. Hence, there would be no possible data comparison between lab and DRP in this case.

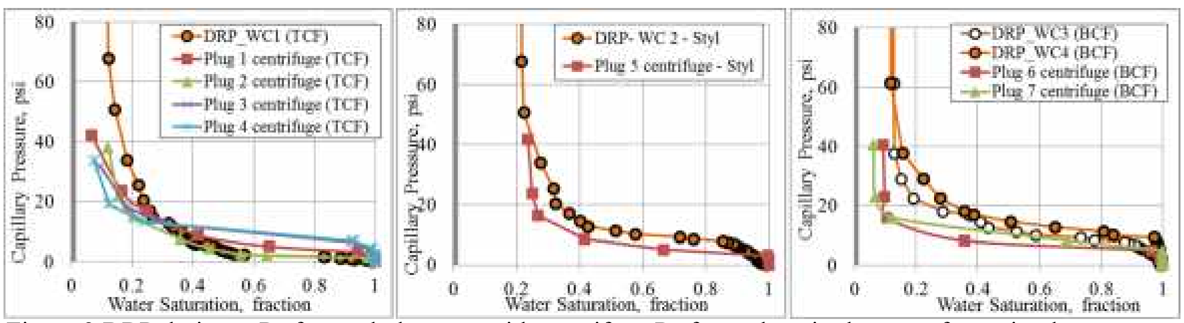

Figure 2 DRP drainage Pc from whole cores with centrifuge Pc from plugs in the same formation layer

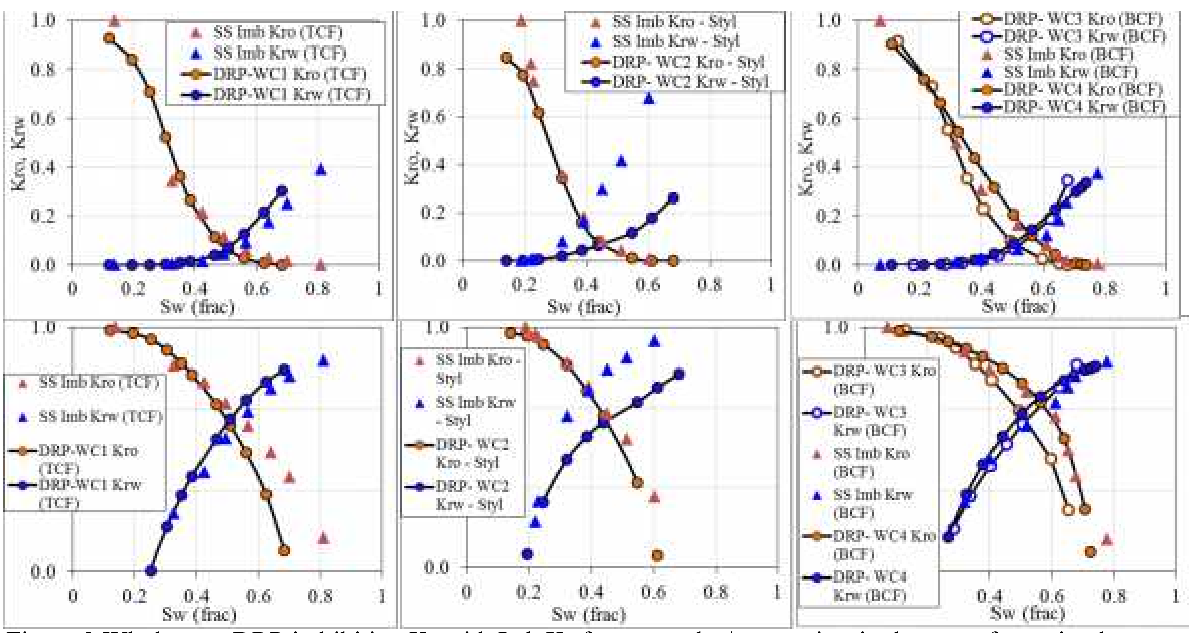

Figure 3 Whole core DRP imbibition Kr with Lab Kr from samples/composites in the same formation layer

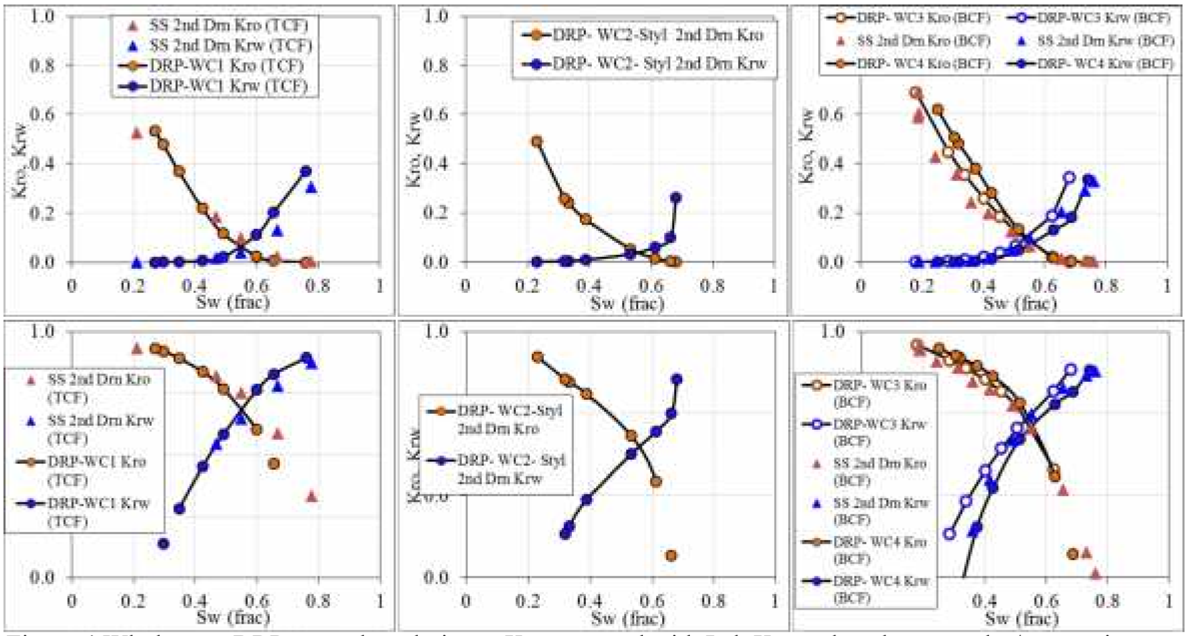

Figure 4 Whole core DRP secondary drainage Kr compared with Lab Kr produced on samples/composites from the same formation layer

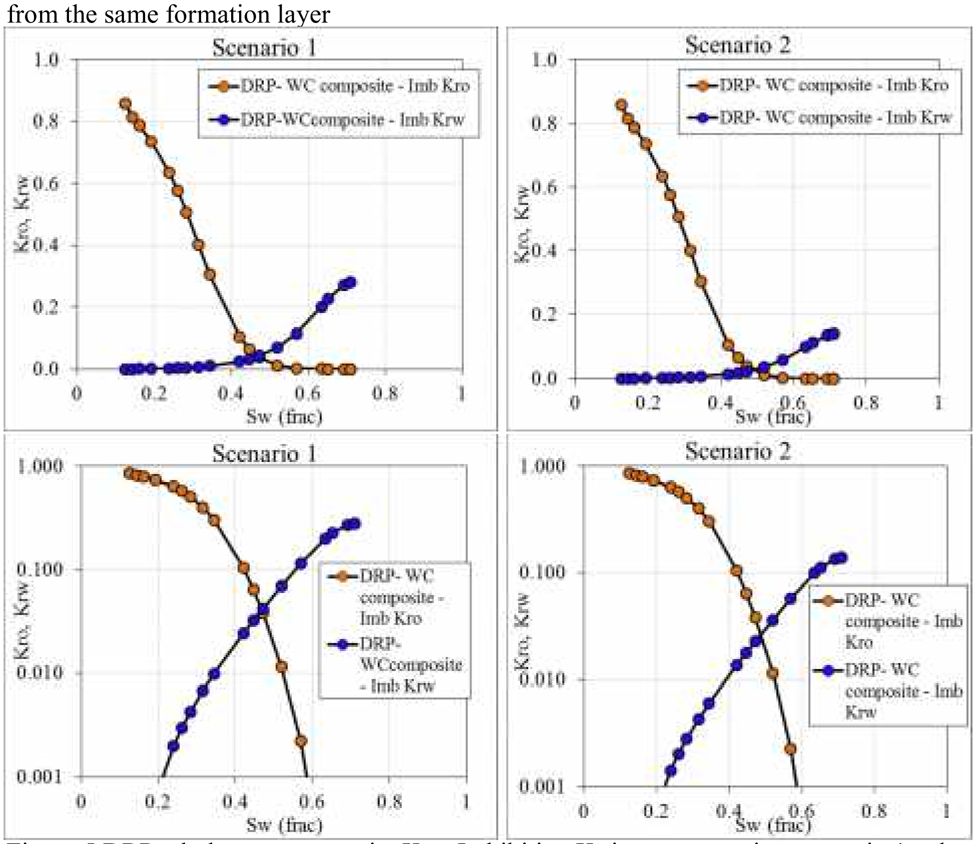

Figure 5 DRP whole core composite Kr – Imbibition Kr in two scenarios: scenario 1, when the stylolite layer has similar wettability conditions to the remaining composite constituents; scenario 2, when the stylolite layer remains water wet with respect to the other constituents.

CONCLUSIONS

1. First finding was that the stylolitic layer is permeable for single and multi-phase flow. It does not act as a barrier. The same was concluded from the lab water flood.
2. The DRP computed SCAL properties from whole cores showed good match with the physical lab measurements conducted on plugs and plug composites from the same formation layers.
3. The DRP technology provided high quality advanced SCAL measurements in a significantly shorter time compared to conventional labs. The laboratory measurements took six years while the DRP work was completed in six months.
4. The DRP technology gave the opportunity to run the Pc and the Kr measurements at full reservoir conditions on the same samples at whole core and whole core composite scales; which is very difficult and impractical to apply in a physical lab.
5. The DRP technology allowed the investigation of various wettability scenarios on one of the whole core composite constituents and its impact on the composite Kr results. Such investigation was easily established unlike the high risk laboratory tests where such sensitivity analysis might take several more years to conduct.

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