BUILDING ANALOG CONFIDENCE FOR RELATIVE PERMEABILITY THROUGH SYSTEMATIC APPROACH ACROSS MAJOR MIDDLE EASTERN CARBONATE FIELDS

Maged Yaslam and Zubair Kalam, Abu Dhabi Company for Onshore Oil Operations

This paper was prepared for presentation at the International Symposium of the Society of Core Analysts held in Avignon, France, 8-11 September, 2014

ABSTRACT

Relative permeability (kr) is crucial in terms of hydrocarbon proliferation (field development) and handling fluids through sophisticated mega surface facilities, in which it significantly contributes to projects success or failure. Due to time, cost and effort in obtaining reliable kr data, especially in case of exploration and undeveloped fields, reservoir engineers depend on "Analog" concept with nearby similar and representative reservoirs. It is even more challenging while dealing with carbonate heterogeneous reservoirs, where rock properties and wettability conditions are not necessary aligned in certain trend. Therefore, validation and level of confidence for the analog data is a challenge for representative models outcomes.
A major oil company in the Middle East region, initiated a large scale internal review aiming to consolidate a representative analog kr profiles across various fields with tens of billions OOIP. The available data were accumulated for over 30 years that included many laboratories, techniques and analyses approaches. The objectives were to produce a kr catalogue that will be used as a reference for new exploration fields and also to support the current performance predictions for the developed ones. A comprehensive approach was adopted in the analysis for different reservoir rock types (RRTs) to be clustered based on reservoir rock properties, capillary pressure profiles, wettability indices, saturation end points and rock/fluid saturation indices such as 'm' and 'n' factors.

Detailed SCAL data were collected and fully analyzed for 4 main fields with various Reservoir Rock Types (RRTs), which exhibit wide range of permeability variation from 0.1 to 1000 mD. Total of 46 water flood kr profiles (primary imbibition) were included in the review, in which they were assigned to different groups based on several discriminators. Blind tests were then performed on different sets of kr data to assess the validation of the proposed analogs.

Relative permeability profiles may possibly be distinguished and grouped, based on RRT and/or Petrophysical Group (PG) characteristics. Proposed "Analog" kr catalogue was an outcome of this investigation, which is a good reference and adds more confidence to modeling of reservoir fluids dynamics. Generally, it has been observed that lower reservoir quality RRTs were well defined with less profiles variation compared with the better quality RRTs. In addition, this catalogue can be used as a guide in designing and quality assurance for laboratory SCAL experiments, as well as providing 'initial' kr data for fields which are yet to be analyzed.

INTRODUCTION

Obtaining reliable experimental SCAL relative permeability profiles was a continuous historical challenge in various reservoir rock types in the field, due mainly to the duration of the full process and level of associated uncertainties. The average duration of SCAL PROJECT was ranging from 2-3 years, including the early preparation and communication cycle between the company and the vendor to the final results submission. In addition, the experiments themselves have their own level of uncertainty especially in carbonate reservoirs that ranges from plug preparation/ageing to the selected method of measurements. Comprehensive analysis of the relative permeability experiment method (Steady State and Un-Steady State) has been carried out to identify the most representative method under certain field conditions for more reliable profiles [1]. “Analog” data with nearby reservoirs under similar conditions has been generally used to fill any gap in the data set. However, in many cases the data can be false if the analog process was not adopted perfectly. Accordingly, an internal review has been initiated to reveal kr analog opportunity among the different fields of similar formation within the company. The ensuing review is expected to support the following objectives:

- Development plans/predictions reliability: water flood kr profiles are critical inputs in the dynamic models in which they control the fluids movements within the reservoir and will have impact on predicted production/water trends and ultimately the final oil recovery.
- Catalogue a consistent analog across company portfolio: ultimate objective of the review is to produce such catalogue(s) for the different reservoirs based on various reservoir characteristics (absolute permeability, reservoir quality index, MICP …etc.). This can be fundamental input in modeling the new explored reservoirs where analog is the only source of the data, until related SCAL measurements are available.
- Essential for any EOR/IOR project: having reliable kr profiles (particularly secondary drainage) is essential to properly model the EOR/IOR projects with anticipated increase in recovery factor.
- QA/QC for SCAL experiments: it will help to support the future data acquisition, and identify deviations from the trend (if any) with proper justification.

METHODOLOGY

The relative permeability Analog methodology and process has been tailored based on the quantity and quality of the available data, as follow:

- Stage 1 (Gathering & Review of last 12 years SCAL experimental data): total of 46 water-oil relative permeability profiles were validated and considered in the review comprising 4 different carbonate reservoirs from the same formation. These experiments were conducted under full reservoir conditions (wettability, reservoir fluids, pressure and temperature using in situ saturation monitoring). It is worth mentioning that reservoir fluids of these fields showed certain level of similarities.

- Stage 2 (Comprehensive profiles analysis) : each of the relative permeability profiles has been analyzed individually considering Swi, Sor, method of measurement and modeling outcomes for some of them. Normalization process has been performed in the following form [2],

$$\text{Sw "Normalized"} = \frac{\text{Sw}-\text{Swi}}{1-\text{Swi}-\text{Sor}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (1)$$

- Stage 3 (Categorization of profiles): there are several factors affecting kr, in which it includes static characteristics (rock properties), fluid properties and dynamics interaction behaviors (wettability, electrical properties...etc.). Rock/core properties were considered in this review, as it describes the internal pores structure and also has minimum associated uncertainty level. In addition, wettability measurements (USBM/Amott Harvey) could not be performed on the kr core plug/composite as these were done at full reservoir conditions, going through both imbibition and drainage displacement cycles. Limited wettability measurements were performed on similar rock type; this is subject to more detailed review for a future publication. It should be noted that the carbonate plugs show a wide variation in wettability measurements even from same rock type. The considered core samples in this review were extensively cleaned using a three-stage flow through cleaning sequence - toluene, methanol and azeotrope [2, 3]. All the samples were restored using live crude at full reservoir condition for 3 weeks (or more) with permeability checked every week to ensure full restoration.

  Accordingly, based on plug/core characteristics the profiles were categorized considering three levels, as follow:

  - ❖ Absolute permeability (K): overall characteristic to represent the flow resistance
  - ❖ Reservoir Quality Index (RQI): the term is defined as follows [5],

    $$\text{RQI} = 0.0314\sqrt{\frac{K}{Phi}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ \ldots\ldots\ldots..\ (2)$$

    This index has been considered since in carbonate reservoir porosity and permeability are not necessary to follow a certain classical trend and accordingly this index will capture the variation of both porosity and permeability in a more synergistic manner.

  - ❖ Pore Throat Size (PTS) Distribution through Mercury Injection Capillary Pressure (MICP), which will provide details of internal pores geometry and connectivity. This is also the classical basis of pore type classification in carbonates.
- Stage 4 (Analog verification): as a blind test to verify the categorized data, a set of the data that has not been included in earlier process was used at this stage to assign the level of uncertainties associated with the final outcomes.

RESULTS & DISCUSSION

The data has been gathered and reviewed from 4 major producing carbonate fields, in which total of 46 water-oil kr profiles were obtained and included in the analog outcomes. The tests details, such as core plug/composite and experiment type is summarized in table 1.

Field Name	Num. of profiles	Kr Experiment Type
Field A	6 plugs	Steady State
Field B	5 plugs/1 comp.	Steady State
	7 comp.	Un Steady State
Field C	10 plugs/1 comp.	Steady State
	10 plugs	Steady State
Field D	6 plugs	Un Steady State

Table 1: Summary of reviewed data

These high quality full reservoir condition kr profiles with live fluids were produced during the last 12 years with significant total expenditure in millions of dollars. Each of the profiles was examined comprehensively to ensure proper core preparation (cleaning, ageing procedure), utilization of reservoir live fluid, full reservoir conditions (pressure and temperature), method of measurements (USS and SS) and numerical modeling to mimic the experiment procedure and verify the outcomes. Also, each kr data set were rigorously checked and corrected for possible capillary pressure end effects, and numerically simulated for consistency in oil production, pressure drop and in situ saturation of brine [2, 3, 4]. Only the accepted data were analyzed to develop the current analog profiles. They were categorized using the different discriminators (as explained in methodology section).

Figures 1-3, show the grouping of the kr profiles using just the absolute permeability as a discriminator.

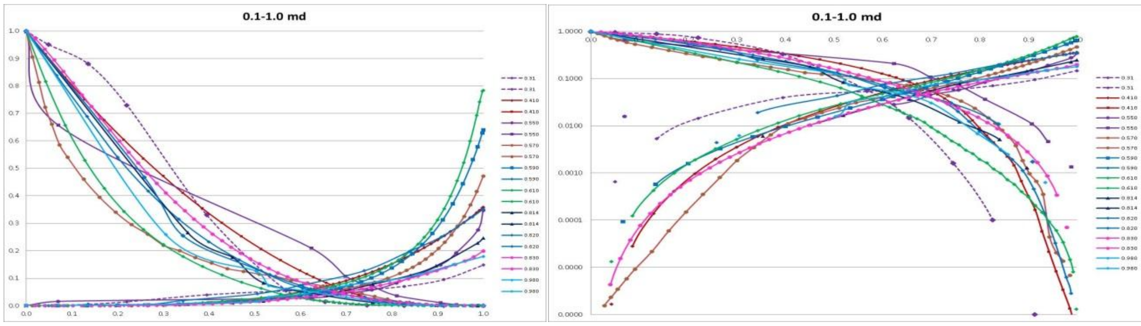

Figure 1: K range of 0.1 – 1.0 md (linear and semi-log scale)

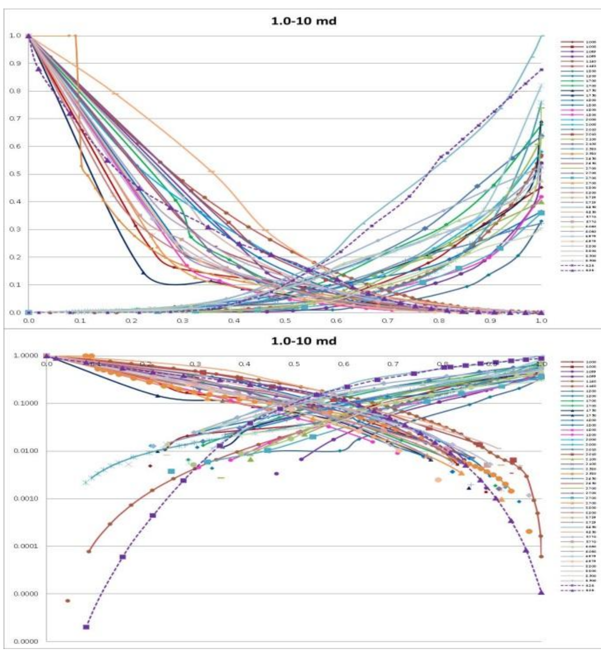

Figure 2: K range of 1.0 – 10 md (linear and semi-log scale)

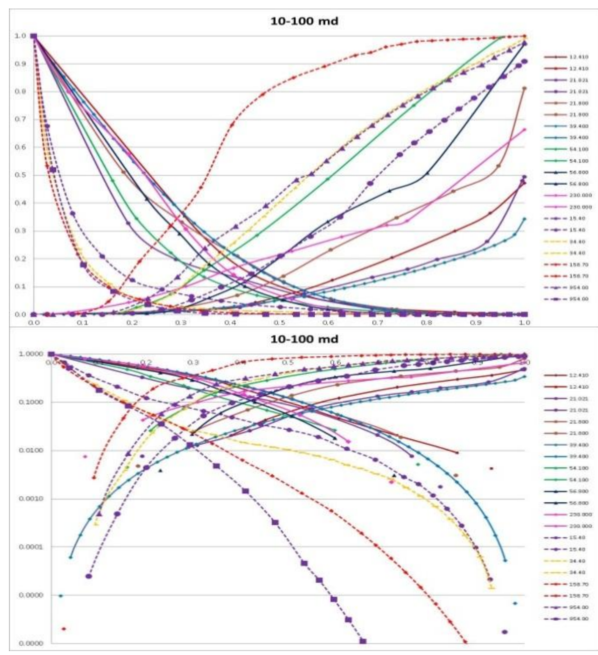

Figure 3: K range of 10 – >100 md (linear and semi-log scale)

The results showed that lowest permeability range as in figure 1 (0.1-1.0 md) has less level of uncertainty and data variation, in which the profiles are close to each other. However, with increase of the permeability range, the profiles are getting apart and uncertainty level is dramatically increased as in figure 3. This might be associated with increase and pronounced effect of dynamic interaction behaviors (wettability conditions) within the pores network, in which they exhibit different levels of mixed wettability conditions (small size pores are water wet and large size pores are oil wet). This is consistent with level of local heterogeneity; $K < 1$ mD is generally most homogeneous while k > 10 most heterogeneous. Dernaika and Kalam [6] also observed changes in Corey coefficients derived from the water-oil relative permeability curves with differences in the pore geometry and/or RRT, as expected from the reservoir characterization data.

Considering the RQI as discriminator, figure 4 captures the variations observed across six defined ranges from the reviewed data set. The data suggests more refined categories with better range of profiles within each of them. It also revealed that getting towards the better reservoir characteristics (higher value of RQI) the profiles turned to exhibit more oil-wet tendency; this is mainly based on Craig's Rule of Thumb – the kr intersection point, and end-point Swi and Sor values. This is explicable in terms of pore geometry, the smaller pores with K < 1 mD and RQI < 0.15 is more water-wet compared with reservoir cores of larger pores with K > 10 mD and RQI > 0.3 which show more oil-wet characteristics. Similarly, samples with 1 < K < 10 mD show more intermediate-wet behavior where competing pores of water and oil wet characteristics dominate flow behavior. Hence, there are two distinct extremes, one with RQI 0.047 - 0.07 and another with RQI > 0.4.

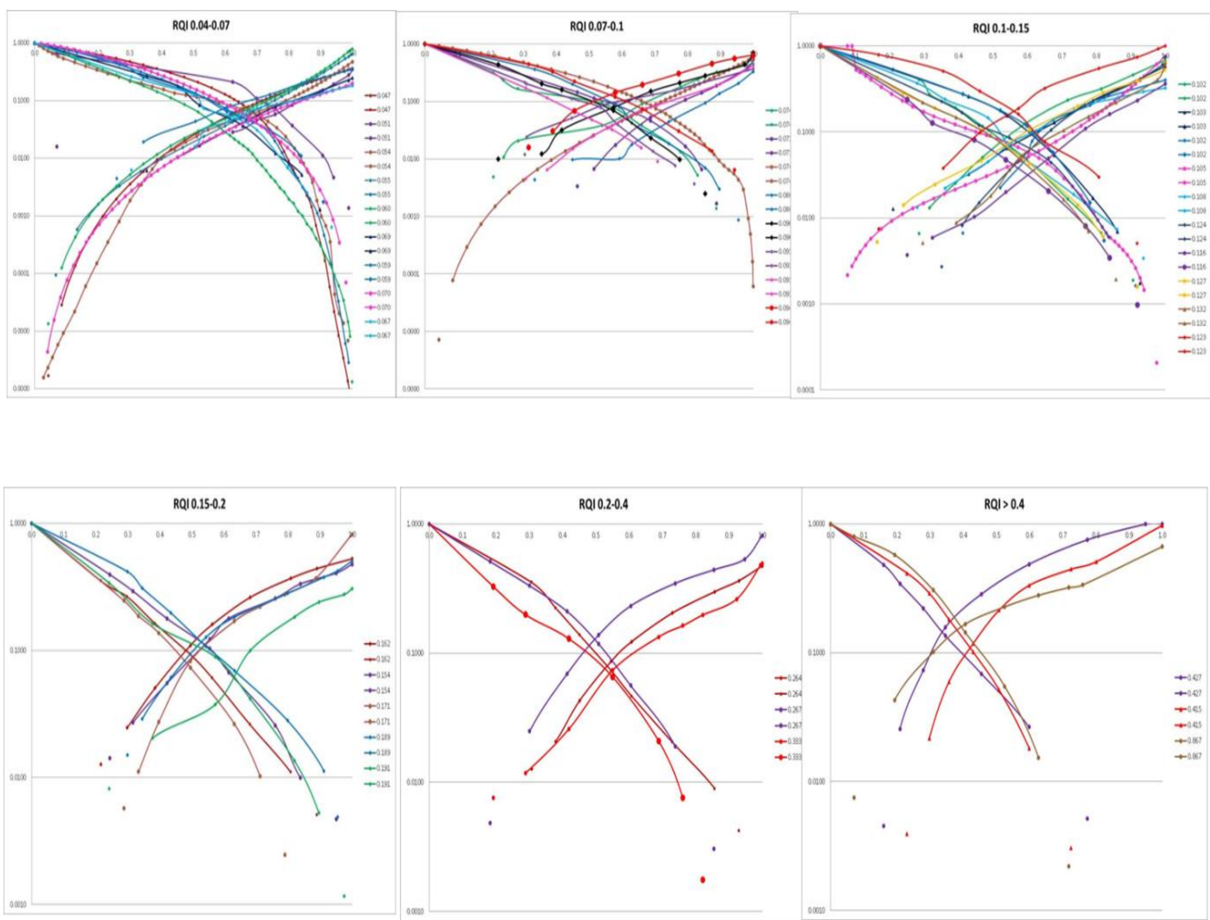

Figure 4: RQI summary comparison (semi-log scale)

To further consolidate the RQI analysis, PTSD data have been incorporated using MICP outcomes, as shown in figures 5-6 for the two extremes, one with RQI between 0.047-0.07 (figure 5) and another for RQI > 0.4 (figure 6). Figure 5 shows that PTSD for this category is generally uni-modal distribution and ranges from 0.5 to less than 1.0 microns. This explains the good match between the different profiles in this low range of RQI and permeability as well. However, looking to the other extreme, where RQI is considered high with good reservoir characteristics, figure 6 indicates most of the plugs are bimodal (or tri-modal) with higher PTSD value of 5 microns. Accordingly this data suggests that with RQI range > 0.4, the produced profiles are expected to have very high level of uncertainty and confidence in analog utilization, typical of the prolific carbonate RRTs.

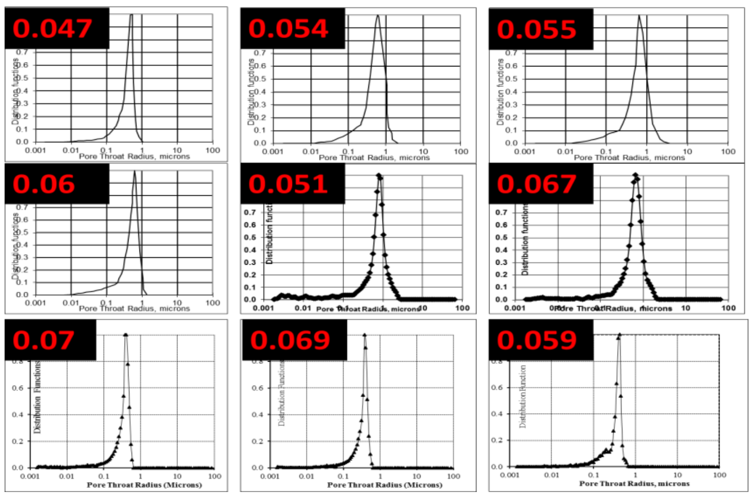

Figure 5: PTSD distribution comparison for RQI cases less than 0.07 (semi-log scale)

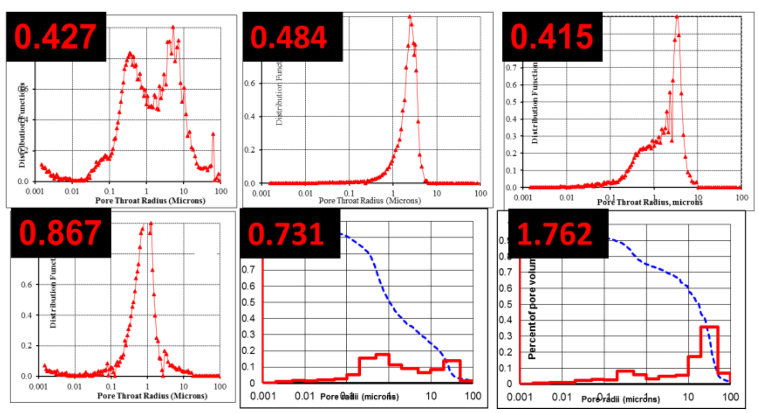

Figure 6: PTSD distribution comparison for RQI cases more than 0.4 (semi-log scale)

Figures 7-10 show PTSD profiles of the intermediate RQI ranges, comprising the analyzed core samples. It is evident that the pore throats are largely uni-modal and approach 1 micron with RQI close to 0.2, while those exceeding 1 micron meter have broader pore throat distributions.

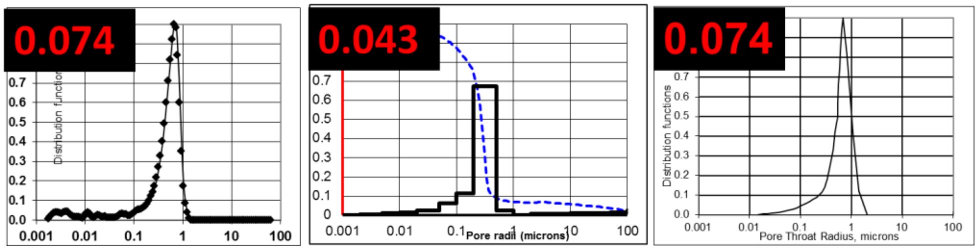

Figure 7: PTSD distribution comparison for RQI cases 0.04-0.07 (semi-log scale)

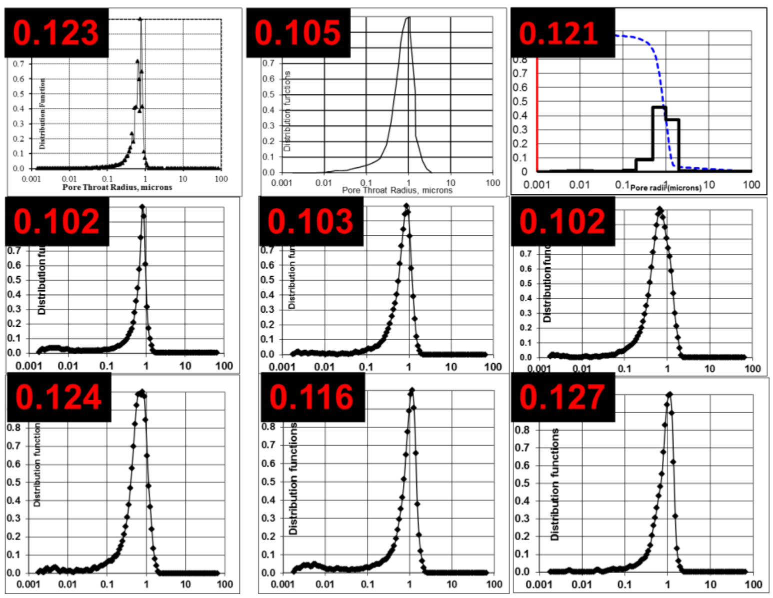

Figure 8: PTSD distribution comparison for RQI cases 0.10-0.15 (semi-log scale)

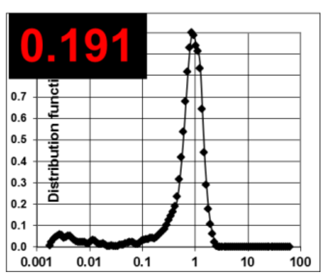

Figure 9: PTS distribution for RQI cases 0.15-0.2 (semi-log scale)

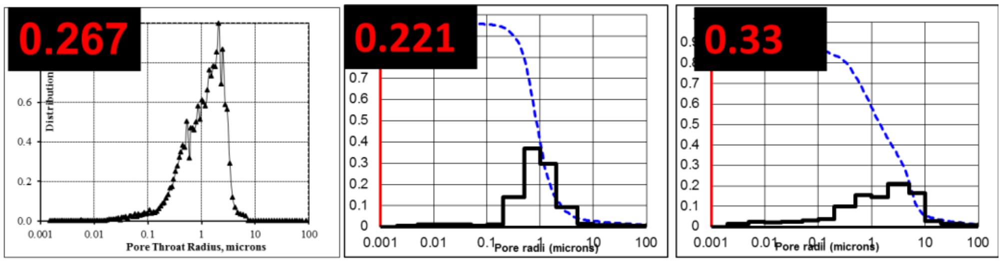

Figure 10: PTS distribution for RQI cases 0.2-0.4 (semi-log scale)

A blind test has been carried out to test the uncertainty level associated with each of the analog profiles. For each of the categories a certain range of uncertainties have been identified based on kr profiles variations (yellow shaded area). Figure 11 shows 3 test cases that lie in RQI range of 0.1-0.15, in which they have valid experimentally established kr profiles. The blind test results of figures 12-14 show the same consistent trends; RQI 0.2 – 0.4 more oil-wet as in figure 12 while RQI 0.04 – 0.07 (figures 13-14) show distinct water-wet behavior.

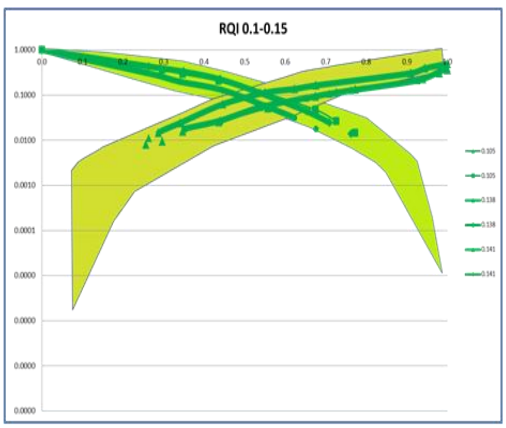

Figure 11: Blind test of analog profiles RQI 0.1-0.15 (semi-log scale)

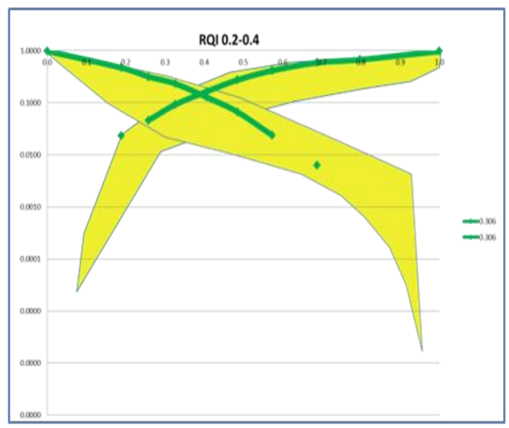

Figure 12: Blind test of analog profiles RQI 0.2-0.4 (semi-log scale)

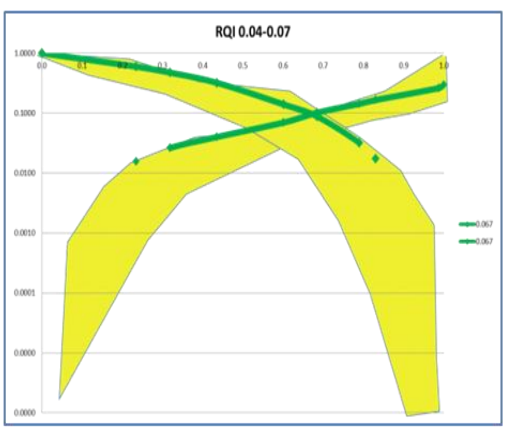

Figure 13: Blind test of analog profiles RQI 0.04-0.07(semi-log scale)

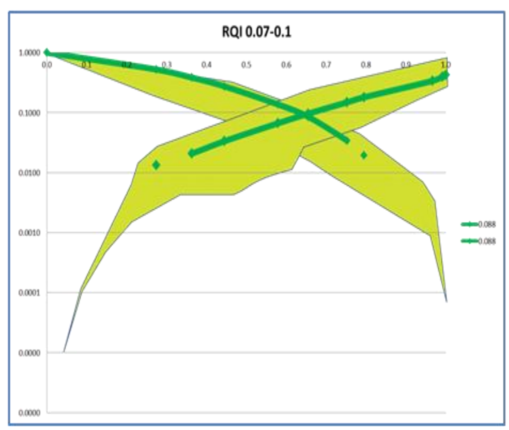

Figure 14: Blind test of analog profiles RQI 0.07-0.1(semi-log scale)

CONCLUSIONS & WAY FORWARD

Analog relative permeability profile is important in developed reservoirs as well as new exploration activities to have more reliable predictions. Different levels of discriminators can be used to categorize the reference data until certain agreed level of accuracy is achieved. Based on the data presented in this paper, clear trends in water-oil relative permeability profiles have been identified with respect to both permeability and RQI. It has been revealed that laboratory experiments reliability and analog level of uncertainty is associated with reservoir characteristics, in which low and medium RQI RRT's are well defined, but the better (prolific) RRT's exhibit wider range of kr & heterogeneity using available limited data. Accordingly, these categories can be used effectively to support analog exercise in homogenous lower quality reservoirs and more data and work is needed to refine the heterogeneous better quality RRT's. The analog profiles respect the lower and maximum limits of the category, in which the produced analog Kr profile will be covering the uncertainty level through probability distribution concept with P10, P50 and P90 cases.

As a way forward, we propose to improve the analog with the following:

- Once sufficient kr profiles are available, obtain certain correlation within each category to cover the range of the anticipated data limits.
- Integration of other SCAL measurements, such as NMR and Pc RI along with impact of depositional effects in the analysis. These inputs will help in further refinements of the categories and possibly narrowing the range of the profiles within each category.
- Generalize the trends to include other reservoirs and formations in the region with similar depositional environment.

ACKNOWLEDGMENT

The authors would like to extend their gratitude and thanks to Abu Dhabi National Oil Company (ADNOC) and Abu Dhabi Company for Onshore Oil Operations (ADCO) for the permission and support to publish the paper. Also special thanks to Mohamed Al Hammadi for the initial analysis of kr variations with respect to permeability.

REFERENCES

1. Yaslam MM, Ghedan S and Kalam MZ (2013), "Revealing Relative Permeability Uncertainties through Integrated Experimental and Modeling Workflow for Giant Carbonate Field in the Middle East: A Case Study", at Reservoir Characterization and Simulation Conference (RCSC), Abu Dhabi, 2013.
2. Spearing MC, Cable AS, Element DJ, Goodfield M, Dabbour Y, Al Masaabi AR, Negahban S and Kalam MZ (2004). "A Case Study Of The Significance Of Water

Flood Relative Permeability Data for TWO Middle Eastern Carbonate Reservoirs", SCA2004-34.

3. Kalam MZ, El Mahdi A, Negahban S, Wilson OB, and Spearing MC. "A Case Study To Demonstrate The Use Of SCAL Data in Field Development Planning Of A Middle East Carbonate Reservoir", SCA2006-18.
4. Koedertiz LF, Harvey AH and Honarpour M, "Introduction to Petroleum reservoir Analysis", Gulf Publishing Company, Houston, USA 1989.
5. Amaefule JO, Altunbay M, Tiab D, Kersey DG, and Keelan DK, "Enhanced Reservoir Description: Using Core and Log Data to Identify Hydraulic (Flow) Units and Predict Permeability in Uncored Intervals/Wells". Paper SPE 26436 presented at the Annual Technical Conference and Exhibition, Houston, 3-6 October 1993.
6. Dernaika M, Kalam MZ and Skjaeveland S. "Understanding Imbibition Data in Complex Carbonate Rock Types", SCA2014-93.