EVALUATION OF WATER SATURATION FROM LABORATORY TO LOGS

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ABSTRACT

An extensive laboratory study to determine initial water saturation as well as remaining oil in water flooded regions has been initiated using porous plate measurements at reservoir temperature and reservoir overburden pressure conditions. We present the results of the primary drainage experiments which capture the capillary pressure (Pc) and the electrical resistivity (Sw-RI) changes all the way down to Swi. The impact of the drainage laboratory results for the well and for the reservoir is also considered.

The initial water saturation was estimated using the RI-Sw curves in drainage. Very low saturation was reached covering the range of saturation of interest in the field. The saturation exponents ‘n’ appear to be around 2 for the reservoir rock types (RRT) containing most of the STOOIP while the tighter RRT’s show lower values. Capillary pressure data when grouped according to lithofacies as J-function plots confirm the distinct RRT characteristics.

The value of the well defined laboratory data and its integration to logs is presented. Despite intermediate to oil wet conditions, ‘n’ values are lower than the default value of 2 and much lower than that expected for oil wet conditions. The laboratory measurements reduced the uncertainties in the oil in place estimations and allowed a realistic evaluation of the water flooding performance.

INTRODUCTION

Capillary pressure curves (Pc) and electrical resistivity measurements (Sw-RI) are two most important factors in formation evaluation. Representative capillary pressure curves can give reliable information for the evaluation of the reservoir fluid distribution. The importance of the capillary pressure parameter comes from the fact that connate water in the reservoir occurs through the mechanism of immiscible fluid displacement which involves capillary action. The electrical resistivity of a fluid-saturated rock is its ability to impede the flow of electric current through that rock. Sw-RI data allow laboratory determination of the saturation exponent ‘n’ which in turn is used to quantify fluid saturations from resistivity logs across the zones of interest in a hydrocarbon bearing formation.

EXPERIMENTAL PROCEDURES & DISCUSSIONS OF RESULTS

Sample Selection And Preparation

Forty four reservoir core plug samples were screened to obtain representative rock types present in a carbonate reservoir zone from a producing field in the Middle East. The core plugs were 1.5” in diameter and the sampling strategy for SCAL was based on X-ray CT scanning, Thin Section description, mercury injection measurements and poroperm analysis. The reservoir core samples examined comprised 8 RRT’s with porosity ranges from 10-33% and permeability ranges from 0.01-6000 mD.

Figure 1 presents the porosity permeability trends for the selected SCAL plugs (20 plugs). This shows the distinct RRT classification in the groupings of samples selected. NMR porosity had also been acquired on the samples and showed good agreement with the Helium porosity results (figure 2). The selected core samples underwent two-stage flush cleaning cycles with various solvent combinations in order to render the samples more water wet. The cleaning procedure was an optimised technique that were used in previous studies on similar rocks and verified through restored wettability experiments.

Formation Resistivity Factor

Figures 3 and 4 show the evaluated cementation exponents ‘m’ at ambient and reservoir conditions, respectively. These confirm ‘m’ to increase slightly from 1.95 to 1.98 upon applying a reservoir temperature of 121ºC, at the same reservoir overburden pressure. Figure 5 shows a decrease in FF with increasing permeability below approximate value of 10 mD. This electric behavior is controlled by changes in pore geometry which can also be linked to changes in permeability. However, the fairly unchanging FF with permeability for the rocks higher than 10mD should be due to similarities in the pore geometry for those rocks despite the large changes in permeability.

Capillary Pressure And Resistivity Index

Combined capillary pressure curves and resistivity index plots were generated by the ceramic porous plate method [Longeron and Wilson et al, refs. 1 &, 2]. All measurements were performed under net overburden pressure and reservoir temperature using stock tank oil as the displacing fluid. The core plugs were de-saturated by increasing capillary pressure in steps and recording resistivity and expelled water on a daily basis. Figure 6 shows the impact of porosity on the evaluated Swi at the end of primary drainage cycle.

Figures 7 and 8 represent typical time steps applied during the equilibrium measurements for the drainage cycle (brine de-saturation), and confirm the long times required for good Pc and Sw-RI data. A full drainage cycle can typically take up to 8 months for many of these carbonate samples. Figures 9 and 10 typify the RI-Sw and Pc data, respectively from such measurements. In figure 9 it is seen that both transient and equilibrium data follow the same trend. Figure 10 also shows a comparison with the water-oil Pc derived from mercury intrusion on the trim of the same sample at no confining stress; the differences are evident from the errors in assumed conversions and the physics of the wetting processes. Such plots, however, enhance confidence in the measured water-oil Pc data from the porous plate.

Figure 11 show the J-function plot of the analyzed samples. It is evident that the lithofacies are impacting the results with RRT 1 and RRT 2 containing grain stones, vugs and rudists conforming to one set while RRT 3 – RRT7 containing mostly pack stones and relatively more homogenous conforming to another set. Similarly, when the RI-Sw plots are examined (as in figure 12), 'n' is shown to vary from 1.99 to 1.61. The range in the data is reminiscent of previously examined data from another reservoir zone of the same field [Fleury et al, ref 3] although the non-linear behavior observed earlier in some of the samples were totally absent in the current study. Further, the data set is consistent and repeatable in showing 'n' approaching 2 in most of the prolific rock types (RRT 1 – RRT 5) while the less permeable RRT (6-8) samples show 'n' approximately around 1.6. The significance of this analysis is demonstrated by examining logs in the same well, and in other wells.

Principal Component Analysis (PCA)

A Principle Component Analysis has been performed on resistivity data acquired from four different fields (A, B, C and D) in the Middle East by three different techniques: Porous Plate, FRIM and CI. The data in this paper comes from field D and the work has been presented elsewhere [Kalam et al, ref 4]. The PCA study confirms the statistical acceptability of the measured samples, despite a wide variation in RRT and poroperms.

Log Calibrations

The new SCAL results are used to calibrate the log response in two wells, one with oil base mud to capture the Swi as accurately as possible (figure 13) and another one from the study well where the SCAL plugs are taken (figure 14). The new results are compared with the old water saturation calculation using previous data where saturation and cementation exponents were derived mathematically using linear regression analysis. The old parameters (m=2.15 and n=1.78) are compared with the new parameters using two ranges: an average range where m=1.95 and n=1.99 representing the two dominant rock types (RRT4 &RRT5) containing most of STOOIP and another where m=1.95 and n=1.60 for the poor quality rock types. New SCAL data matches closely to that derived from oil base mud (filled dots), and hence more dependable.

CONCLUSIONS AND RECOMMENDATIONS

Porous plate at reservoir temperature and reservoir overburden pressure is indeed a dependable tool for water-oil Pc and RI-Sw measurements during primary drainage of carbonate reservoir cores. Interesting observations of RRT dependency on RI-Sw behaviour is confirmed for first time, and shows that 'n' can be as low as 1.60 in tight carbonate samples. The impact on the calibrated logs is significant as a lower 'n' value means a higher amount of remaining oil and STOOIP. Non-linear RI-Sw behaviour is not observed despite presence of local heterogeneity such as vugs and rudists. NMR derived porosity is an excellent tool to capture representative carbonate porosities, and needs to be considered as an essential SCAL measurement tool where core matrix preservation is required prior to various displacement tests.

ACKNOWLEDGEMENTS

The authors acknowledge ADNOC and ADCO Management for permission to share the contents of this on-going study.

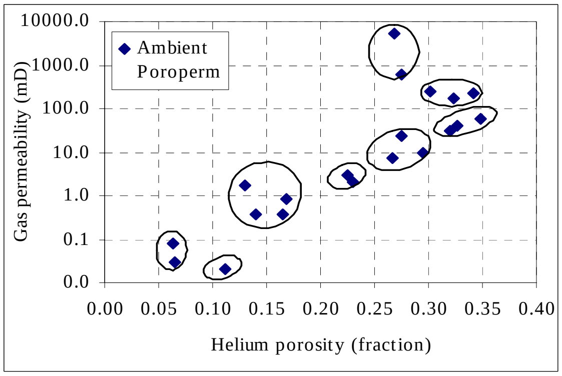

Figure1. Poroperm Distribution And RRT

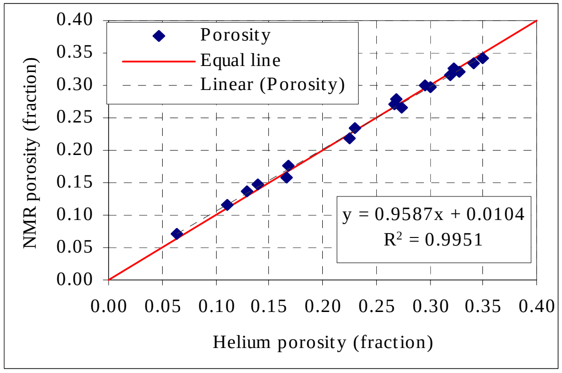

Figure 2. Porosity - NMR Vs Helium

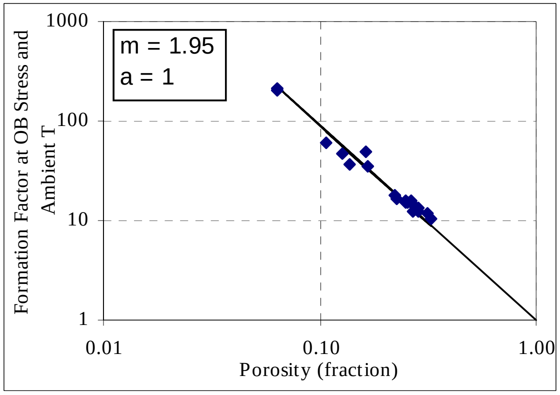

Figure 3. FF Vs Porosity At OB, Amb T

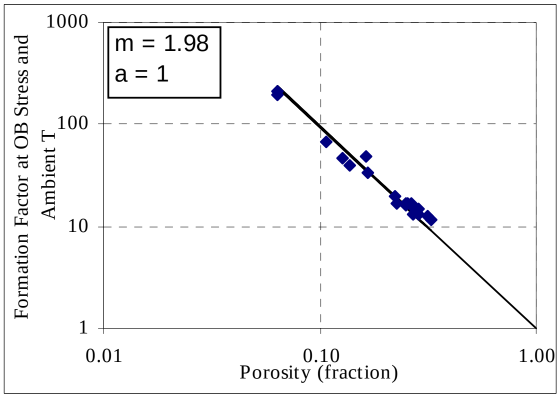

Figure 4. FF Vs Porosity at OB, RT

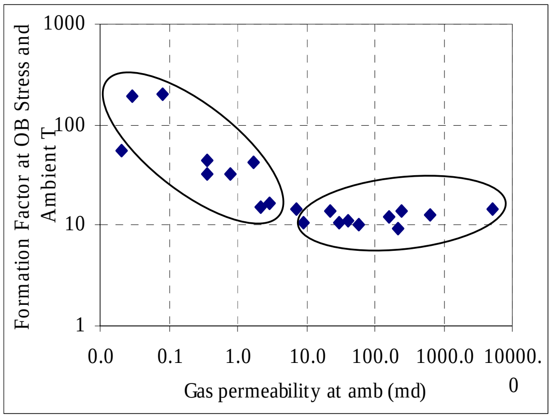

Figure 5. FF Vs Permeability At Ambient T

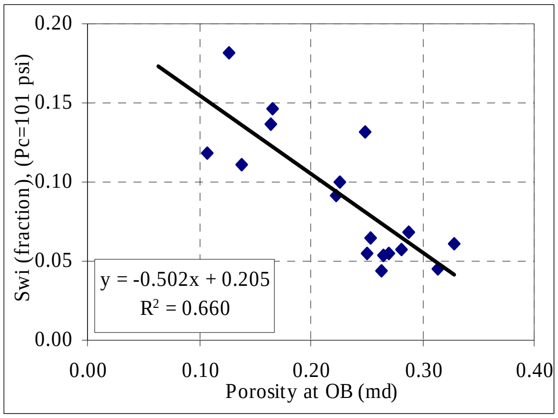

Figure 6. Swi Vs Porosity

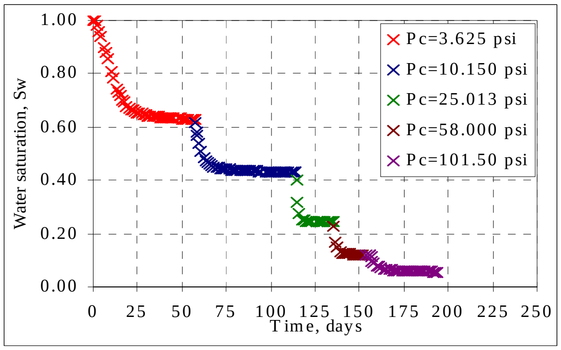

Figure 7. Sw Vs Time-plug B

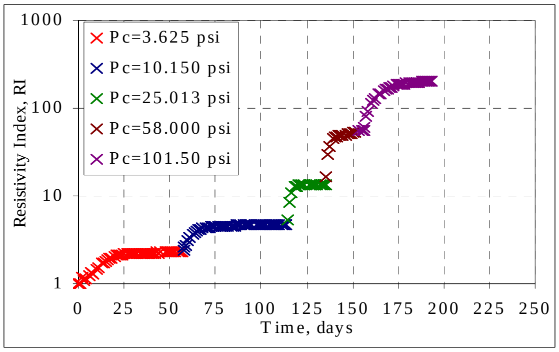

Figure 8. RI Vs Time-plug B

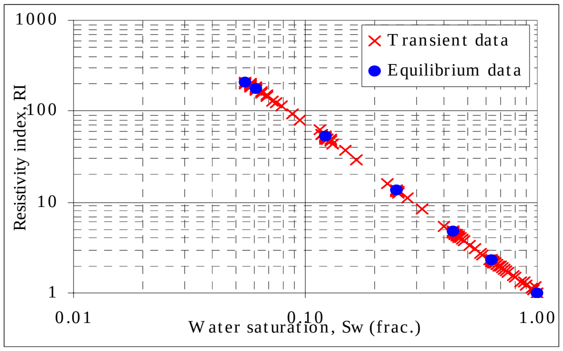

Figure 9. Transient RI - plug B

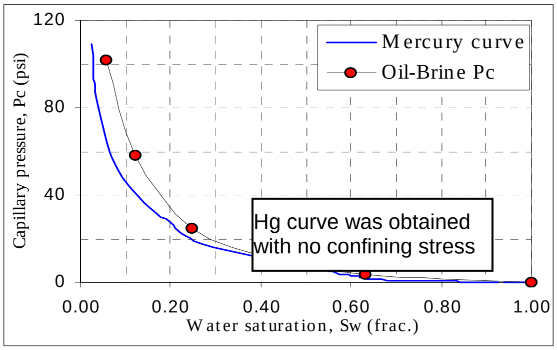

Figure 10. Capillary Pressure Curve-Plug B

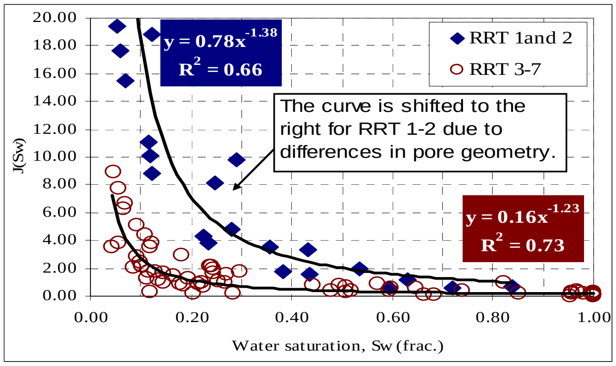

Figure 11. Pc J-function plot

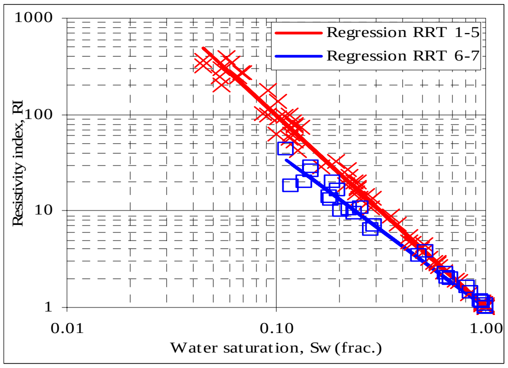

Figure 12. RI versus Sw for all samples

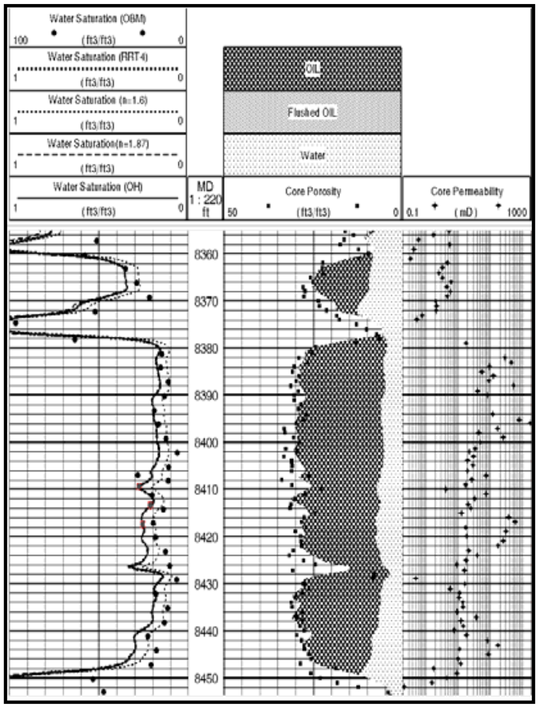

Figure 13. Comparison of Calculated Sw from Resistivity Log Using Measured Resistivity Data With Sw from Cores Taken With Oil Base Mud

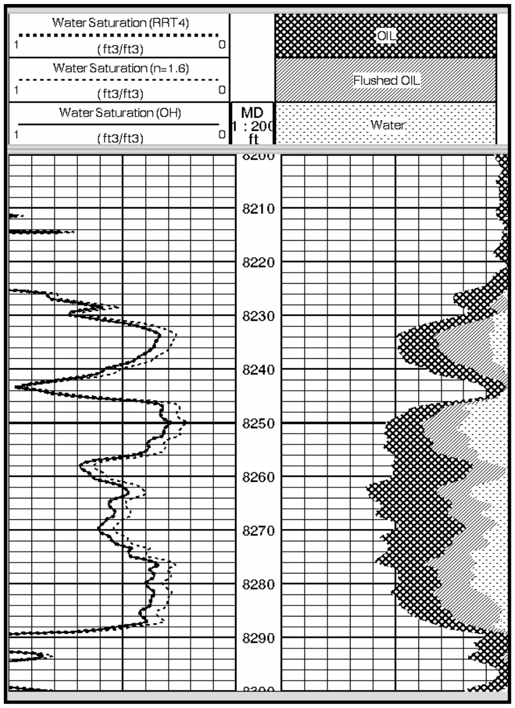

Figure 14. Study Well

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