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USE OF WELL LOGS TO SUPPORT AND VALIDATE LABORATORY RESULTS IN CHALK

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Abstract

Support or validation of laboratory measurements on field cores can be obtained by comparing measurements with that obtained from field well logs. Since the laboratory measurements are needed for interpretation of field electrical measurements, the process of matching field and laboratory data can become an iterative one. In many cases, measurements through this process can indicate the appropriate saturation and wettability state of the reservoir and the appropriate core plug preparation procedures. In our studies, laboratory data were compared to well log data from water-flooded zones of a chalk reservoir. Our primary core preparation method, the Soxhlet extraction of chalk core plugs with toluene and methanol, did not match field results, indicating that in some cases more than a single core preparation technique may be needed in the laboratory. N-decane for most laboratory tests was found to be more suitable than field stock tank crude oil. Saturation versus porosity trends were found capable of indicating wettability and comparing field with laboratory data.

Introduction

Laboratory measurements are essential for calibrating field and well log data, and field measurements are needed to guide laboratory experimentation. While this may seem to be obvious, it is common for laboratory studies and interpreted field behavior to be treated independent from one another. Consequently, errors in well log interpretation and in laboratory experimental procedures can occur. This can be a particular problem during the secondary recovery of hydrocarbons because reservoir management decisions must rely upon well logs to obtain accurate information on the local reservoir response to water injection. With both the laboratory and the field measurements dependent upon each other, the circular nature of the problem may require an iterative approach to obtain meaningful information. Key to this approach for chalk reservoirs was the recognition that water saturation/porosity cross-plots from laboratory chalk measurements could be constructively compared to the data obtained from well logs of waterflooded zones. This paper focuses on the methodology used to guide laboratory procedures.

Methodology and Procedures

Cleaning/Restoring

The first step to mimicking reservoir behavior in the laboratory was the cleaning, preparation and restoration of core materials. Initial decisions to clean core material for laboratory studies should be based on the unique characteristics of the reservoir fluids and the reservoir porous rock. It is a common misconception that a particular procedure is universally applicable to all fields and reservoir conditions. If the coring and handling procedures introduce potential artifacts related to wettability, hysteresis and/or fluid behavior, it may be better to clean and/or restore. The resultant laboratory system should eliminate possible artifacts and preserve as many of the in-situ properties as possible.

For the chalk reservoirs under study, the original laboratory core preparation procedures used native state plugs (some preserved and some unpreserved) and extracted plugs that were restored with stock tank crude oil. Ambient temperature core preparation and experimentation with the stock tank crude oil was found to be difficult. The major reason for this was due to the nature of the highly paraffinic stock tank crude oil that possessed cloud points near ambient temperature (70 degrees Fahrenheit) as measured by viscosity (Figure 1). Consequently, a number of probable laboratory artifacts due to paraffin crystallization often occurred in both native-state and extracted/crude restored chalk core material.

1) Large paraffin crystals in the crude oil plugged the small pore necks of the chalk or reduced the chalk oil permeability at ambient temperatures.
2) Laboratory tests for wettability using the Amott Harvey Relative Displacement Index yielded varied and often unpredictable wettability states for plugs restored with stock tank crude oil. Wettability was highly dependent upon the temperature and procedure history of the core plug and the crude oil.
3) Crude oil flow tests in porous material indicated that the rock permeability was reduced after cooling to the cloud point (Figure 2). Reduced permeability was still observed when the system was reheated above reservoir temperature.
4) Imbibition tests restored with stock tank crude oil showed sensitivity to the test temperatures with elevated temperature tests showing higher imbibition end-points (Figure 3).

Since practical reasons did not allow for the conduction of a large number of tests with live crude at reservoir temperatures, alternative laboratory procedures for ambient temperature tests were developed. Two major laboratory procedural changes were made.

1) The chalk core material was extracted to remove the crude oil and yet preserve as much as possible, the original wettability characteristics of the chalk. The extraction procedure consisted of batch processing of core plugs by alternating a sequence of mild solvents, toluene and methanol, in a Soxhlet unit. Earlier procedures (data set 1) continued the extraction until acceptable grain densities were obtained for the plugs and later procedures (data set 2) continued the extraction until the effluent from both solvents was clear. Baldwin[1] had shown that mild solvent cleaning would remove the crude oil components, but generally preserve the more tightly bound organic material on the pore surfaces. An infrared spectra comparison of the toluene extracted effluent with that of the stock tank crude oil (Figure 4) showed the capability of toluene to remove the crude oil. However, repeated batch soaks of the

core plugs in the Soxhlet unit with toluene following methanol were found necessary to clean the chalk plugs.

2) With paraffin crystallization being the probable culprit for problems encountered with core tests conducted at ambient temperature, n-decane was selected as a replacement for the stock tank crude oil. The ambient temperature viscosity of the n-decane preserved the mobility ratio calculated for live crude and brine at reservoir temperature (approximately 1.0). Additionally, n-decane was not expected to alter the wettability of the chalk.

Grain Density, Porosity and Saturation

Porosity and grain density were determined on extracted plugs using Boyle’s law. Measured grain densities were compared with the ideal density of calcium carbonate (2.7 grams/cubic centimeter) and quartz (2.65 grams/cubic centimeter). X-ray diffraction and mass spectroscopy also confirmed that the reservoir chalk normally had little clay. Acceptable grain densities for cleaned core plugs varied from 2.68 to 2.71 grams/cc with the lower number corresponding to chalk from quartz containing zones (Figure 5). Porosity in the laboratory was also determined from gravimetric measurements and compared with that obtained by Boyle’s law.

Laboratory measurements were made at a hydrostatic overburden of 1580 psig to bring the rock back to a reservoir stress state. Adjustments were made to correct the pore volume and saturation for changes in porosity based on a correlation from measurements (Figure 6). The same correlation was applicable for both high and low quartz containing chalk. The decrease in pore volume (δPV) was calculated from:

$$dPV = \frac{df}{f} \times PV(ambient),$$

where ϕ was ambient porosity. The adjustment to saturation assumed that the more mobile fluid is displaced, oil at initial water saturation or water at residual oil saturation. The corrections to water saturation were:

$$Swi(stressed) = \frac{PV}{PV - dPV} \times Swi(unstressed),$$

$$Swf(stressed) = 1 - \left[\frac{PV}{PV - dPV} \times \left(1 - Swf(unstressed)\right) \right],$$

where Swi was initial water saturation and Swf was the water saturation after water imbibition.

Wettability

Measurements of wettability were based on the Spontaneous Imbibition Index (SII) which is defined as:

$$SII = \frac{dSw\ (measured)}{dSw\ (highly\ water-wet)},$$

where δSw was the water saturation change from spontaneous water imbibition. The use of this index, described by Spinler[2], was easy to measure and was defined in terms of water saturation and porosity (readily obtainable in the laboratory and from well log measurements).

Electrical

Spinler and Hedges[3] had previously established the parameters used for well log interpretation via the empirical Archie equations for chalk reservoirs. The electrical and other measurements were obtained from the chalk plugs of data set 2, described previously. The tortuosity factor and the cementation exponent, "a" and "m" respectively, were obtained on plugs with measured porosity containing a brine of known resistivity. Saturation exponents (n) were obtained for both drainage and imbibition and were found to be different. Imbibition "n" was larger than the drainage "n" and noted to increase with increasing water saturation at higher saturation values. An average value of imbibition "n" was used for interpretation of the well logs in waterflooded zones.

Discussion and Results

Laboratory

Soxhlet solvent extraction, as described above, left all of the chalk plugs with degrees of water-wet behavior, as measured by SII. Plugs that were cleaned until acceptable grain densities were obtained had a greater variety of wettability than the plugs cleaned until the solvents remained clear. These wettability states provided a suitable starting point in the laboratory and were believed to be in the same "ballpark" as the reservoir, also water-wet. The wettability of the field was deduced from the combination of four observed facts:

1) the virtually water-free primary production,
2) low connate water saturation,
3) electrical log readings indicating excellent formation brine continuity, and
4) the lack of rapid water breakthrough during waterflood (formation is highly fractured with low matrix permeability).

This combination of facts was expected to only occur with a continuous water phase in contact with the pore walls and with positive capillary forces trapping most of the injected water in the tight chalk matrix.

Laboratory experiments were used to establish the mechanistic behavior of the primary fluids in reservoir chalk under the scenarios of forced imbibition (forced or viscous displacement are equivalent terms), highly water-wet spontaneous imbibition, and less than highly water-wet spontaneous imbibition (Figure 7). Water saturation versus porosity was a convenient way to compare these displacement mechanisms because similar data were readily obtainable from the field well logs. The laboratory determined that:

1) Forced displacement had an increasing water saturation (decreasing residual oil) with increasing porosity.
2) Highly water-wet spontaneous imbibition had increasing water saturation with increasing porosity.
3) Less than highly water-wet spontaneous imbibition had poorer oil recovery.

It was also observed that viscous recovery of hydrocarbons improved with decreasing wettability over the range of observed wettability (SII > 0.2).

Well Log Comparison

Log calculations of saturation using Archie's equation are not independent of laboratory measurements. To verify the laboratory input, an Archie-independent measure of water saturation was obtained via a Carbon/Oxygen (C/O) log. In this case, the C/O tool had been logged across a waterflooded zone. Since the C/O tools are shallow reading, a comparison was possible with the Archie interpretation from resistivity obtained using a focused microresistivity log, also a shallow measurement, over the same zone. A cross plot of water saturation obtained via Archie and the C/O log indicated that the Archie interpretation in such waterflooded zones was generally correct (Figure 8). Some of the deviation in the plot from the 45 degree reference line can be attributed to the statistical nature of the C/O log. Some deviation in the Archie interpretation may also be due to:

1) the use of a single average "n" rather than one that varies with water saturation (see electrical above),
2) variations in the mixed salinity of mud filtrate, formation and flood waters, and
3) thermal gradients.

The cross-plot of water saturation from the C/O log versus porosity in this near well bore flooded zone showed an increasing water saturation with increasing porosity (Figure 9). Since the waterflooded zone was encountered during drilling using water-based mud, the drilling process may have contributed to or induced forced displacement in the near well bore. A comparison with laboratory forced displacement data (Figure 9) showed a fair match of the laboratory and field saturation/porosity trends. By selecting only the most highly water-wet spontaneous imbibition laboratory data of set 2 and comparing with the same C/O log data, another fair match of the laboratory and field saturation/porosity trends was also obtained (Figure 10). These trends represent a measure of the *ultimate potential* waterflood recovery of oil by viscous displacement and/or highly water-wet spontaneous imbibition.

Since the drilling process can potentially introduce viscous displacement as well as mixed salinity in the near well bore, a better evaluation of a waterflood response was to compare laboratory saturation data with saturation measurements from deep reading electrical well logs. Away from the well bore, salinity variations are limited to connate and flood water mixing. The displacement mechanism would also be more common to the bulk of the reservoir. Such a cross plot (Figure 11 – flooded zone) for the same waterflood zone as examined above showed a decreasing water saturation versus porosity, unlike that of near-well bore trend from the C/O log.

From the saturation versus porosity comparison plots between the deep resistivty log data and the core data (see Figure12), the importance of using proper experimental techniques/procedures becomes apparent. Parameters for an Archie-log interpretation should be based on electrical measurements from plugs that match reservoir behavior. More than one core preparation procedure may be necessary to span the entire range of field observations. The examples cited herein also illustrate the iterative nature of the process often required to match laboratory data to field observations.

Conclusions

1. Saturation/porosity cross plots can be used for comparison of laboratory and field measurements.
2. Matching laboratory and field wettability characteristics in the laboratory can be an iterative process.
3. Multiple core preparation procedures may be needed to needed to match laboratory results with field behavior.
4. Non-Archie techniques may be necessary to correct for the variation of imbibition “n” with water saturation.

Acknowledgement

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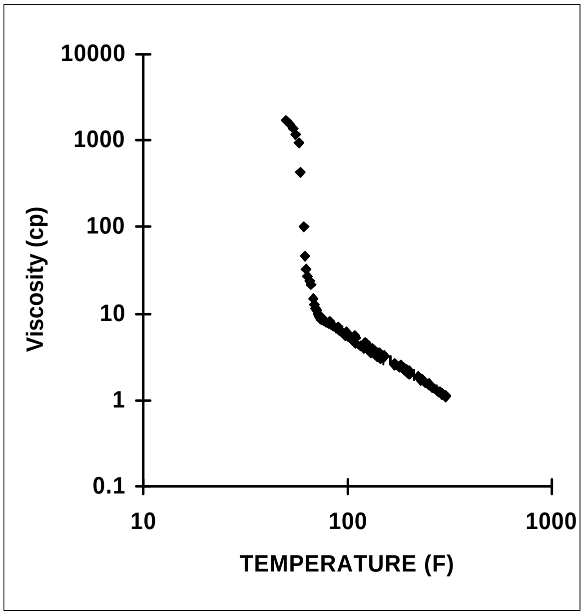

Figure 1: The viscosity of stock tank crude oil is a function of temperature showing a cloud point (non-Newtonian behavior) at approximately 70 degrees Fahrenheit.

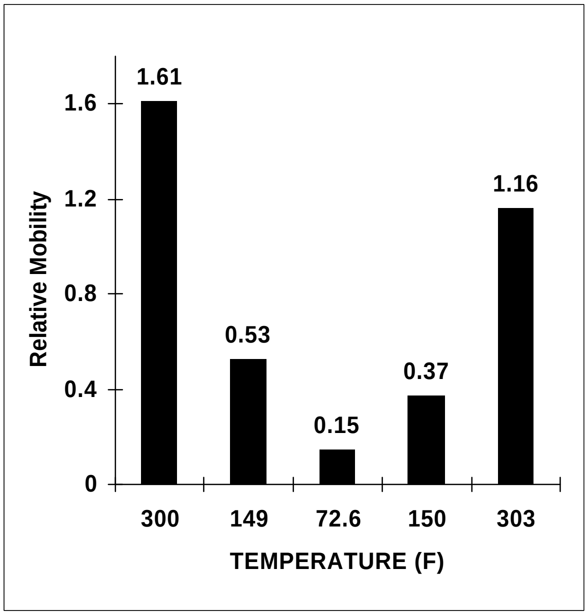

Figure 2: Fluid mobility as measured in porous rock is shown with measurements proceeding time-wise from left to right. A permanent loss in mobility can be seen after cooling to ambient temperature.

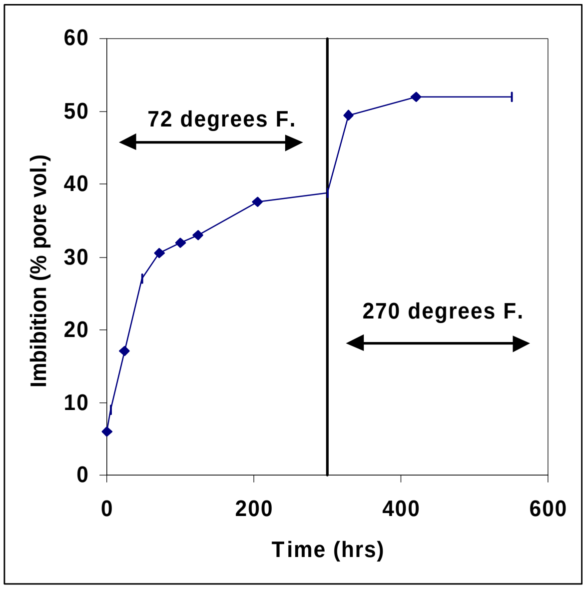

Figure 3: A spontaneous water imbibition test that was conducted with stock tank crude oil in chalk at ambient and reservoir temperature illustrates sensitivity to test temperature.

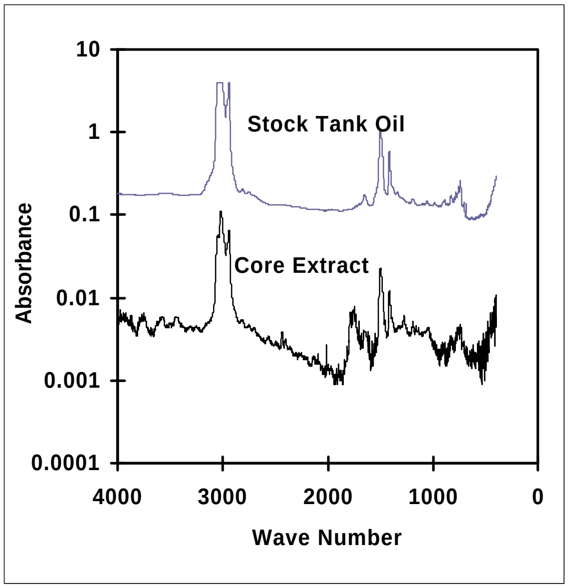

Figure 4: A comparison of infrared absorbance spectra shows that the toluene removes crude oil from reservoir chalk core plugs.

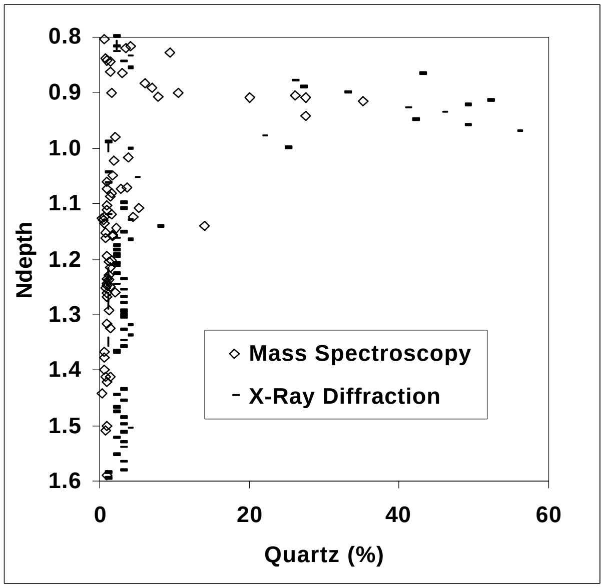

Figure 5: The quantity of quartz in the chalk varies with normalized well depth (Ndepth) in the reservoir.

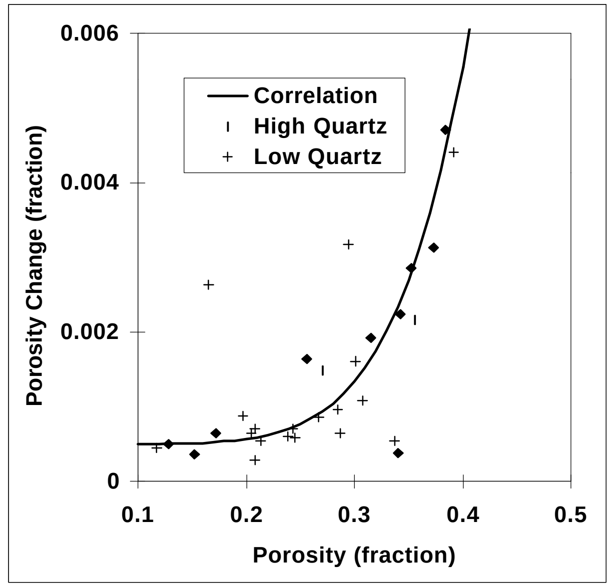

Figure 6: The porosity of the chalk varies with the change in stress from ambient to reservoir pressures with the higher porosity chalk showing greater decreases.

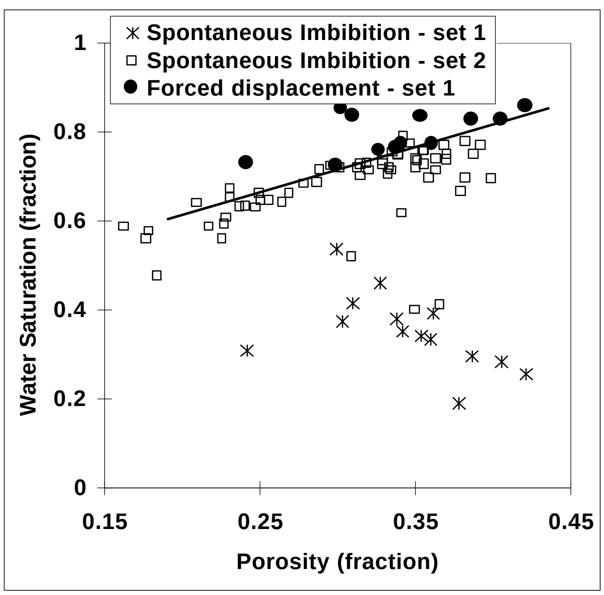

Figure 7: Laboratory tests established the saturation behavior of reservoir chalk plugs with displacement mechanism. The line is the trend for highly water-wet spontaneous imbibition and forced imbibition.

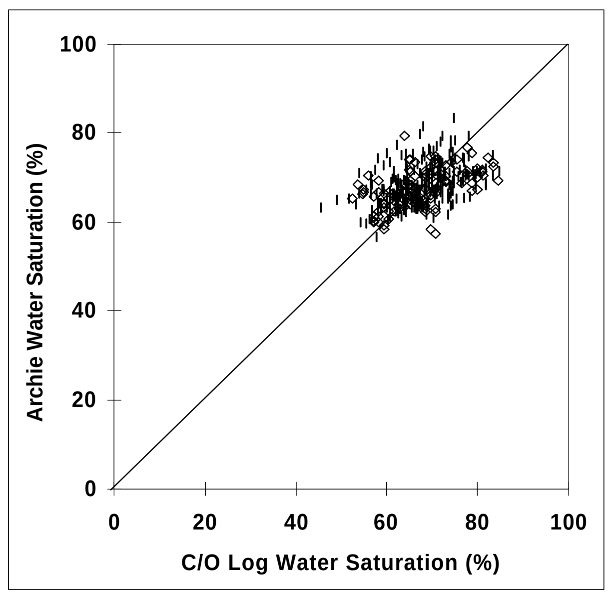

Figure 8: The comparison between different interpretation methods showed general agreement for the near well bore saturations of a waterflood zone.

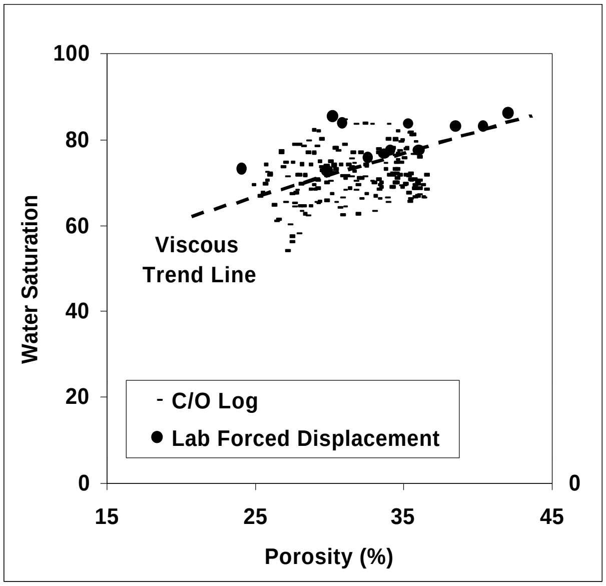

Figure 9: The near well bore in the water flooded zone exhibited the same trend as observed in the laboratory for forced imbibition (forced/viscous displacement) from data set 1.

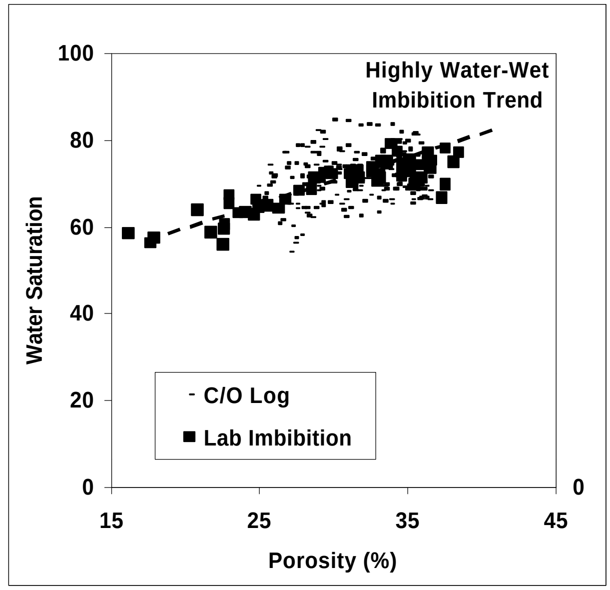

Figure 10: The near well bore in the water flooded zone exhibited the same trend as observed in the laboratory for highly water-wet chalk which are the upper most data points of set 2.

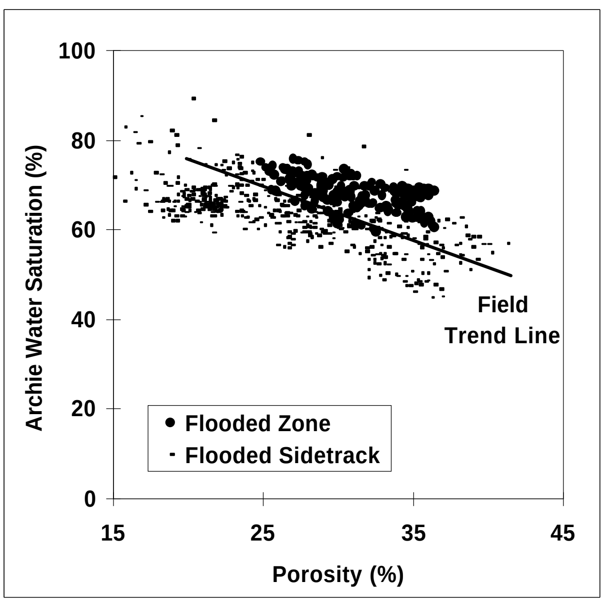

Figure 11: Interpretation away from the near well bore showed a decreasing water saturation with porosity in waterflooded zones. The line indicates the direction of the trend.

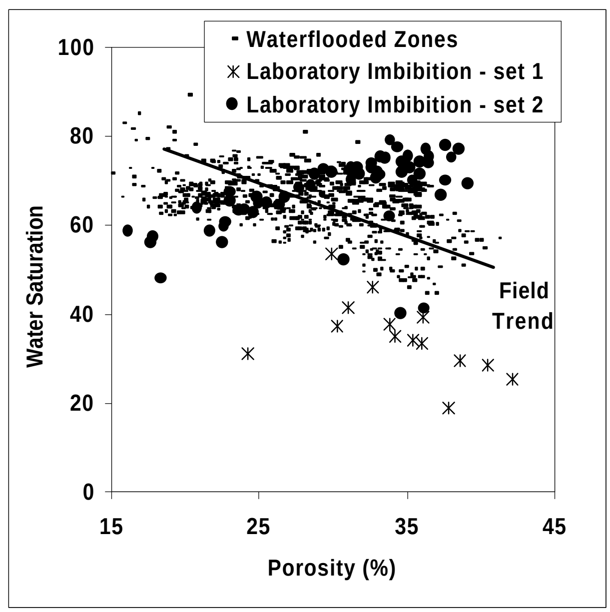

Figure 12: Comparison of laboratory imbibition measurements with field reservoir behavior show different trends and water saturations.