Appendix C

Mississippian Reservoir

I- Introduction

There are 17 wells with complete suites of porosity and resistivity logs available in sections 28, 29, 32, 33, and 2-32 drilled from 1956 to 2016. Also, there were five older wells with older completion dates from 1936 to 1948. These wells had one porosity log, usually neutron logs with no scale or counts/API units. Resistivity logs were not recorded in these wells. The neutron logs of the five older wells were normalized with the neutron logs of the key well (1-32) and then converted to the equivalent formation porosity using Well 1-32. The 17 newer wells were quality controlled and analyzed by Techlog in terms of porosity, water, oil saturation, and minerals. Three of these 16 wells (1-32, 1-28 and 2-32) had NMR logs. The NMR logs were analyzed by Techlog to derive effective porosity, Coates permeability and Pc curves. Only Well 1-32, 2-32 and Peasel 1 had core data. These core data had porosity, permeability (90 degree and maximum), and matrix density. Based on the production history of the field, the field production started in 1929 without any significant water production prior to 1943. Newer wells were drilled after this date and must be invaded by formation water or water flood. Therefore, water saturation derived from Techlog using resistivity logs is not representative of initial water saturation of the reservoir. Moreover, the older wells didn't have any resistivity logs; therefore, initial water saturation couldn't be derived from resistivity logs.

Well 1-32 has the most complete set of data and was used as the key well. Routine core data of this well was analyzed by FZI method, and FZI was correlated with log-derived porosity and water saturation of this well (NMR irreducible water saturation). Based on irreducible water saturation and porosity, permeability in Well 1-32 was estimated, which matched very well with core data. Since initial water saturation was not available in other wells to be converted to irreducible water saturation to find permeability, permeability of these wells were estimated by another technique. The reservoir was divided into six zones based on log signatures and FZI, and then the permeability of each zone was estimated.

II. Permeability Determination

a. Permeability of Well 1-32

Permeability of this well can be obtained by different methods and different sources of data. The basic permeability data source is routine core analysis, which was discussed above. Another method is Coates equation (equation 3), which relates permeability to porosity, FFI, and BWT:

$$K_{Coates} = A * (10 * \phi)^B * \left(\frac{FFI}{BWT}\right)^C \quad \text{(Equation 3)}$$

Coates permeability was calculated using FFI and BWT from NMR; however, different A pre-factors in the above equation were used in different intervals of the reservoir to match Coates permeability with core permeability.

The reservoir was divided into three intervals and the following pre-factors were applied.

- Zone 1: from 3,658 to 3,668 ft, A= 4.5
- Zone 2: from 3,668 to 3,720 ft, A=0.8
- Zone 3: from 3,720 to 4,100 ft, A=3

Coates permeability is compared with core data in fig. A3 (Appendix A). The match between Coates permeability and core data is acceptable but not perfect. In addition to Coates, permeability of this well was obtained according to "*Determination of Reservoir Permeability based on Irreducible Water Saturation and Porosity from Log Data and Flow Zone Indicator (FZI) from Core*, IPTC-17429." Equation 4 was used to calculate permeability.

$$K = 1014\left[\frac{a}{S_{wir}\phi_e} + b\right]^2 \frac{\phi_e^3}{(1-\phi_e)^2} \qquad \text{(Equation 4 or FZI-SWIPHI)}$$

Constants ***a*** and ***b*** in the above equation can be found by relating FZI to $\frac{1}{S_{wir}\cdot\phi_e}$ as follow:

$$FZI = \frac{a}{S_{wir}\phi_e} + b \qquad \text{(Equation 5)}$$

For this purpose, FZI from core was statistically related to the reciprocal of porosity and irreducible water saturation from NMR. To find the right constants, the reservoir interval had to be divided into two zones, A and B. Zone A is mainly the chat conglomerate sequence, which has bimodal T2 distributions; the dolomite and limestone sections below the chat conglomerate, generally, have single modal pore size distribution (fig. A3—Appendix A) (zone A and B). Due to changes in T2 distribution shape, two correlations were necessary. The first correlation is derived for zone A (chat conglomerate), which is shown in fig. 1 and equation 6.

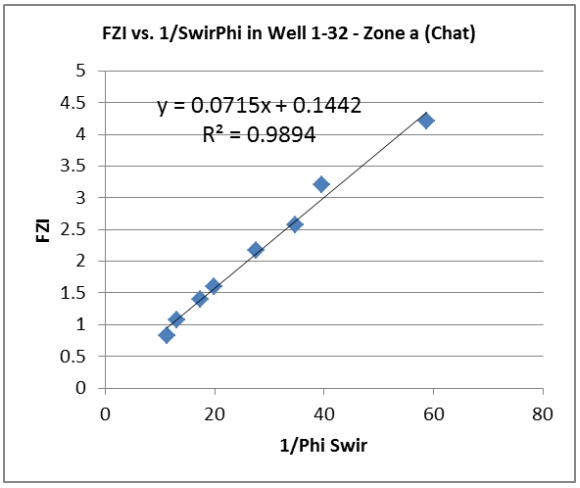

Figure 1: FZI vs. 1/PhiSwir for zone A (chat)

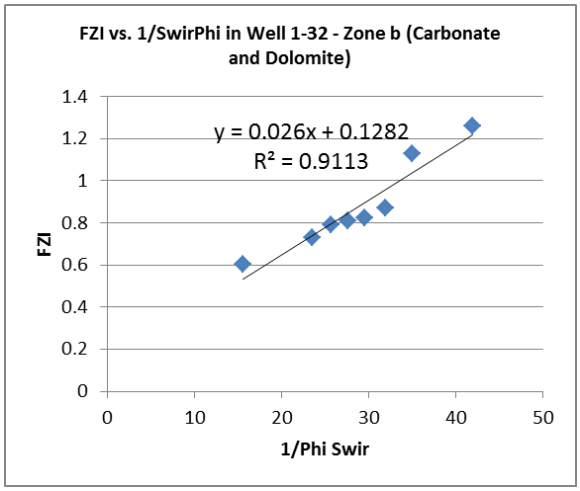

Figure 2: FZI vs. 1/PhiSwir for zone B (dolomite and carbonate)

The permeability equation for zone A is given in equation 7.

$$\mathrm{FZI}_{\mathrm{ZoneA}} = \frac{0.0715}{\mathrm{S_{wir}}\phi_\mathrm{e}} + 0.1442 \qquad \text{(Equation 6)}$$

$$K = 1014\left[\frac{0.0715}{S_{wir}\phi_e} + 0.1442\right]^2 \frac{\phi_e^3}{(1-\phi_e)^2} \quad \text{(Equation 7)}$$

For zone B, the correlation between FZI and $\frac{1}{S_{wir}.\phi_e}$ is obtained and illustrated in fig. 2. Substituting FZI in the Tiab equation by this correlation, the following permeability equation (equation 9) for zone B is obtained.

$$FZI_{ZoneB} = \frac{0.026}{S_{wir}\phi_e} + 0.1282 \quad \text{(Equation 8)}$$

$$K = 1014\left[\frac{0.026}{S_{wir}\phi_e} + 0.1282\right]^2 \frac{\phi_e^3}{(1-\phi_e)^2} \quad \text{(Equation 9)}$$

Equations 7 and 9 were applied respectively to zones A and B of Well 1-32 and permeability versus depth was generated. Permeability by this method matches better with core data as shown in fig. A3 (Appendix A) (FZI-SWPHI). This method could, easily, be applied to all of the wells in the field if initial water saturation and porosity existed. Initial water saturation data can be converted to irreducible water saturation by a method that was discussed in the paper. However, in the Wellington Field, application of this method to other wells is not practical due to lack of initial water saturation due to logging after a long period of water flooding in the Mississippian reservoir.

b. Permeability in Well 2-32

Well 2-32 has NMR log data, and two methods can be used to determine its permeability. 1) Coates permeability in this well was obtained using the same **A** factors that were used in Well 1-32. 2) Permeability was calculated for this well using equation 4.

Coates permeability is compared to permeability by equation 4 in fig. 3 (Appendix A) where there is a better match between permeability by equation 4 with core data.

c. Permeability in Well 1-28

Well 1-28 has NMR log data, and two methods were used to determine permeability in this well. 1) Coates permeability in this well was obtained using the same **A** factors that were used in Well 1-32.
2) Permeability was calculated for this well based on assigned FZI values to different zones of the reservoir and calculation of permeability by the Tiab equation (Equation 10). The method of assigning FZI will be discussed in the next section.
Coates permeability is compared with the second approach in fig. A10 (Appendix A), where there is a better match between permeability by the second approach with core data.

d. Equivalent FZI Zones in Other Wells Corresponding to Well 1-32 FZI

Equations 7 and 9 could be used for permeability determination in all of the wells, if reliable initial water saturation existed in these wells (initial water saturation can be converted to irreducible water saturation by Pc equations). This method could not be used effectively in this case because log-based water saturations are generally affected by oil production from the reservoir and water injection in the reservoir. Another method, which has often been used and is described in the literature, is relating FZI from core in the key well with log signatures through regression or Neural Network and subsequent application of the resulting correlation to other wells with similar logs. It is doubtful that this process gives accurate results

in the Mississippian formation because, generally, wells are old and do not have high-quality logs. In addition, the method works better if a deep resistivity log is included in regression analysis for correlation determination. However, in this field, deep resistivity in Well 1-32 and other wells is affected by production or water injection.

Another method is proposed, which is not ideal and is not theoretically correct but which might provide the best possible permeability model for predicting permeability based on the existing data.

Comparison of T2 distribution, before hydrocarbon correction, in Well 1-32 and Well 1-28, shows that there are intervals with similar shape and size of pore in both of the wells. It is concluded that tortuosity, shape factor of grains and surface area per grain volume are similar in both wells in co-relatable intervals. Therefore, it can be said that zones of equal FZI exist in both of the wells.

FZI values of Well 1-32 are plotted versus depth in fig. A3 (Appendix A). Study of FZI variation with depth indicates that the reservoir can be divided into six zones (3 zones in chat and 3 zones in the carbonate interval), each zone with a distinct average FZI. These zones are shown in fig. A4 (Appendix A) and table 1:

Table 1: Average FZI in six zones of Well 1-32

Zone	from (ft)	to (ft)	FZI (µm)
1	3,656	3,659	2.605
2	3,659	3,662.5	1.618
3	3,662.5	3,665.5	4.285
4	3,665.5	3,698.5	1.007
5	3,698.5	3,720	0.476
6	3,720	3,766	0.925

It is assumed that equivalent zones with equal FZI value exist in other wells, which can be defined by log correlation. Porosity, density, and GR logs of the wells were used to find equivalent zones in other wells corresponding to six zones of Well 1-32. Well cross sections of figs. A5–A9 (Appendix A) show boundaries of the zones in other wells. FZI values in table 1 were assigned to respective zones in other wells and a permeability log was generated, as will be discussed below.

e. Permeability in Well Peasel 1

Well Peasel 1 had core data, which are plotted in fig. A11 (Appendix A). Average FZI values from Well 1-32 were assigned to equivalent zones in well Peasel 1, and permeability of this well was calculated based on assigned FZI values using the Tiab Equation (equation 10). The calculated permeability is also plotted in fig. A11 (Appendix A) and is compared with core permeability. There is a good match between the derived permeability using FZI and core data.

f. Permeability in Other Wells

It was assumed that each zone in figs. A5–A9 (Appendix A) had a specific FZI value; these are listed in table 1. This assumption is approximately but not theoretically correct and may give a good estimate of

permeability in other wells, where no other viable and more accurate method exists. Based on FZI of each zone and effective porosity of the wells, the permeability of all zones in all wells was calculated using the Tiab equation (equation 10).

$$K = 1014\ FZI^2 \frac{\phi_e^3}{(1-\phi_e)^2} \qquad \text{(Equation 10)}$$

Although there was a good match between calculated permeability by this method in well Peasel 1 with core permeability, it is admitted that the predicted permeability in other wells, except for Well 1-32 and Well 1-28, are not ideal. However, considering the available data, it is believed it is the best that could be estimated. Calculated permeability data of wells are shown in Figs. A10 to A24 (Appendix A).

The obtained permeability data can be used in the construction of the dynamic model of the reservoir. During history matching of the dynamic model, when there is mismatch, permeability of the well can be multiplied by a factor to obtain the desired match between actual production data and simulation results. By this procedure, model permeability could be improved.

III. Calculation of Capillary Pressure Curves Prior to Receiving SCAL Data

Available data for determination of Pc curves are generalized Pc curves for the Mississippian formation, NMR data of Well 1-32 and Well 1-28. Data used to generate Pc curves for both chat and carbonate sequences of this reservoir were drawn mainly from key well (Well 1-32). The shape of the generalized Pc curves was also used in the process.

Often Pc curves are related to the permeability of the rock or the FZI in the literature, while in geological sedimentary environments, different Pc curves could exist for a single permeability or a specific FZI. In this work, endpoints of Pc curves (entry pressure, irreducible water saturation) and therefore the Pc curve of a rock are related to its Reservoir Quality Index (RQI). In this section, using data of the key well and generalized data, Pc curves are defined for different RQI values in the Mississippian formation. Since permeability in all wells against depth is found according to Section I of this report, RQI at each depth can be determined and Pc curves based on RQI can be applied to all wells to find initial water saturation. Often the grid of the dynamic or static model of the reservoir is divided into several saturation regions, each with a specific RQI. Pc curves and relative permeability tables are prepared for each region.

Both drainage and imbibition Pc curves were calculated for the reservoir. Depending on the path of oil migration into the Mississippian formation, either drainage or imbibition Pc curves could be applied to the model and wells to represent the initial condition of the reservoir.

Drainage and imbibition capillary pressure curves were calculated according to "A *Novel Technique for Generation of Accurate Capillary Pressure (Pc) Curves from Conventional Logs and Routine Core Data and New Pc Endpoint Functions after Considering the Sedimentary Environment and Pore Throat size Distribution Shape (PTSDS).*"

Eight capillary pressure curves were calculated for drainage and imbibition for nine average RQI values according to the paper cited above. The formula constitutes a function for the shape of Pc curves and functions for the end-points that are entry pressure (P_{entry}) and Irreducible water saturation (Swir). The end-points are correlated to RQI. P_{entry} was calculated from entry radius (R15) and Winland R35 (R35). There is a relationship between R35 and R15 and a relationship between P_{entry} and R15; therefore, P_{entry} can be calculated from R15 derived from R35. Swir was calculated from the NMR log at a Pc equal to 20 bars (290 psi). For calculating the imbibition curves, another term which is the residual oil saturation (SO_r) was needed. SO_r was calculated based on a correlation that was derived based on SCAL data of other reservoirs and modified for this field.

a. Irreducible Water Saturation (Swir)

Based on the paper mentioned above, there is a good correlation between irreducible water saturation of reservoir rocks and RQI. In the Mississippian reservoir, initial water saturation was not available from logs due to production of the field. However, NMR data from three of the wells can provide irreducible water saturation in these wells.

NMR data of Well 1-32 was used to determine the irreducible water saturation at a Pc of 20 bars (290 psi). Also interfacial tension between oil and water was entered in the TechLog Module to find Swir versus depth for this well. Previously, permeability for the Mississippian in Well 1-32 was determined by equation 7 and equation 9. Based on porosity and calculated permeability of Well 1-32, RQI in this well was determined. Figure 5 plots the irreducible water saturation in Well 1-32 in the chat conglomerate against RQI.

Equation 15 was determined from Figure 5 that is the relationship between Swir and RQI, where R2 is equal to 0.99, indicating good correlation.

$$S_{wir} = 0.0685 RQI^{-1.082} \qquad \text{Equation 15}$$

The same procedure was repeated for the carbonate section of the Mississippian formation. Figure 6 is the plot of Swir vs. RQI for this section:

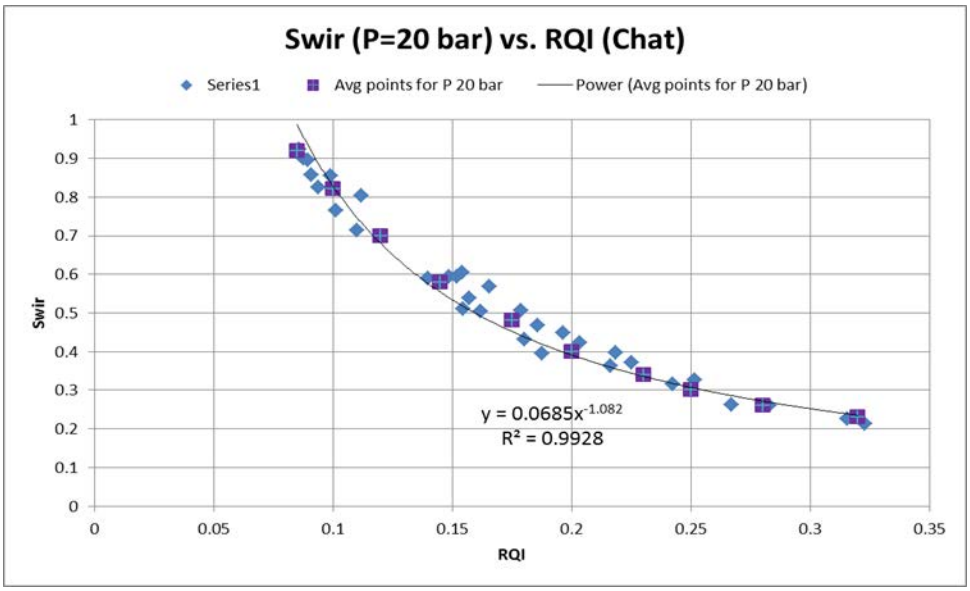

Figure 5: Swir vs. RQI for Zone zone A (chat)

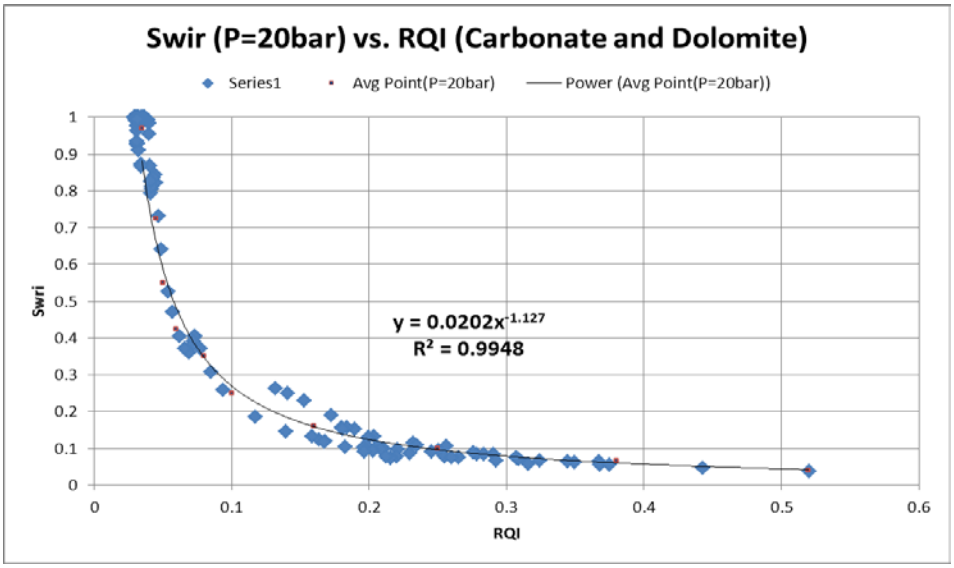

Figure 6: Swir vs. RQI for Zone zone B (carbonate and dolomite)

Equation 16 can be used to determine Swir for the carbonate section.

$$S_{wir} = 0.0202RQI^{-1.127} \qquad \text{Equation 16}$$

b. Entry Pressure (Pe)

There is a good correlation between capillary entry pressure and RQI. Entry pressure in Well 1-32 was determined from NMR data using oil and water interfacial tension. In the Mississippian formation, two correlations were obtained: one for the chat conglomerate and another for the carbonate section of this formation. Figure 7 plots entry pressure from the NMR against RQI in the chat conglomerate.

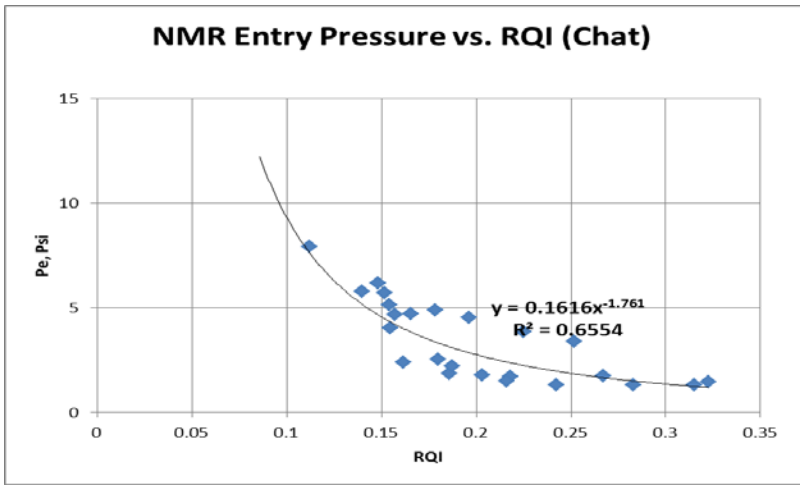

Figure 7: Entry pressure vs. RQI in zone A (chat)

The following equation shows that entry pressure is a function of RQI in the chat conglomerate.

$$P_e = 0.1616RQI^{-1.761} \quad \text{(Equation 17)}$$

Also, fig. 8 plots entry pressure versus RQI in the carbonate section. This plot results in equation 18, which relates entry pressure in this section with RQI.

$$P_e = 0.1467RQI^{-1.312} \quad \text{(Equation 18)}$$

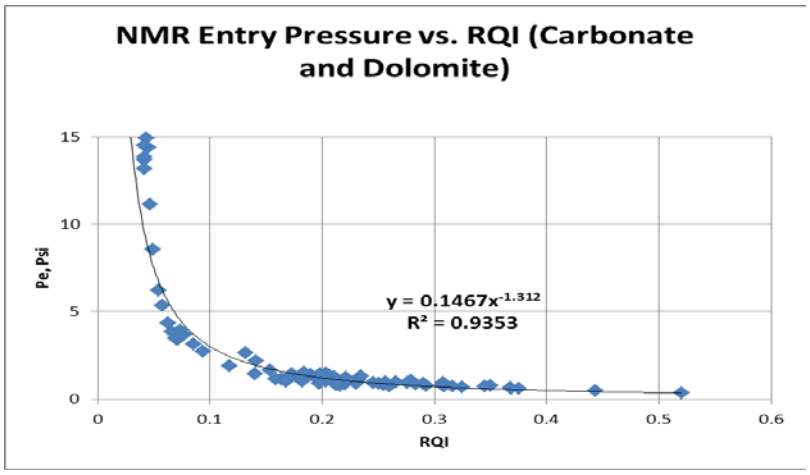

Figure 8: Entry pressure vs. RQI in zone B (carbonate and dolomite)

c. Residual Oil Saturation

A correlation between residual oil saturation and RQI is necessary for derivation of imbibition capillary pressure curves. Reliable SCAL data for the Mississippian formation are not available at the present time to drive this correlation. In the absence of such data, the following correlation was used for the carbonate section. The correlation has been derived based on SCAL data of other reservoirs and modified for this field.

$$1 - S_{or} = 0.5811RQI^{-0.139} \quad \text{(Equation 19)}$$

For the chat section of the Mississippian formation, the equation for the residual oil saturation has been adjusted to the following:

$$1 - S_{or} = 0.427RQI^{-0.407} \quad \text{(Equation 20)}$$

d. Shape of Pc curves

A function between normalized non-wetting phase saturation (Snwn) and equivalent radius (EQR) is needed. Snwn is defined according to equation 21.

$$S_{nwn} = \frac{1-S_{wi}}{1-S_{wir}} \quad \text{(Equation 21)}$$

Snwn is a function of equivalent radius (EQR) (equation 22). Constants *a* and *b* in this equation will be found from the shape of generalized Pc curves later.

$$S_{nwn} = (1 - aEQR)(1 - EQR^b) \quad \text{(Equation 22)}$$

EQR depends on entry pressure and capillary pressure (equation 23), where entry pressure is a function of RQI, which will be derived from the NMR log of Well 1-32.

$$EQR = \frac{P_e}{P_c} \quad \text{(Equation 23)}$$

Snwn correlations were obtained for Chat and Carbonate individually. Snwn was calculated for several water saturations along the curves for Chat and plotted against respective EQR, fig. 9.

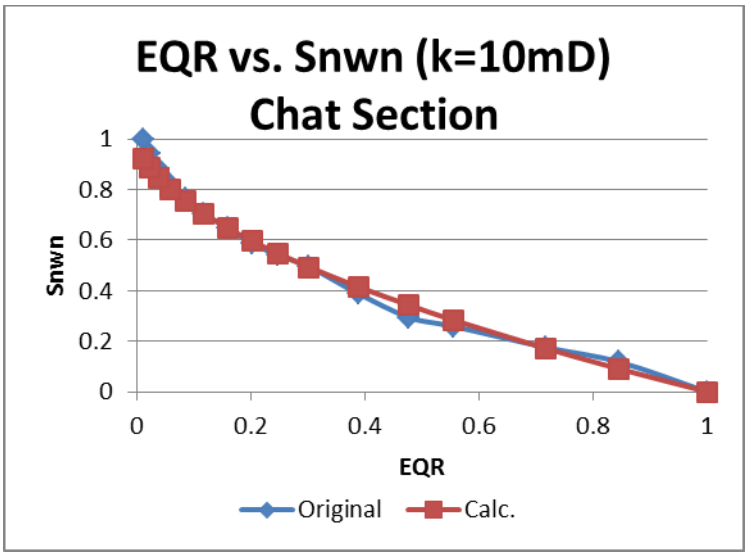

Figure 9: Snwn vs. EQR for chat section at K=10mD

Constants *a* and *b* of equation 22 were derived by regression and resulted in the following equation for the chat conglomerate of this reservoir.

$$S_{nwn} = (1 - 0.00155EQR)(1 - EQR^{0.5697}) \quad \text{(Equation 24)}$$

Snwn was calculated for several water saturations along the curves for Carbonate and plotted against respective EQR, fig. 10.

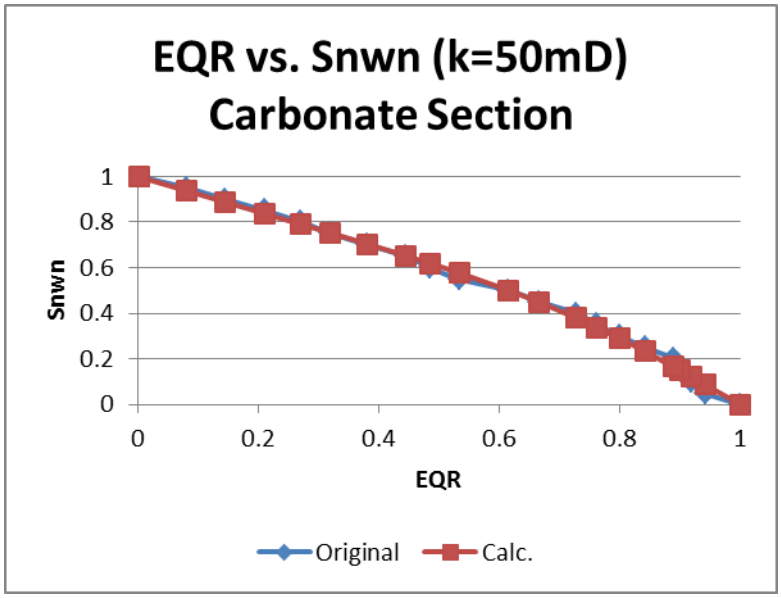

Figure 10: Snwn vs. EQR for the carbonate section at K=50mD

Constants *a* and *b* of equation 22 were derived by regression and resulted in the following equation for the Carbonate zone of this reservoir.

$$S_{nwn} = (1 - 0.5245EQR)(1 - EQR^{3.1249}) \quad \text{(Equation 25)}$$

e. Calculation of Drainage Capillary Pressure Curves

Equation 25 is proposed for drainage water saturation. According to equation 26, initial water saturation (Swi) is a function of Swir and Snwn. It was shown that irreducible water saturation is a function of RQI (equations 15 and 16) and Snwn is a function of RQI and Pc (equations 22 and 23). Swir and Snwn in equation 26 can be replaced by respective functions and an equation can be obtained that expresses Swi in terms of RQI and Pc.

$$S_{wi} = 1 - S_{nwn}(1 - S_{wir}) \quad \text{(Equation 26)}$$

For the chat conglomerate, equations 15 and 22 were incorporated into equation 26 to obtain equation 27, which gives water saturation for every Pc and RQI.

$$S_{wi} = 1 - \left(1 - 0.0015\frac{0.1616RQI^{-1.761}}{P_c}\right)\left(1 - \left(\frac{0.1616RQI^{-1.761}}{P_c}\right)^{0.569}\right)(1 - 12.885RQI^2 + 8.031RQI - 1.4924) \quad \text{(Equation 27)}$$

It was decided to calculate eight capillary pressure curves for the chat conglomerate to be used in the reservoir model. RQI in chat ranges from 0.108 to 0.340. This range was divided into eight subdivisions (table 2).

Table 2: Subdivisions of RQI range in chat section

RT	From	To	Avg RQI
1	0.300	0.340	0.320
2	0.265	0.300	0.280
3	0.240	0.265	0.250
4	0.215	0.240	0.230
5	0.188	0.215	0.200
6	0.160	0.188	0.175
7	0.133	0.160	0.145
8	0.108	0.133	0.120

The mid-range of each subdivision was used to calculate eight Pc curves (equation 27, table 3). The generated Pc curves are shown in fig. 11. These curves are in agreement with generalized curves, when the right permeability and RQI are considered and compared.

Table 3: Drainage Pc table for different RQI groups in the Mississippian chat

a 0.0016	b 0.570	Drainage Table in Mississippian Chat						
RQI	0.32	0.28	0.245	0.22	0.2	0.175	0.145	0.12
Pe	1.20	1.52	1.92	2.33	2.75	3.48	4.84	6.76
Swir	0.23	0.26	0.3	0.34	0.4	0.48	0.58	0.7
Pc	**Swi**							
0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
0.1	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
0.2	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
0.3	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
0.4	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
0.5	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
0.6	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
0.7	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
0.8	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
0.9	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2	0.806	0.893	0.985	1.00	1.00	1.00	1.00	1.00
3	0.687	0.763	0.844	0.911	0.971	1.00	1.00	1.00
4	0.618	0.687	0.761	0.825	0.885	0.960	1.00	1.00
5	0.572	0.636	0.706	0.767	0.827	0.903	0.993	1.00
6	0.538	0.599	0.666	0.725	0.785	0.861	0.952	1.00
8	0.492	0.547	0.611	0.667	0.727	0.804	0.896	0.973
10	0.460	0.513	0.574	0.628	0.688	0.765	0.858	0.940
12	0.438	0.488	0.547	0.599	0.659	0.737	0.831	0.916
14	0.420	0.469	0.526	0.577	0.637	0.715	0.810	0.898
20	0.385	0.431	0.484	0.534	0.594	0.672	0.767	0.862
30	0.353	0.395	0.446	0.494	0.554	0.632	0.729	0.828
40	0.335	0.375	0.424	0.471	0.531	0.609	0.706	0.809
50	0.322	0.361	0.409	0.455	0.515	0.594	0.691	0.796

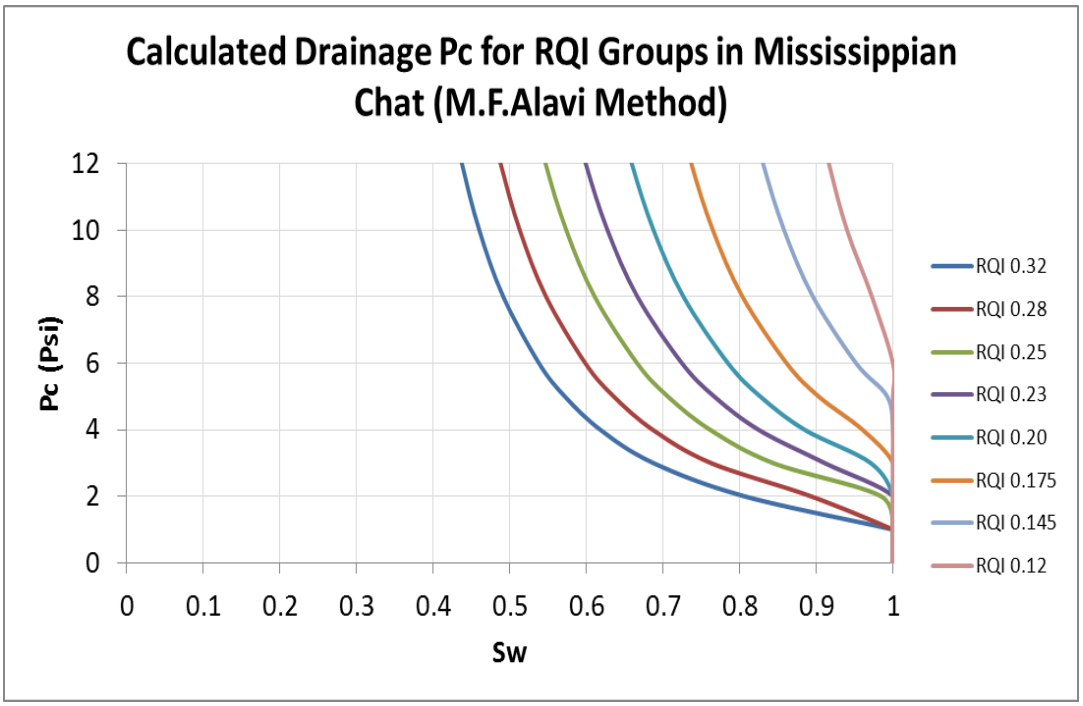

Figure 11: Calculated drainage Pc curves for the Mississippian chat

For the carbonate section of the reservoir, equations 16 and 25 were integrated into equation 26 to obtain an equation expressing Swi in terms of RQI and Pc (equation 28).

$$S_{wi} = 1 - \left(1 - 0.5245 \frac{0.1467 RQI^{-1.312}}{P_c}\right)\left(1 - \left(\frac{0.1467 RQI^{-1.312}}{P_c}\right)^{3.125}\right)(1 - 0.0202 RQI^{-1.127})$$

(Equation 28)

The RQI in the carbonate section ranges from 0.045 to 0.590. The range was divided into eight smaller intervals (table 4). The midpoint of each range was found and, based on these RQI values, eight Pc curves were calculated for the carbonate section of the reservoir (table 5 and fig. 12).

Table 4: RQI subdivisions in the Mississippian carbonate

RT	From	To	Avg RQI
1	0.450	0.590	0.520
2	0.315	0.450	0.380
3	0.205	0.315	0.250
4	0.130	0.205	0.160
5	0.090	0.130	0.100
6	0.070	0.090	0.080
7	0.055	0.070	0.060
8	0.045	0.055	0.050

Table 5: Drainage Pc table for different RQI groups in the Mississippiancarbonate

a 0.524	b 3.125	Drainage Table in Mississippian Carbonate						
RQI	0.52	0.38	0.25	0.16	0.1	0.08	0.06	0.05
Pe	0.346	0.522	0.904	1.624	3.009	4.033	5.882	7.471
Swir	0.04	0.065	0.1	0.16	0.25	0.35	0.425	0.55
Pc	**Swi**							
0	1	1	1	1	1	1	1	1
0.1	1	1	1	1	1	1	1	1
0.2	1	1	1	1	1	1	1	1
0.3	1	1	1	1	1	1	1	1
0.4	0.809	1	1	1	1	1	1	1
0.5	0.582	1	1	1	1	1	1	1
0.6	0.450	0.821	1	1	1	1	1	1
0.7	0.367	0.658	1	1	1	1	1	1
0.8	0.312	0.547	1	1	1	1	1	1
0.9	0.272	0.468	1	1	1	1	1	1
1	0.243	0.410	0.872	1	1	1	1	1
2	0.131	0.205	0.371	0.769	1	1	1	1
3	0.099	0.154	0.260	0.487	1	1	1	1
4	0.084	0.131	0.214	0.378	0.732	1	1	1
5	0.075	0.117	0.189	0.324	0.592	0.816	1	1
6	0.069	0.108	0.173	0.291	0.511	0.701	0.983	1
8	0.062	0.097	0.154	0.255	0.426	0.578	0.782	0.956
10	0.057	0.091	0.143	0.234	0.383	0.517	0.678	0.836
12	0.055	0.086	0.136	0.221	0.357	0.482	0.619	0.766
14	0.052	0.083	0.131	0.212	0.340	0.459	0.582	0.721
20	0.049	0.078	0.121	0.196	0.311	0.423	0.524	0.655
30	0.046	0.074	0.114	0.184	0.290	0.397	0.487	0.614
40	0.044	0.071	0.111	0.178	0.280	0.385	0.471	0.596
50	0.043	0.070	0.109	0.174	0.274	0.378	0.461	0.586

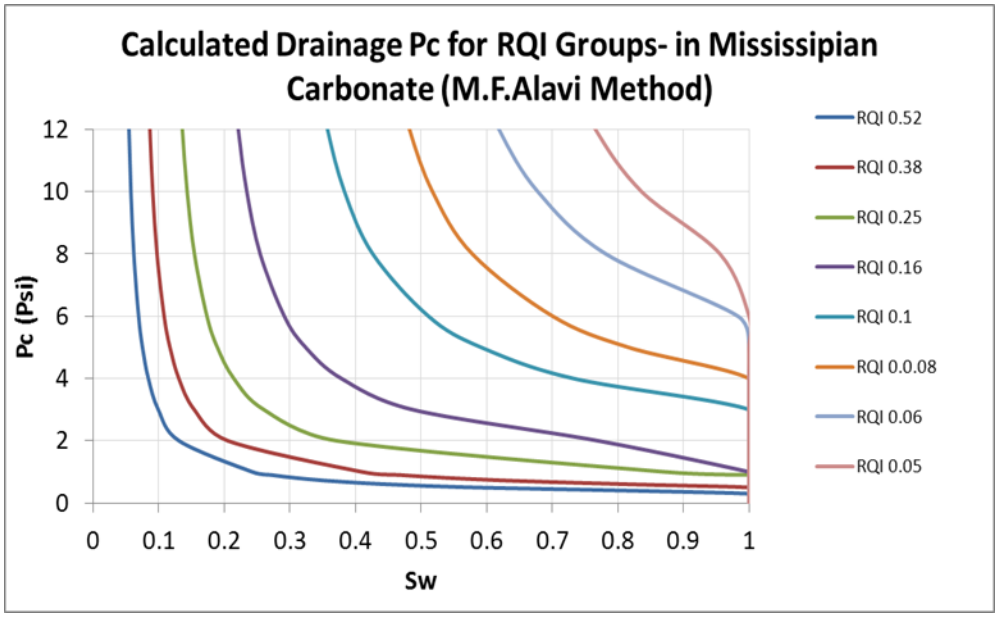

Figure 12: Calculated drainage Pc curve for the Mississippian carbonate

f. Calculation of Imbibition Capillary Pressure Curves

Normalized non-wetting phase water saturation is defined according to equation 29 for imbibition.

$$S_{nwn} = \frac{1-S_{wi}-S_{or}}{1-S_{wir}-S_{or}} \qquad \text{(Equation 29)}$$

Snwn is equal to 0 when Pc is 0; therefore, EQR in terms of entry pressure and Pc should be expressed by the following equation:

$$EQR = \frac{P_e}{P_c+P_e} \qquad \text{(Equation 30)}$$

Equation 31 is proposed for derivation of initial water saturation for imbibition in terms of Swir, Sor, and Snwn. Correlations for Swir, Sor, and Snwn were proposed. Substituting these correlations in equation 31 result in two equations that give initial water saturation based on RQI and Pc: the first (equation 32) is for the chat conglomerate and the second (equation 33) was derived for the carbonate section of the Mississippian formation.

$$S_{wi} = 1 - S_{0r} - S_{nwn}(1 - S_{wir} - S_{or}) \qquad \text{(Equation 31)}$$

$$S_{wi} = 0.427RQI^{-0.407} - (1 - 0.00155\frac{0.1616RQI^{-1.761}}{P_c+0.1616RQI^{-1.761}})\left(1 - \left(\frac{0.1616RQI^{-1.761}}{P_c+0.1616RQI^{-1.761}}\right)^{0.569}\right)(-12.885RQI^2 + 8.031RQI - 1.4924 + 0.427RQI^{-0.407}) \qquad \text{(Equation 32)}$$

$$S_{wi} = 0.5811RQI^{-0.139} - \left(1 - 0.5245\frac{0.1467RQI^{-1.312}}{P_c+0.1467RQI^{-1.312}}\right)\left(1 - \left(\frac{0.1467RQI^{-1.312}}{P_c+0.1467RQI^{-1.312}}\right)^{3.125}\right)(-0.0202RQI^{-1.127} + 0.5811RQI^{-0.139}) \qquad \text{(Equation33)}$$

Based on equation 32 for imbibition, eight capillary pressure curves were generated for the chat conglomerate (table 6 and fig. 13).

Table 6: Imbibition Pc table for different RQI groups in the Mississippian chat

a 0.001553	b 0.570	Imbibition Table in Mississippian Chat						
RQI	0.32	0.28	0.245	0.22	0.2	0.175	0.145	0.12
Pe	1.20	1.52	1.92	2.33	2.75	3.48	4.84	6.76
Sor	0.32	0.3	0.27	0.24	0.21	0.155	0.09	0.03
Swir	0.23	0.26	0.3	0.34	0.4	0.48	0.58	0.7
Pc	**Swi**							
0	0.679	0.700	0.730	0.760	0.790	0.845	0.910	0.970
0.1	0.659	0.684	0.718	0.750	0.782	0.839	0.906	0.968
0.2	0.642	0.670	0.706	0.741	0.775	0.834	0.902	0.966
0.3	0.626	0.657	0.696	0.732	0.768	0.828	0.899	0.963
0.4	0.612	0.645	0.686	0.724	0.761	0.823	0.895	0.961
0.5	0.599	0.634	0.677	0.716	0.755	0.818	0.892	0.959
0.6	0.587	0.624	0.668	0.709	0.749	0.813	0.889	0.957
0.7	0.576	0.615	0.660	0.702	0.743	0.809	0.886	0.955
0.8	0.566	0.606	0.653	0.695	0.737	0.804	0.883	0.953
0.9	0.557	0.598	0.646	0.689	0.732	0.800	0.880	0.951
1	0.548	0.590	0.639	0.683	0.727	0.796	0.877	0.950
2	0.487	0.533	0.587	0.635	0.686	0.762	0.851	0.933
3	0.450	0.497	0.552	0.602	0.656	0.736	0.831	0.919
4	0.425	0.471	0.527	0.578	0.634	0.716	0.814	0.907
5	0.406	0.452	0.507	0.559	0.616	0.700	0.800	0.897
6	0.392	0.437	0.492	0.543	0.602	0.686	0.789	0.888
8	0.371	0.415	0.469	0.520	0.579	0.665	0.769	0.873
10	0.356	0.399	0.452	0.502	0.563	0.649	0.754	0.861
12	0.345	0.387	0.439	0.489	0.550	0.636	0.742	0.851
14	0.336	0.377	0.429	0.478	0.539	0.626	0.732	0.843
20	0.318	0.357	0.408	0.456	0.517	0.603	0.710	0.823
30	0.300	0.338	0.387	0.434	0.495	0.581	0.687	0.803
40	0.290	0.327	0.374	0.420	0.482	0.567	0.673	0.790
50	0.283	0.319	0.366	0.411	0.472	0.557	0.663	0.780

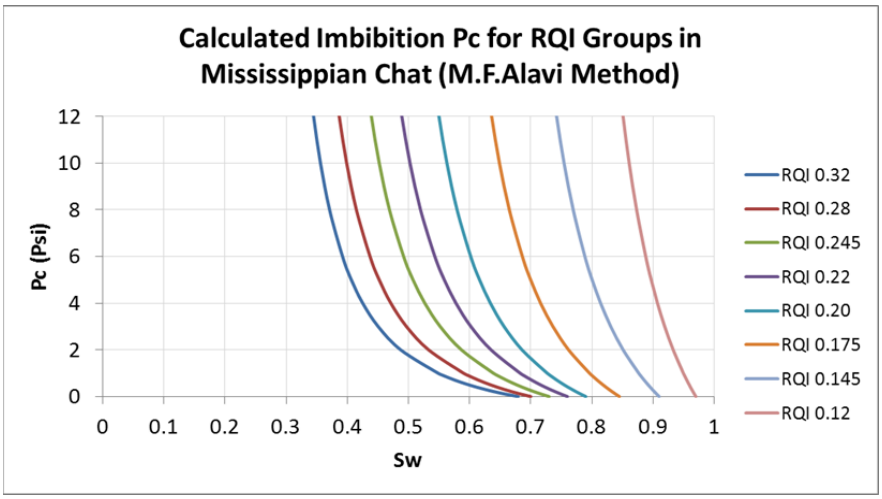

Figure 13: Calculated imbibition Pc curve for the Mississippian chat

For the carbonate section, equation 33 was used to calculate eight capillary pressure curves (table 7 and fig. 15).

Table 7: Imbibition Pc table for different RQI groups in the Mississippian carbonate

a 0.52	b 3.12	Imbibition Table in Mississippian Carbonate						
RQI	0.52	0.38	0.25	0.16	0.1	0.08	0.06	0.05
Pe	0.35	0.52	0.90	1.62	3.01	4.03	5.88	7.47
Sor	0.36	0.34	0.31	0.28	0.25	0.22	0.20	0.17
Swir	0.04	0.065	0.1	0.16	0.25	0.35	0.425	0.55
Pc	Swi							
0	0.636	0.658	0.685	0.722	0.750	0.780	0.800	0.826
0.1	0.443	0.518	0.599	0.673	0.726	0.765	0.791	0.820
0.2	0.334	0.423	0.530	0.631	0.703	0.750	0.782	0.815
0.3	0.268	0.358	0.475	0.593	0.683	0.736	0.773	0.810
0.4	0.226	0.311	0.431	0.560	0.663	0.723	0.765	0.805
0.5	0.197	0.277	0.396	0.531	0.645	0.710	0.757	0.800
0.6	0.175	0.251	0.366	0.505	0.628	0.698	0.749	0.795
0.7	0.159	0.230	0.342	0.482	0.612	0.687	0.741	0.791
0.8	0.146	0.214	0.321	0.462	0.597	0.676	0.734	0.786
0.9	0.136	0.200	0.304	0.443	0.583	0.665	0.727	0.782
1	0.128	0.189	0.289	0.427	0.570	0.656	0.720	0.777
2	0.088	0.133	0.208	0.327	0.477	0.580	0.663	0.741
3	0.073	0.112	0.176	0.281	0.424	0.532	0.623	0.713
4	0.065	0.102	0.159	0.255	0.390	0.500	0.593	0.692
5	0.060	0.095	0.149	0.238	0.367	0.477	0.571	0.675
6	0.057	0.090	0.141	0.227	0.351	0.460	0.553	0.661
8	0.053	0.084	0.132	0.212	0.329	0.437	0.528	0.641
10	0.050	0.080	0.126	0.202	0.315	0.422	0.511	0.627
12	0.049	0.078	0.122	0.196	0.305	0.412	0.499	0.616
14	0.048	0.076	0.119	0.191	0.298	0.404	0.490	0.609
20	0.045	0.073	0.113	0.182	0.285	0.389	0.473	0.593
30	0.044	0.070	0.109	0.175	0.274	0.377	0.458	0.580
40	0.043	0.069	0.107	0.172	0.268	0.371	0.451	0.574
50	0.042	0.068	0.105	0.169	0.265	0.367	0.446	0.569

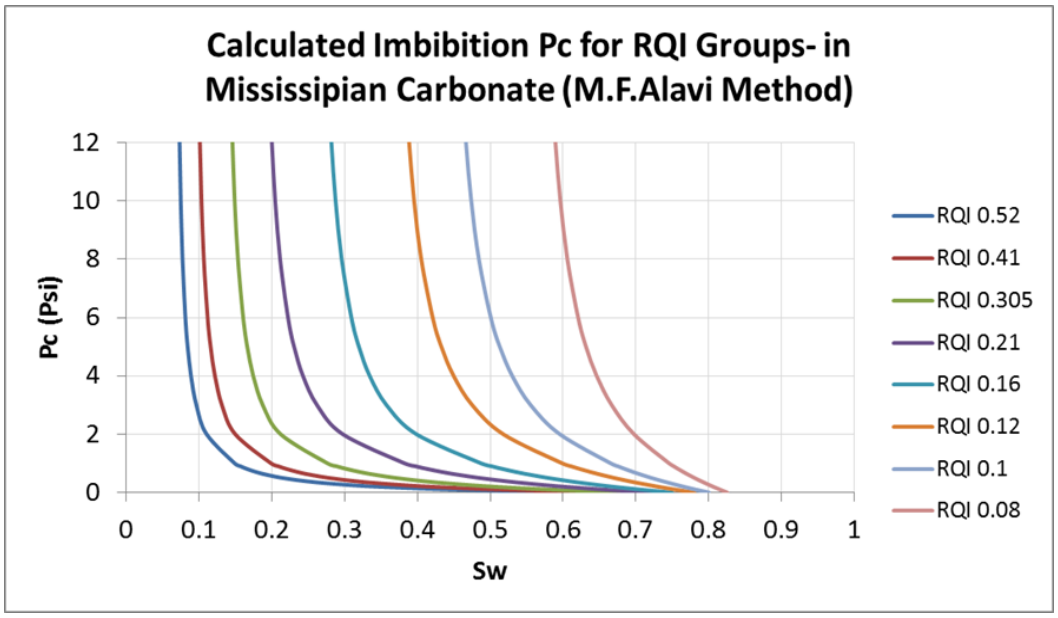

Figure 15: Calculated imbibition Pc curve for the Mississippian carbonate

IV. Calculation of Imbibition Relative Permeability Curves prior to receiving SCAL data

Relative permeability tables are critical data in reservoir simulation. It was proposed before to define eight saturation regions in the chat conglomerate model and eight in the carbonate section, based on the RQI of grid cells. Assuming that the reservoir is under saturated and that its pressure will always remain above bubble point pressure, only oil and water relative permeability tables are estimated for eight saturation regions each in the chat conglomerate and carbonate section of the Mississippian reservoir. To estimate relative permeability for these regions, the following modified Corey equations were used.

$$Kro = kro_{Swi}(1 - Sw_D)^p \quad \text{(Equation 34)}$$

$$Krw = krw_{Sorw} * (Sw_D)^q \quad \text{(Equation 35)}$$

$$Sw_D = \frac{(Sw - Swc)}{(1 - Sorw - Swc)} \quad \text{(Equation 36)}$$

Corey exponent p (Oil Corey Exponent) and q (Water Corey Exponent) were assumed at 2.5 and 1.5, respectively, based on experience from SCAL in other fields. Critical water saturation (Swc) was taken from Pc curves where capillary pressure is 10 psi. Residual oil saturation (Sor) was previously estimated by equations 19 and 20 based on SCAL data of several fields.

Oil relative permeability at Swc and max water permeability at Sor was derived from equations 37 and 38, which are correlations obtained from SCAL data in other fields.

$$Krw_{Sorw} = 0.1371 RQI^{-0.348} \quad \text{(Equation 37)}$$

$$Kro_{Swi} = 0.8909 RQI^{0.0194} \quad \text{(Equation 38)}$$

Tables B1 to B8 (Appendix B) present the parameters that were used to calculate the relative permeability of the chat conglomerate. Tables C1 to C8 (Appendix C) present the same parameters for the carbonate section of the Mississippian reservoir.

Eight sets of relative permeability tables were generated for the chat conglomerate (fig. 16), and eight sets of these curves were calculated for the carbonate section (fig. 17). All eight relative permeability curves for each chat and carbonate section can be found in Appendix B (figs. B1 to B8) and Appendix C (figs. C1 to C8).

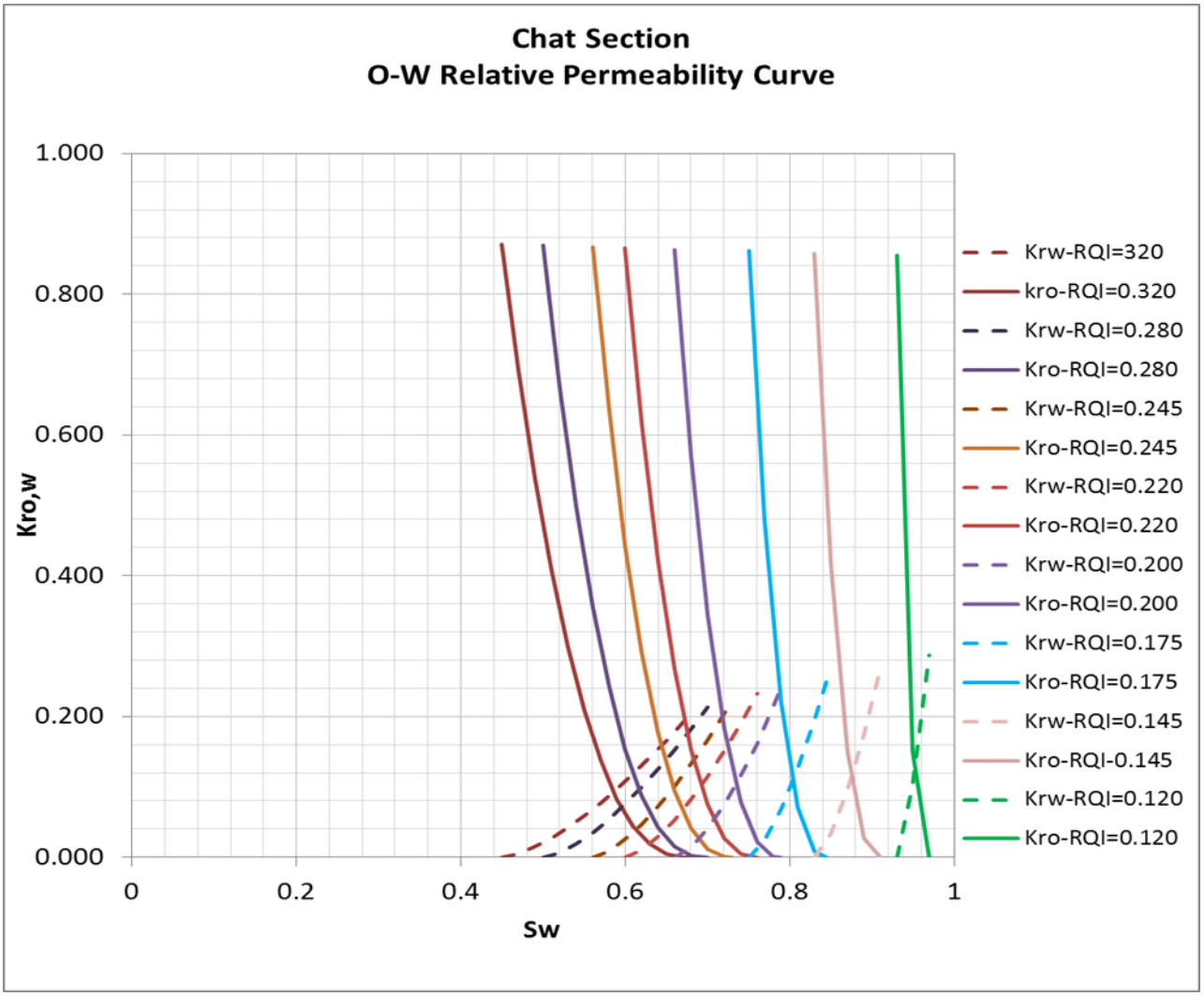

Figure 16: Relative permeability curves for the chat section at different RQI groups:

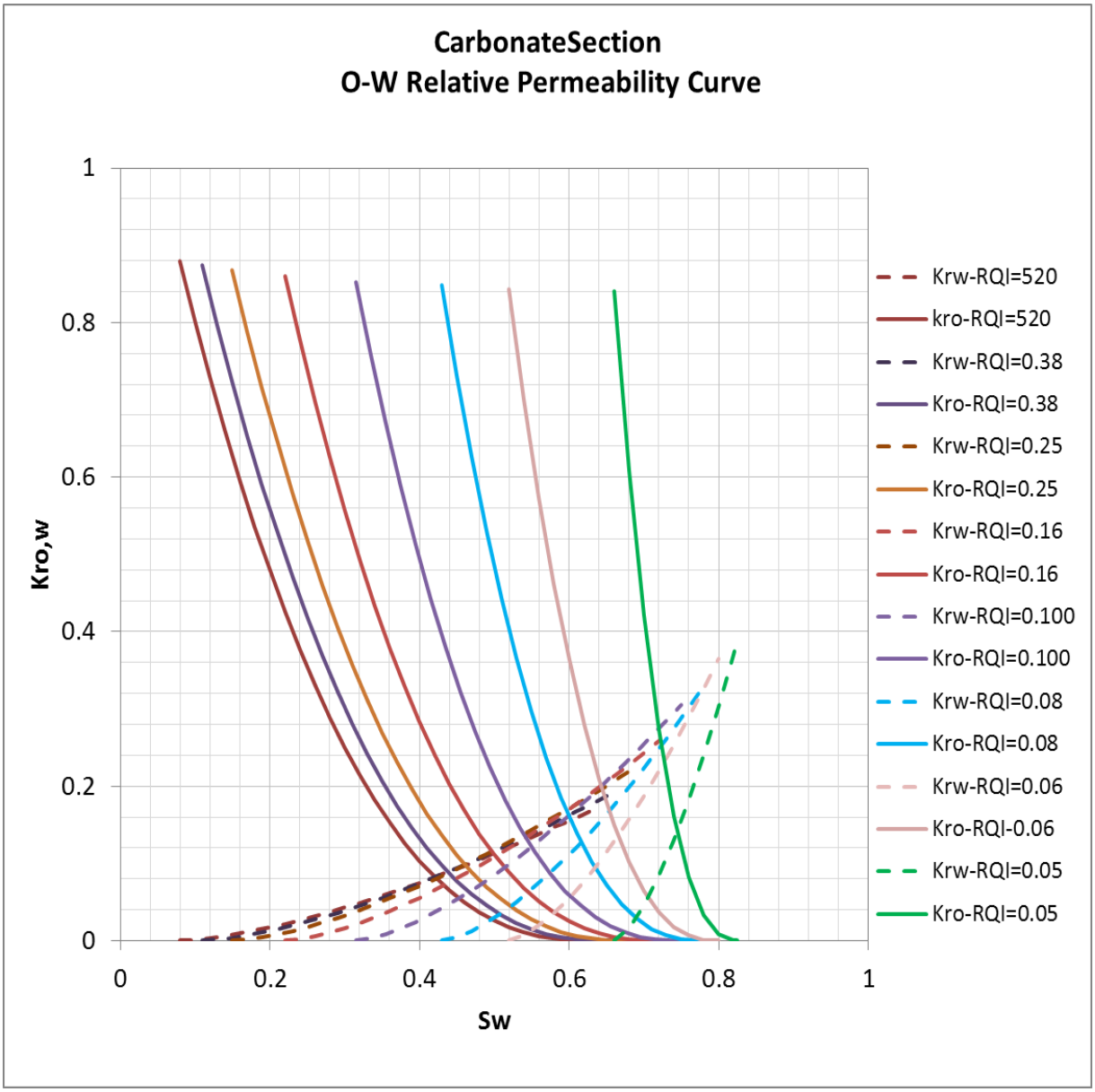

Figure 1 7: Relative permeability curves for the carbonate section at different RQI groups

V. Calibration of Previously Calculated Capillary Pressure and Relative Permeability Curves using Special Core Analysis (SCAL)

The relative permeability and capillary pressure curves were calculated twice in the Mississippian. The First time was prior to the receipt of receiving the laboratory Pc and relative permeability core measurements and the second time was after receiving the core measurements and this time they were calibrated using the core measured endpoints . Two core plug samples with similar RQI were sent to the Core lab for Pc and relative permeability measurements. The initial estimation of Pc curves was based on the endpoints that were calculated from NMR log. As shown in figure 5, there is a slight difference between calculated Pc and measured Pc before calibration. However, there is an excellent match between the calculated Pc and measured Pc after calibration, figure 5. Moreover, there is a slight difference between the initial calculated relative permeability and measured relative permeability. However, the match between them is excellent after calibration, figure 11.

Previously, the Mississippian was divided into two zones, chert (upper part) and carbonate (Lower part). The chert zone is not present in all wells in the Mississippian. Chert is about 20ft thick in Well 2-32 and about 13ft thick in Well 1-32, figure A3 and A1. Due to the variability in pore size shape from chert to carbonate zone, distinct sets of capillary pressure (Pc) and relative permeability curves were derived in each zone . Chert zone was neither implemented in the Geo-model nor the simulation due to its complexity; therefore, only the Pc and relative permeability curves for the carbonate zone were calibrated. Relative permeability and Pc curves were measured by Core Lab in two core-plugs in the carbonate zone of well 2-32. The 2 samples had identical reservoir quality index (RQI) that results in identical Pc and relative permeability curves. The two samples were used to calibrate the previously calculated Pc and relative permeability curves. First part of this report (A) is calibration of the Pc curves and second part (B) is calibration of the relative permeability curves.

A. Calibrating Capillary Pressure Curves

I. Irreducible Water Saturation (Swir)

Previously, Irreducible water saturation (Swir) was calculated for all depths from NMR T2 distribution and capillary pressure module in Techlog. The two Swir from the Pc core measurements were plotted on the previously plotted Swir from NMR against RQI, figure 1. Swir from Pc core measurements (in green) for RQI of 0.2 and 0.17 were lower in values than the calculated Swir from NMR module (in blue); therefore, the fitted curve was adjusted to pass through the Swir from the two Pc core measurements. The adjusted power equation of the curve will be used to calculate Pc curves for each RQI.

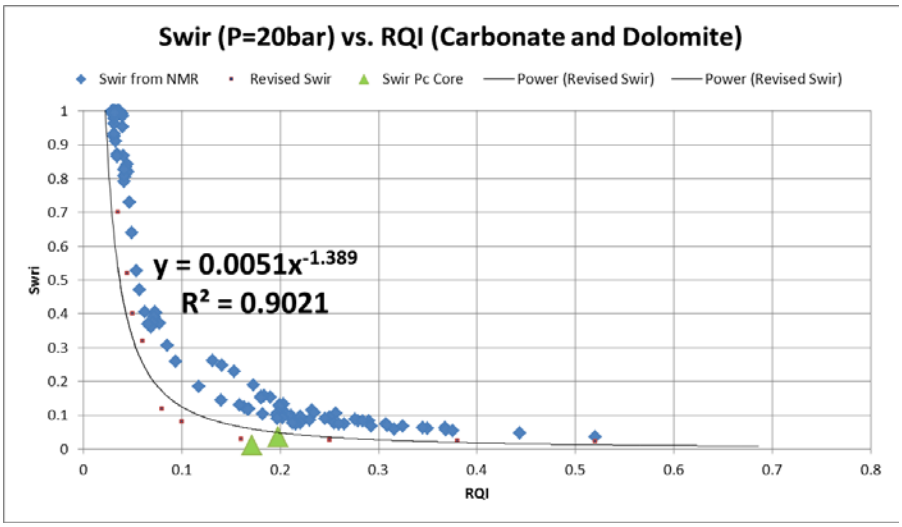

Figure 2: Irreducible water saturation (Swir) versus reservoir quality index (RQI)

II. Entry Pressure (P_e)

Previously calculated P_e from NMR did not match very well with the P_e from the Pc core measurements for RQI of 0.2 and 0.17, figure 2. Therefore, an alternative method that is entry pressure derivation from Winland R35 was attempted.

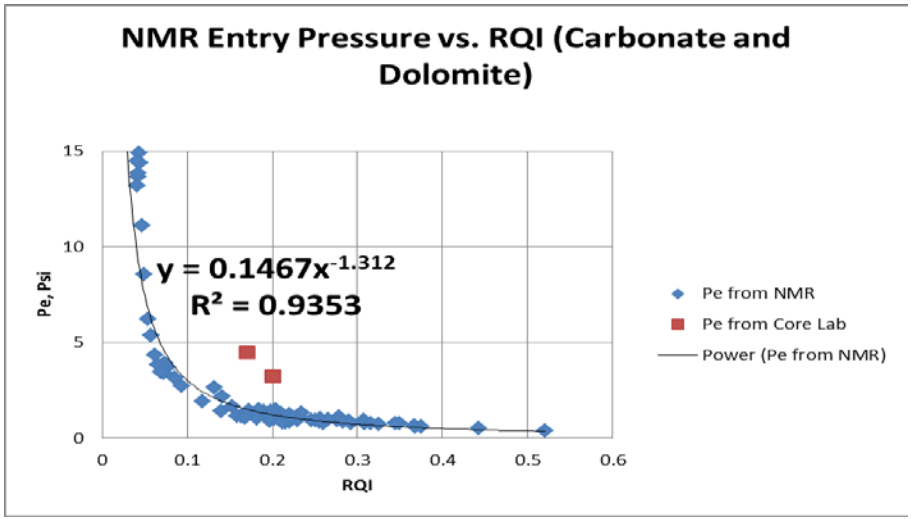

Figure 3: Entry pressure from NMR versus RQI

P_e was calculated for all depths from entry pore throat radius (R_{entry}) in which R_{entry} is calculated from Winland R35. It was noted previously that entry pressure (P_e) has a strong relationship with RQI. Also, there is a strong power correlation between R35 and RQI. On the other hand, there is a linear relationship between Windland 35 and R_{entry}; therefore, both R_{entry} and P_e can be correlated to RQI. R35 was calculated using equation 1:

$$\log R35 = 0.732 + 0.588 \log K - 0.864 \log \phi \qquad \text{Equation 1}$$

Previously calculated porosity and permeability in the Mississippian formation were used in equation 1 to calculate R35. Winland R35 was plotted against RQI (figure 3) and the power equation was used for determination of R_{entry}.

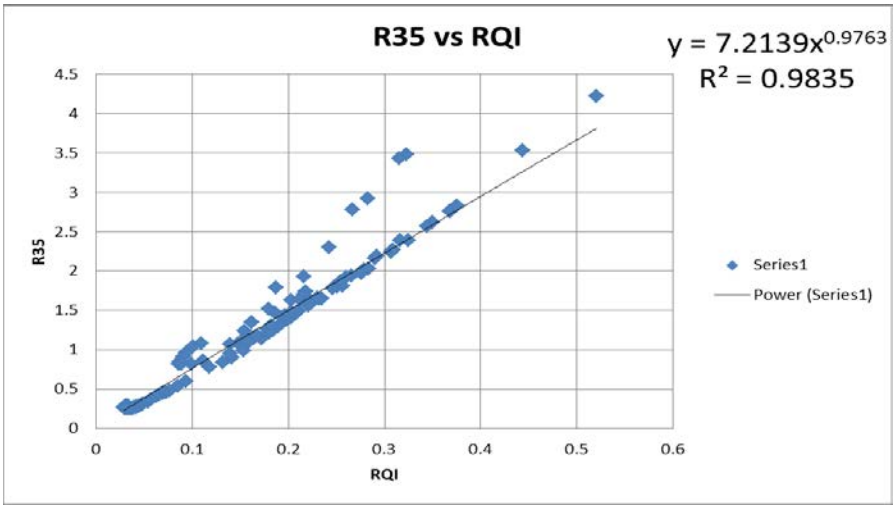

Figure 3: R35 Winland versus Reservoir Quality Index (RQI)

Figure 3 results in equation 2 which relates R35 to RQI. This relationship is

$$R35=7.21RQI^{0.98} \qquad \text{(Equation 2)}$$

R_{entry} is related to the relationship between R35 and RQI (figure 2) multiplied by a pre-factor, equation 3:

$$R_{entry}=c*(a*RQI^{b}) \quad \text{Equation 3}$$

Where:

C is a pre-factor, a=7.21 and b=0.98 from equation 2

Pre-factor c in equation 3 depends on the size of pores, degree of sorting and T2 distribution. This factor was determined by try and error so that the entry pressures (P_e) from laboratory for the two RQI match with the P_e calculated by equation 4, figure 4:

$$P_e=\frac{2*\sigma cos\theta*0.147}{c*(a*RQI^{b})} \qquad \text{Equation 4}$$

Where,

σ is interfacial tension

θ is contact angle in oil-brine system

Pre-factor c was determined by try and error by equation 4 which resulted in a value of 1.05. Interfacial tension of 20 dyne/cm and contact angle of 30 were used for oil-brine system. P_e was plotted against RQI to derive an equation to relate P_e to RQI which will be later used to calculate the Pc curves for each RQI in the Mississippian.

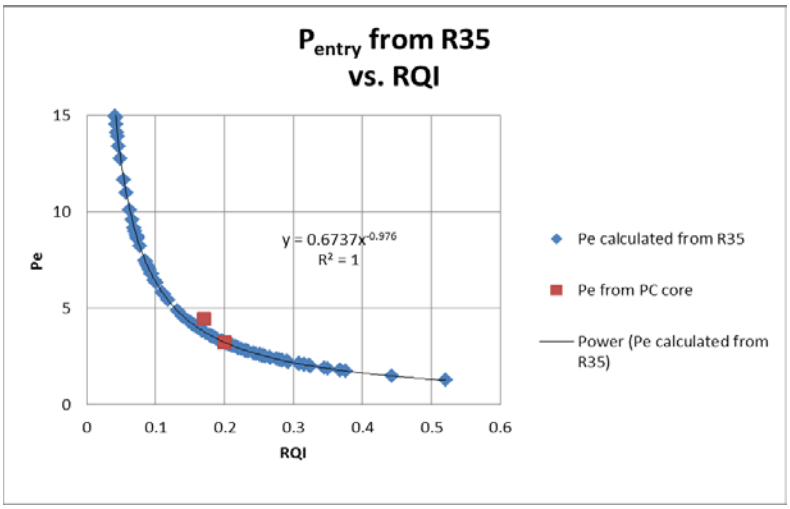

Figure 4: Entry pressure from R35 Winland

II. Shape of Pc curves

The previously calculated function between Normalized Non-wetting phase saturation (Snwn) and Equivalent radius (EQR) was revised. This function was previously derived from the generalized Pc curves from (Bhattacharya et al., 2003). This function was re-calculated using one of the Pc core samples that had RQI of 0.17. To calibrate the shape of Pc curves for all RQI, equivalent radius (EQR) which is P_e/pc and Normalized Non-wetting phase saturation (Snwn) which is (1-sw)/ (1-swir) were calculated for all Lab water saturations. Snwn was plotted against EQR (figure 4) and constants a and b of the curve were calculated by regression.

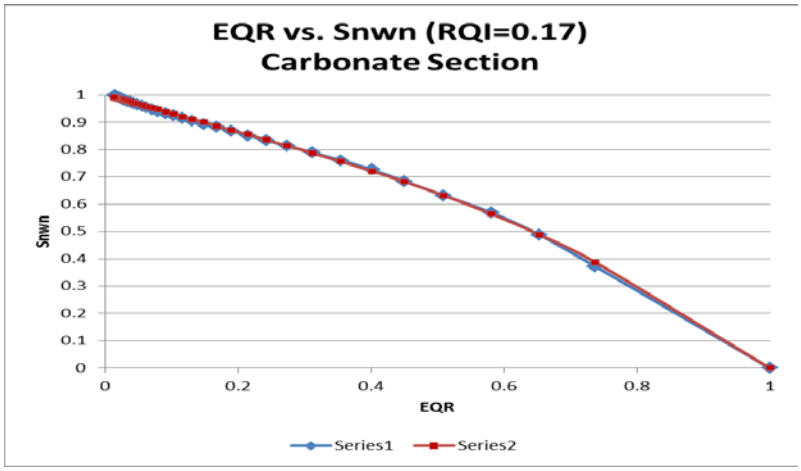

Figure 5: Non-wetting phase saturation (Snwn) versus reservoir quality index (RQI)

Figure 4 results in constants a and b equal to 0.67 and 4.79 respectively. The two constants, a and b, define the shape of Pc curves.

Drainage Capillary Pressure Curves

Drainage capillary pressure curves were re-calculated by incorporating equations from sections I, II and III into equation 5:

$$S_{wi} = 1 - \left(1 - 0.671\frac{0.707RQI^{0.976}}{P_c}\right)\left(1 - \left(\frac{0.707RQI^{0.976}}{P_c}\right)^{4.79}\right)(1 - 0.0051RQI^{-1.39})$$

Calculated Pc after calibration is compared with the calculated Pc before calibration and measured Pc from the core plug for the respective RQI of 0.2, figure 5. There is a good match between calculated Pc and measured Pc after calibration.

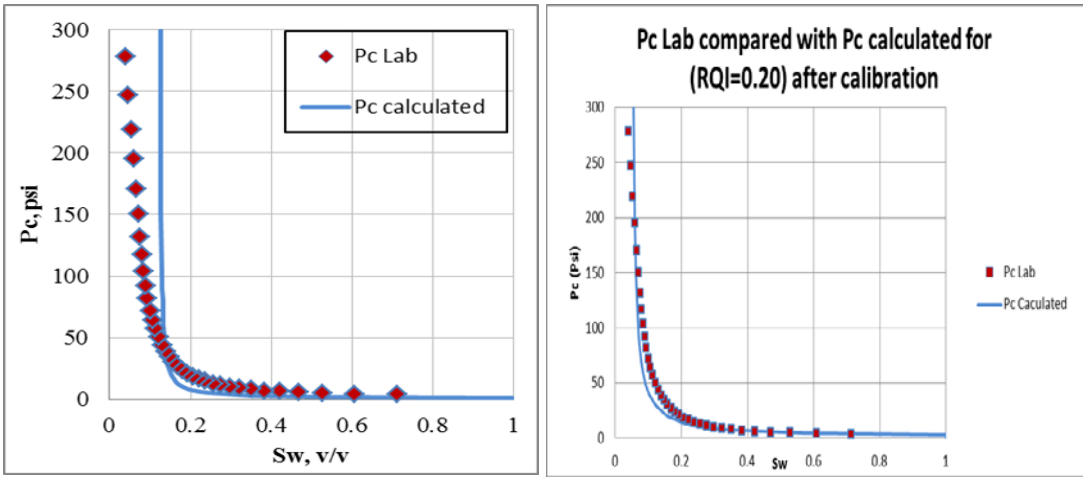

Figure 6: Capillary pressure curves for RQI 0.2 before calibration (left) and after calibration (right)

Since there is a good match between the calculated and measured Pc in figure 5; therefore, drainage Pc curves were calculated for eight RQI average that was sub-divided previously, figure 6:

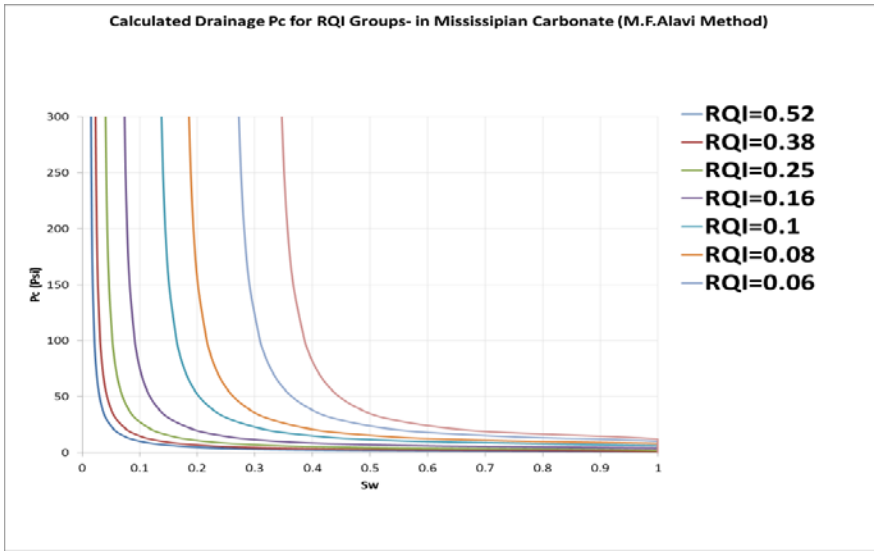

Figure 7: Drainage Pc curves for all RQI

Imbibition Capillary Pressure Curves

For revising the imbibition Pc curves, the same correlations as drainage curves were used; except, an additional term of residual oil saturation was incorporated. A relationship between Initial oil saturation (Soi) and residual oil saturation (Sor) was obtained from literature and the curve was adjusted slightly to lie on the residual oil measured from the relative permeability core measurements, figure 7.

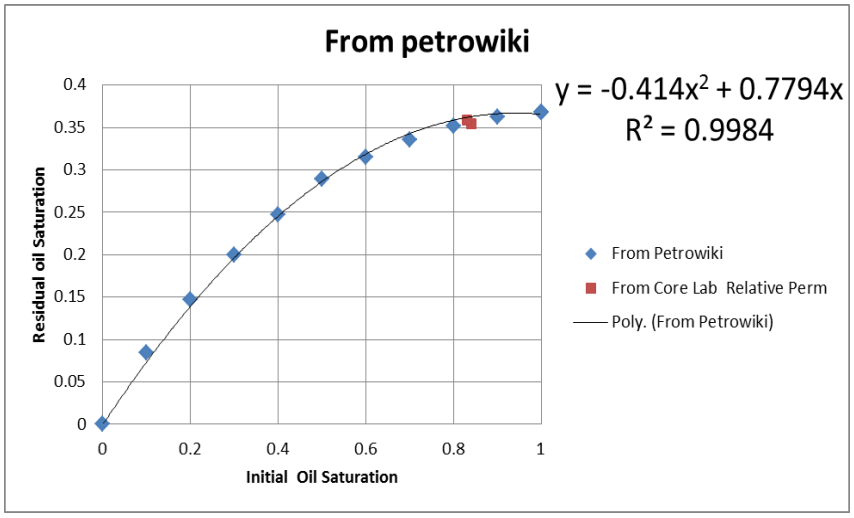

Figure 7: Relationship between residual oil saturation (Sor) and Initial oil saturation (Soi)

B. Calibrating Imbibition Relative Permeability Curves

I. Corey Exponents for Water and Oil

Relative permeability curves were measured in two core plug samples by Core Lab for RQI of 0.15 and 0.18 respectively. The laboratory relative permeability curves to water and oil were normalized for determination of Corey exponents for water and oil using equation 1.

$$KriN=\frac{Kri}{Krimax} \qquad \text{Equation 1}$$

Where,

i represent fluid (oil, water etc)

KriN: Normalized relative permeability for that fluid

Krimax: Maximum relative permeability for that fluid

To find Corey exponents for water and oil, Corey relative permeability correlations in equation 2 and 3 were used to curve fit the normalized relative permeabilities (KroN and KrwN). Normalized water saturation (SwN) in equation 2 and 3 was calculated by equation 4. Corey exponents for water and oil (b and a) are the fit parameters that were determined by least square regression.

$$KrwN = SwN^{b} \quad \text{Equation 2}$$

$$KroN = (1 - SwN)^{a} \quad \text{Equation 3}$$

$$SwN = \frac{Sw - Swi}{1 - Swi - Sor} \quad \text{Equation 4}$$

Where,

KrwN : Normalized relative permeability to water
SwN : normalized water saturation.
b: Corey exponent for water
KroN: Normalized relative permeability to oil
a: Corey exponents for oil

Figure 8 shows the fitted Normalized relative permeability for oil and water and the best-fit values for b and a are 0.88 and 2.12 respectively.

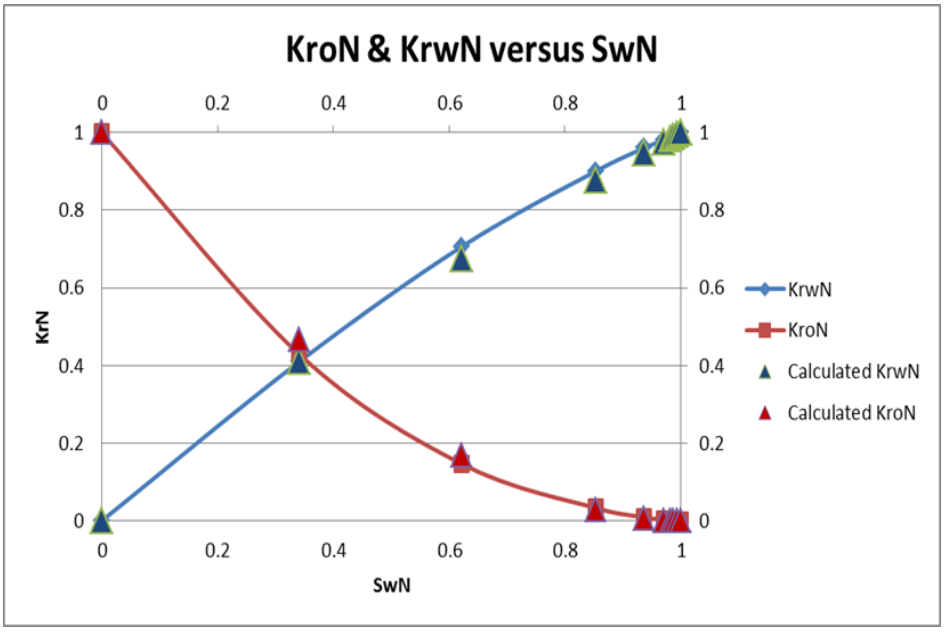

Figure 8: Normalized relative permeability (KroN) versus normalized water saturation (SwN) and best fit for a and b

The calculated Corey exponents for water and oil (b and a) from the two samples were averaged and will be used in the previously proposed relative permeability formula. The Corey exponents for each core sample and the average of the two are listed in table 1:

Table 1: Calculated Corey exponents for each sample individually and average values

Sample No	RQI	a	b
1	0.18	2.4	0.93
2	0.15	1.84	0.83
Average	**0.165**	**2.12**	**0.88**

II. Connate Water Saturation (Swc) and Residual Oil Saturation (Sor)

Previously connate water saturation (Swc) was taken from Pc curves where capillary pressure is 10 psi , figure 9. The average Swc of the two samples from Lab is slightly less than the previously plotted connate water for the same RQI; therefore, the curve was adjusted to match the Swc from Lab, figure 10.

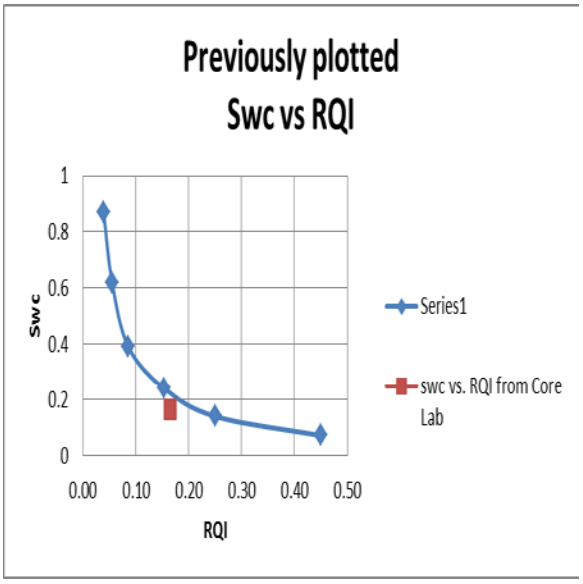

Figure 9: Previously Swc versus RQI

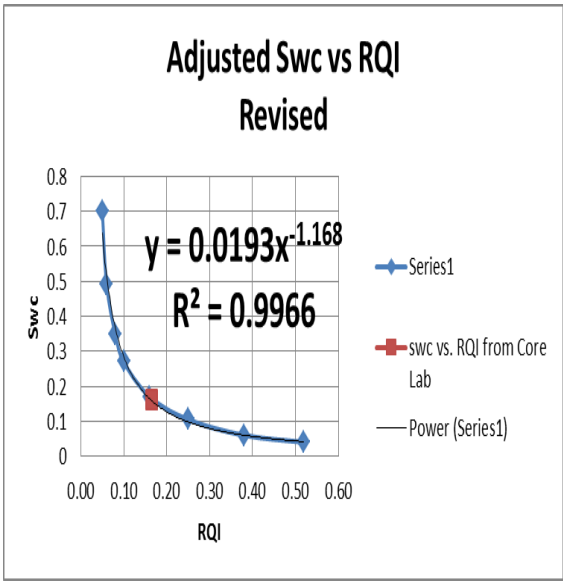

Figure 10: Adjusted Swc to match with Swc form Lab

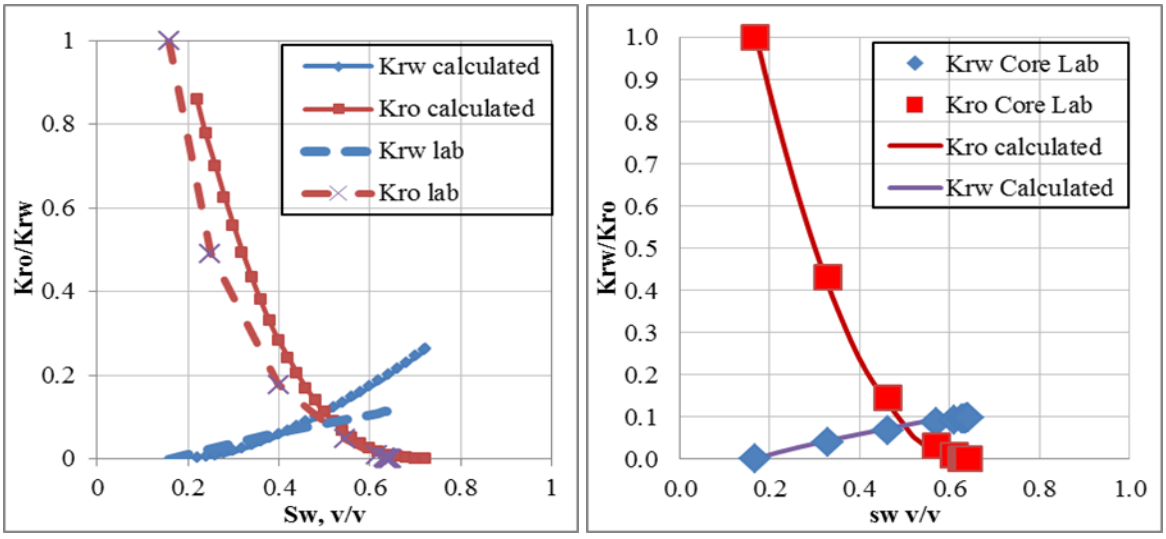

Figure 1 1: Relative permeability curves for RQI 0.16 before calibration (left) and after calibration (right)