Permeability From NMR Log of Well 1-32

Arbuckle Formation

Wellington Field (Rev 1)

Revised: May 2013, By: Mina F. Alavi

First it was attempted to calculate NMR permeability using Coates and SDR equations. However, a reasonable match between calculated and core permeability could not be obtained using these equations, although several pre-factors of the equations were tried. It was decided to calculate permeability by relating core FZI to 1/(Swir*Phi) and using the new technique. Predicted permeability was first calculated based on FZI from 90-degree core permeability and the same process was repeated for max permeability of core samples.

Pore structure in the Arbuckle is very complex and there are a lot of variations in pore size distribution (unimodal, bimodal, and trimodal) versus depth in very short intervals. Due to this complexity and non-homogeneity in pore size distribution, Arbuckle permeability was calculated based on pore size classification (micro, meso, and mega pores). FZI in each pore size class was correlated to 1/(Swir*Phi) of the same class.

To obtain a better match between calculated permeability and core permeability, the Arbuckle was divided into two zones. Zone 1 was considered to be from 4,160 to 4,700 ft and zone 2 from 4,700 to 5,200 ft.

Part 1: Determination of Permeability Using Permeability at 90 degree from Core

Permeability in Zone 1 (4,160 – 4,700 ft)

Permeability in zone 1 was calculated based on correlations between FZI from core and 1/(Swir*phi) from log. FZI from core data was calculated using permeability at 90 degree, and 1/(swir*phi) was calculated using effective porosity and irreducible water saturation from the NMR log. FZI and 1/(swir*phi) were sorted from low to high values. All FZI values less than 2 and 1/(swir*phi) values less than 48 were considered for micro pore sizes, which correspond to permeability values less than about 0.5 mD. Similarly, FZI from 2 to 11 and 1/(swir*phi) from 48 to 106 were considered for meso pore sizes, which correspond to permeability from about 0.5 to 25 mD. Finally, FZI from 11 to 150 and 1/(swir*phi) from 106 to 851 were considered for mega pore sizes, which correspond to permeability greater than about 25 mD. Table 1 lists the ranges.

Table 1: Ranges of FZI and 1/(Swir*Phi)

	Approx k	FZI	Excel Row	1/(Swir*Phi)	Excel Row
Micro	<0.5	<2.02	4–82	<48.62	4–430
Meso	0.5-25	2.02-10.97	83–170	48.62-106	431–937
Mega	>25	10.97-150	170–246	106-851	938–1,083

Percentiles (5, 10, 20… 90) of FZI population in each class were correlated with respective percentiles of 1/(Swir*phi) population (figs. 1, 2, and 3). Four different correlations between FZI and 1/(swir*phi) were derived for micro, meso, and mega pore sizes. Figures 1, 2, and 3 show these correlations. Two of the equations are for micro pore sizes.
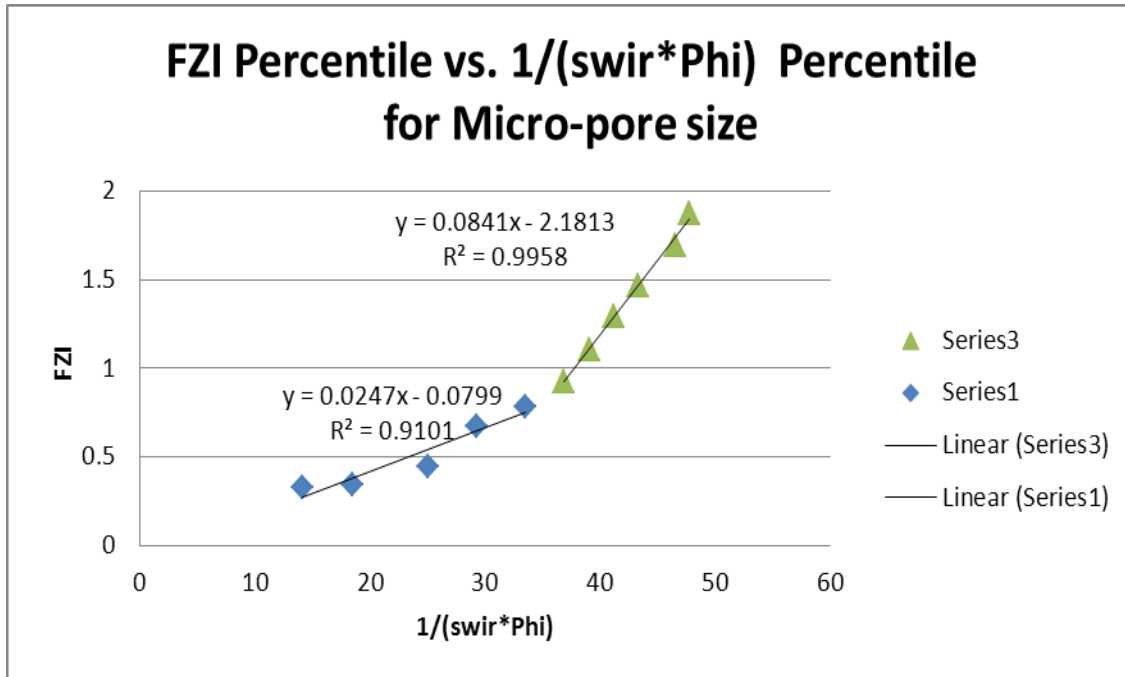

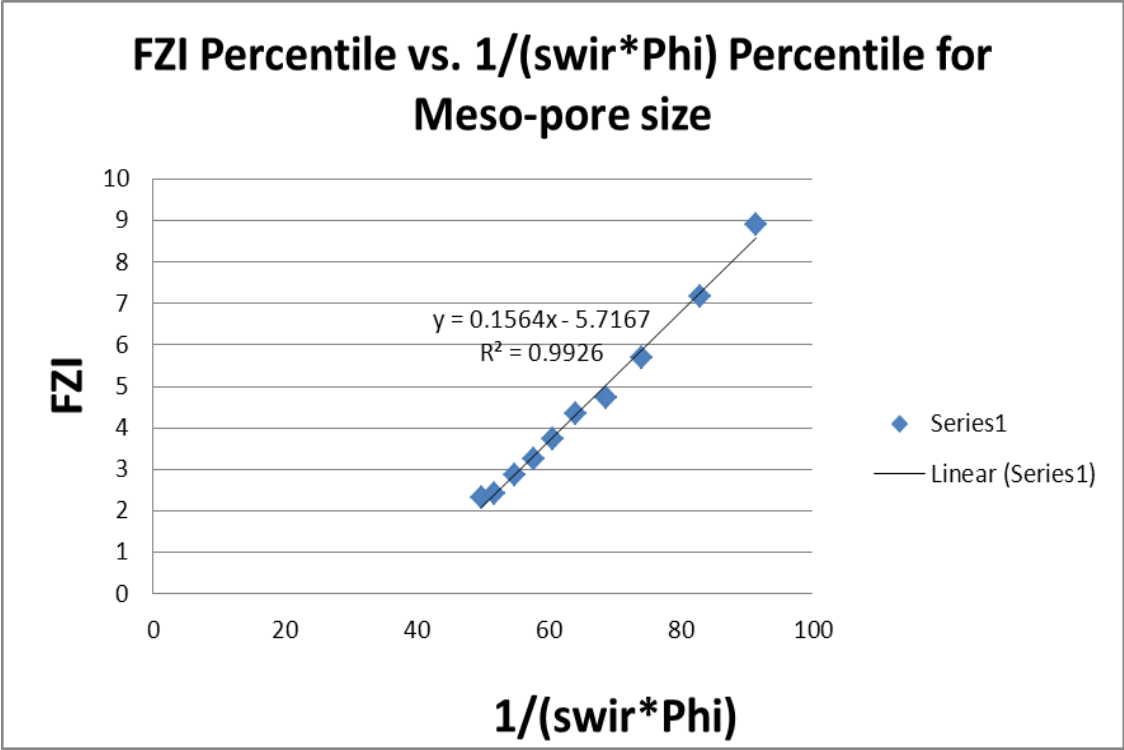Figure 1: Plot of FZI vs 1/(swir*phi) for micro pore sizes

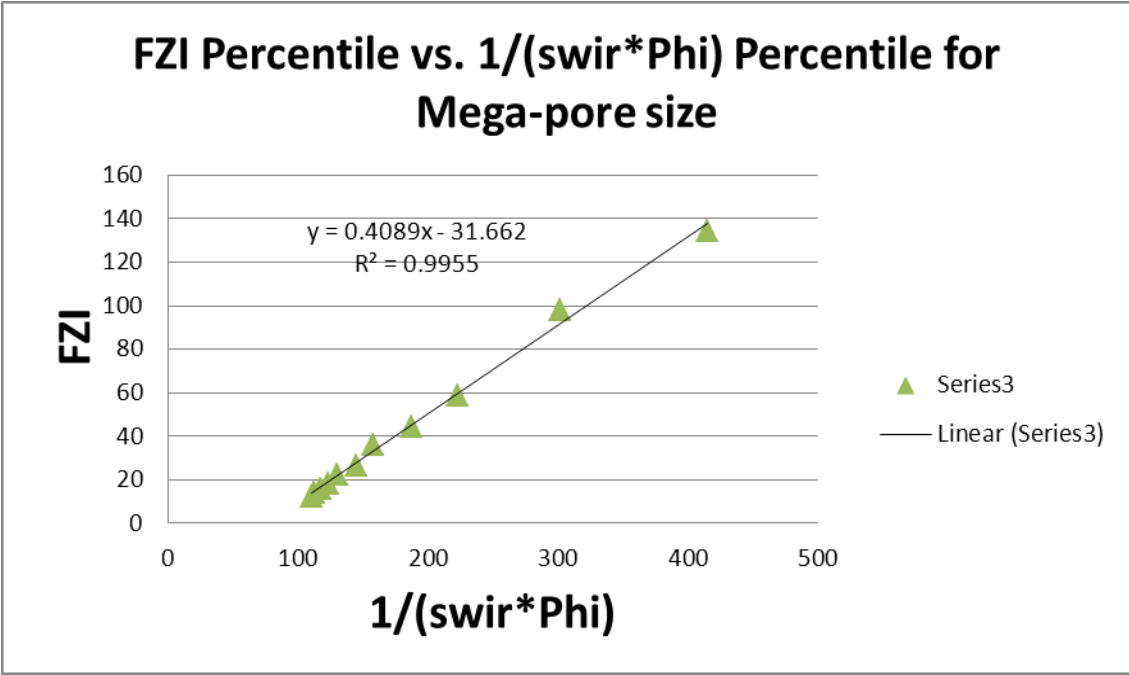Figure 2: Plot of FZI vs 1/(swir*phi) for meso pore sizes

Figure 3: Plot of FZI vs 1/(swir*phi) for mega pore sizes

Permeability in Zone 1 was calculated using Equation 3 and coefficients *a* and *b,* which were derived from the correlations.

$$\text{Eq. 1:} \qquad K = 1014[FZI]^2 \frac{\phi_e^3}{(1-\phi_e)^2}$$

$$\text{Eq. 2:} \qquad FZI = \frac{a}{S_{wir}\phi_e} + b$$

$$\text{Eq. 3:} \quad K = 1014\left[\frac{a}{S_{wir}\phi_e} + b\right]^2 \frac{\phi_e^3}{(1-\phi_e)^2}$$

Table 2 lists coefficients *a* and *b,* which were obtained by the correlations and their 1/(Swir*Phi) range of application. The table also gives the approximate T2 distribution range for each pore size class.

Table 2: Coefficients *a* and *b* of Equation 3

	a	*b*	R2	1/(Swir*Phi)	Approx T2
Micro	0.0247	-0.0779	0.9101	<36	<50
Micro	0.0841	-2.1813	0.996	<48	<50
Meso	0.1564	-5.7167	0.9926	48–106	50–1,100
Mega	0.4089	-31.662	0.9955	>106	50–10,000

Figure 4 plots calculated permeability versus depth where they are compared with core permeability. Calculated micro pore permeability is shown by brown dots in this plot, while meso and mega pore permeability values are shown by green and blue dots, respectively. Although T2 distribution curves were very complex, it is believed that calculated permeability matches very well with core data.

Figure 4: Permeability vs. depth (micro, meso, and mega pore permeability values)
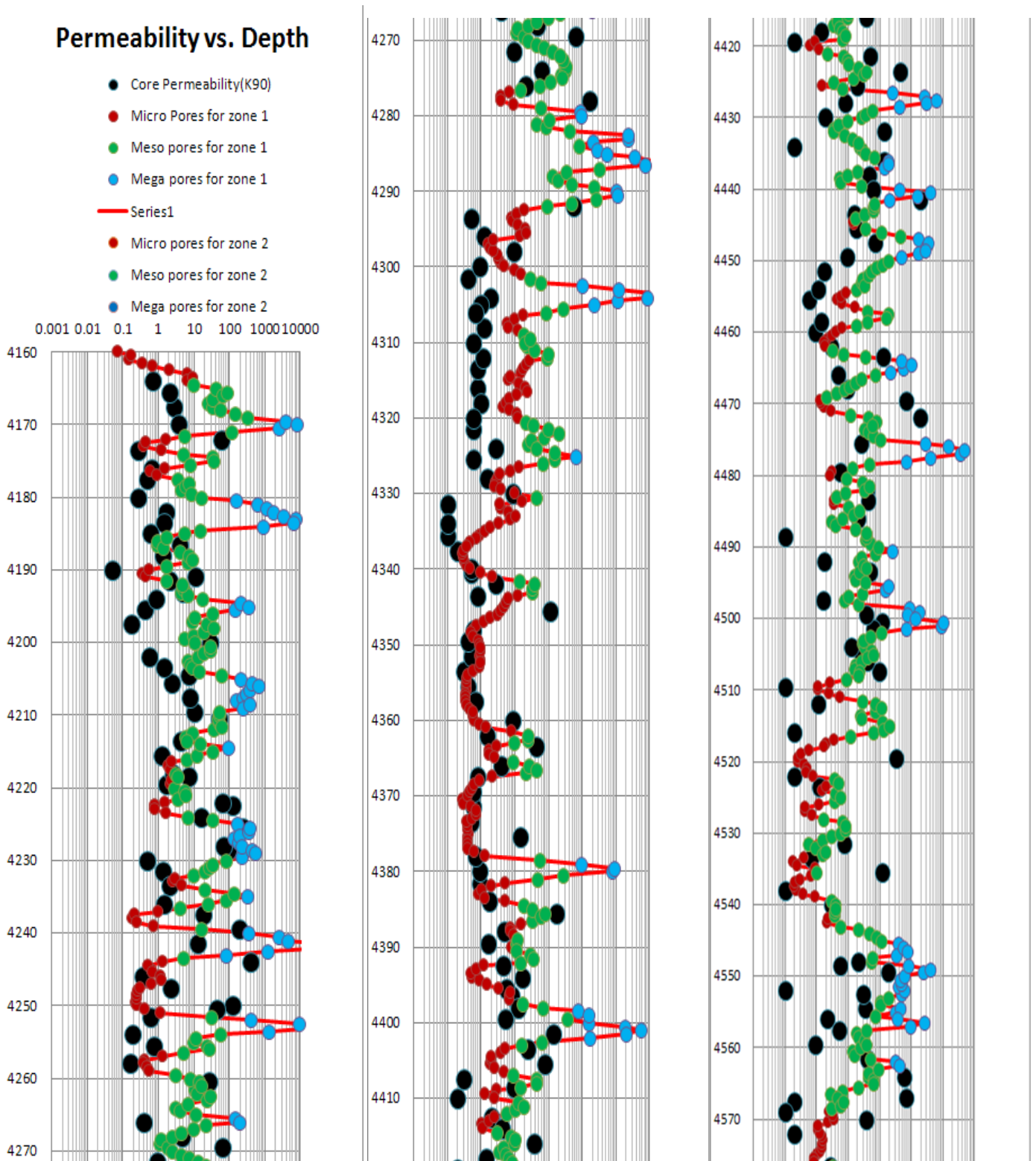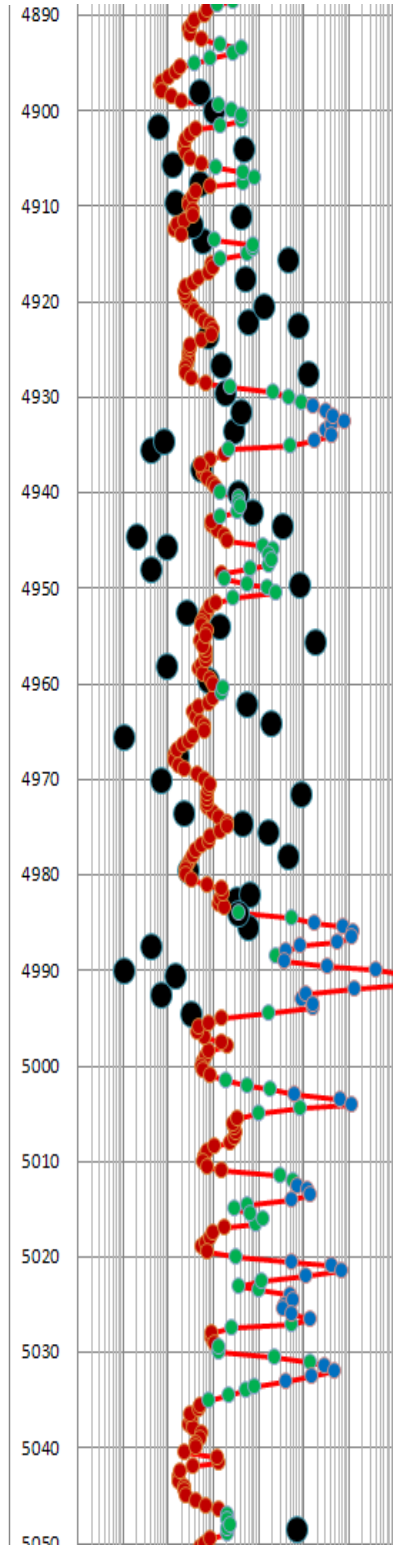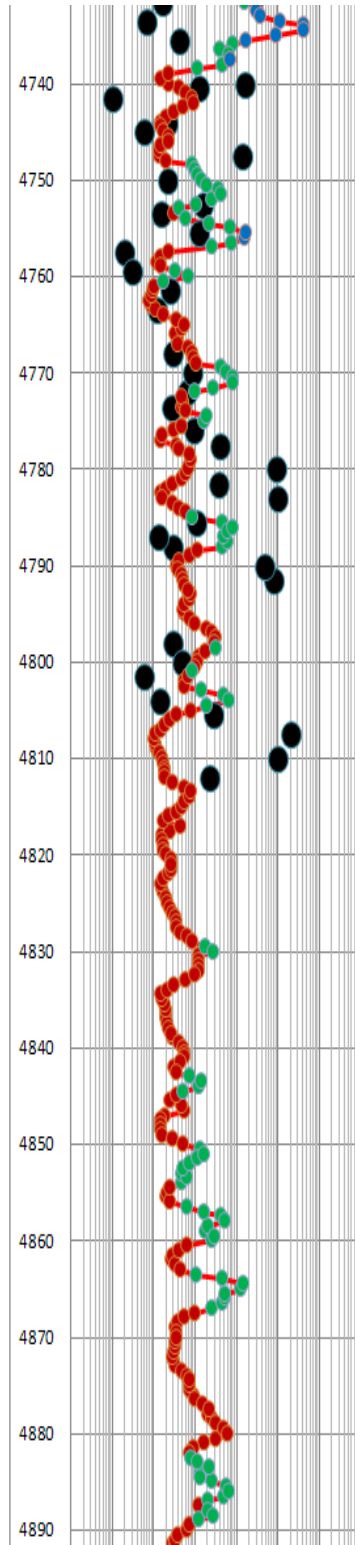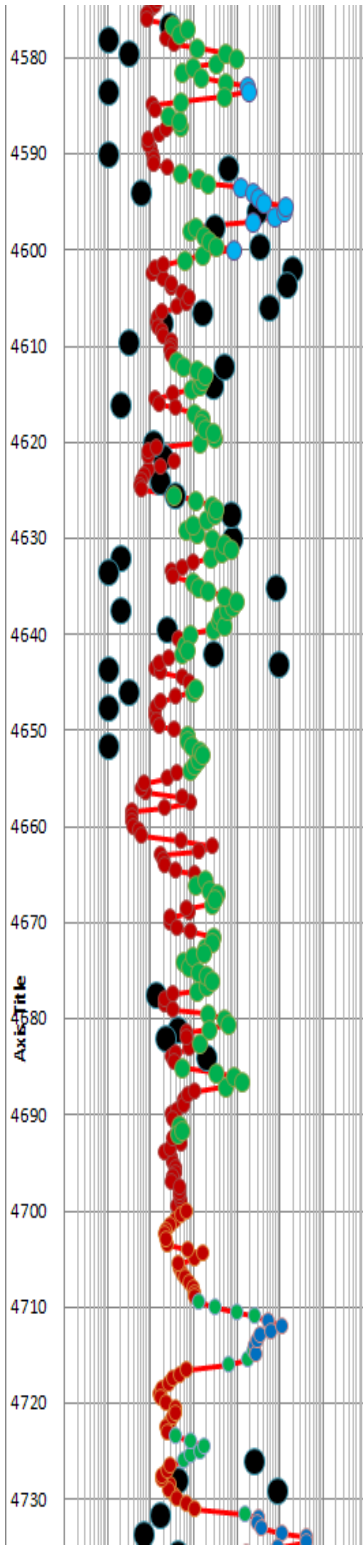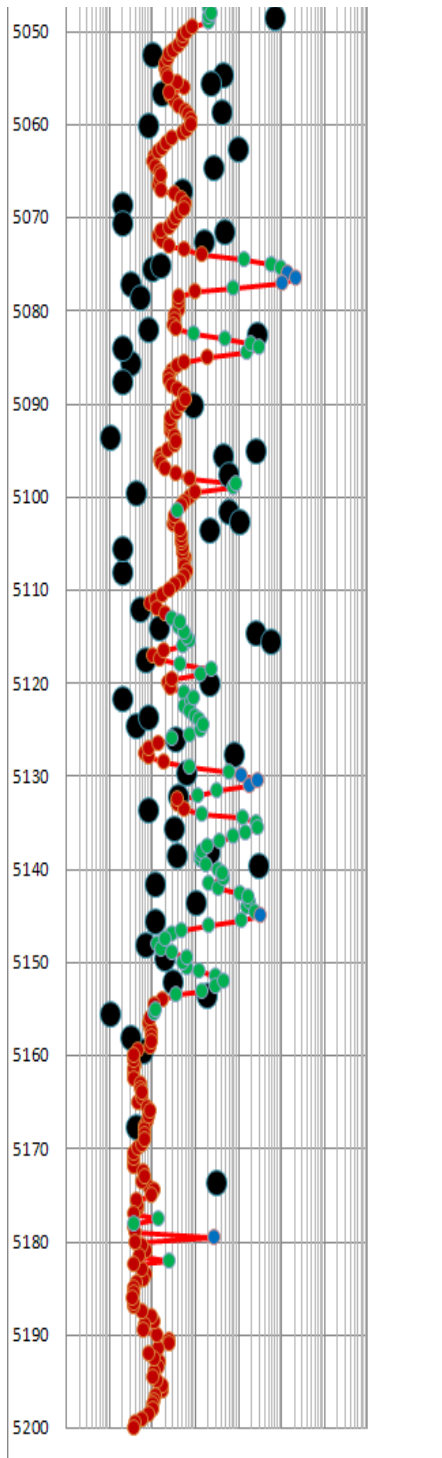
Permeability in Zone 2 (4,700 – 5,200)

The same ranges of FZI and 1/(swir*phi) were considered for micro, meso, and mega pore size classifications in Zone 2, which correspond to approximate permeability ranges of less than0.5mD, from 0.5 to25mD, and greater than 25mD, respectively. Table 3 lists the ranges.

Table 3: Ranges of FZI and 1/(Swir*Phi)

	Approx k	FZI	Excel Row	1/SwPhi	Excel Row
Micro	0–0.5	0–2.02	247–297	0–48.62	1,084–1,750
Meso	0.5–25	2.02–10.97	298–366	48.62–106	1,751–2,011
Mega	>25	10.97–150	367–404	106–851	2,012–2,080

Percentiles (5, 10, 20 … 90) of FZI population were correlated with respective percentiles of 1/(Swir*phi) population for each pore size category (figs. 5, 6, and 7). Four different correlations between FZI and 1/(swir*phi) were derived for micro, meso, and mega pore sizes. Figures 5, 6, and 7 show these correlations. Two of the equations are for micro pore sizes.
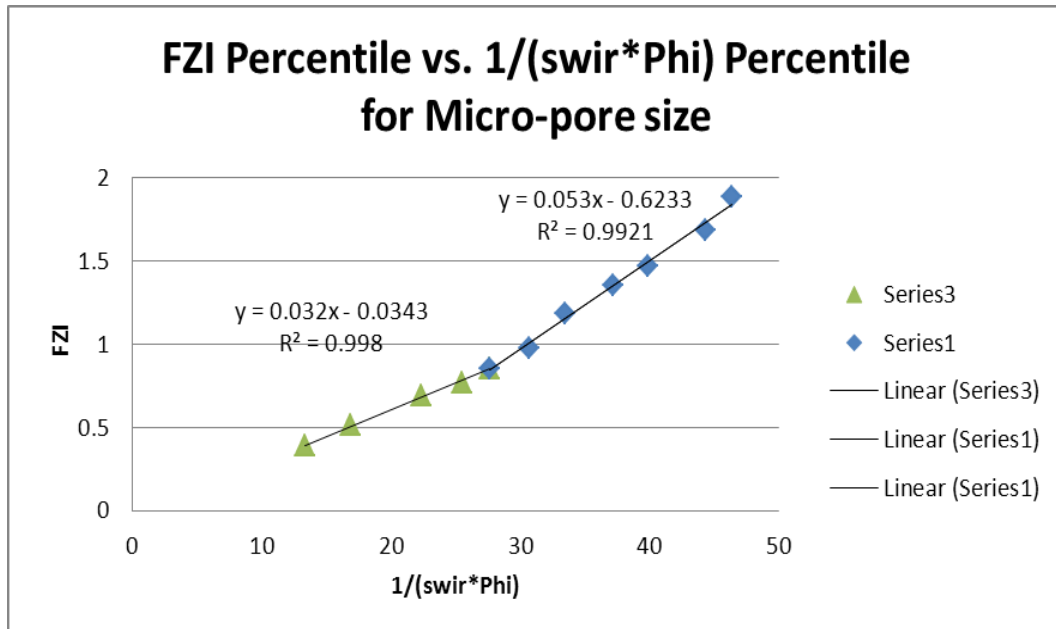

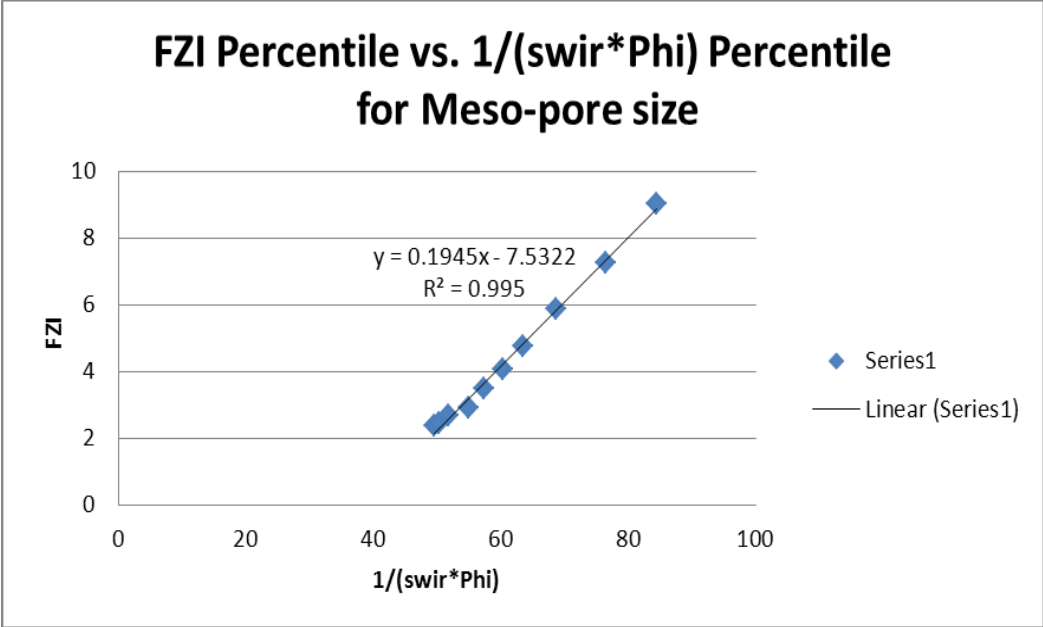Figure 5: Plot of FZI vs 1/(swir*phi) for micro pore sizes

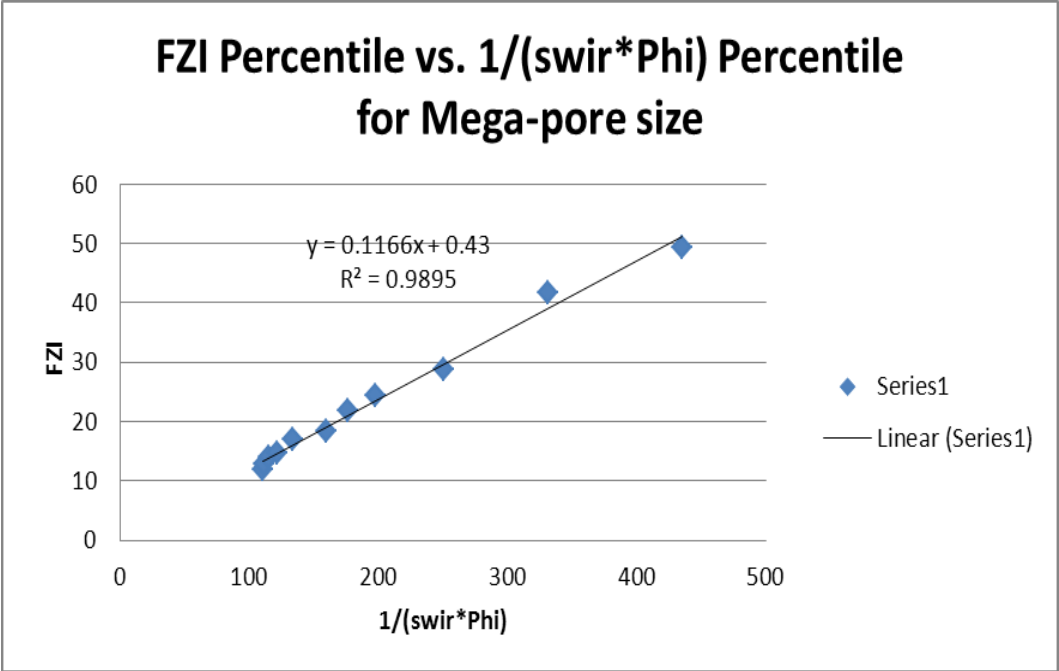Figure 6: Plot of FZI vs 1/(swir*phi) for meso pore sizes

Figure 7: Plot of FZI vs 1/(swir*phi) for mega pore sizes

Permeability in zone 2 was calculated using Equation 3. Table 4 lists coefficients *a* and *b,* which were obtained by the correlations, and their 1/(Swir*Phi) range of application. The table also gives the approximate T2 ranges.

Table 4: Coefficients *a* and *b* of Equation 3

	a	*b*	R2	1/(Swir*Phi)	Approx T2
Micro	0.032	-0.034	0.998	<28	< 50
Micro	0.053	-0.623	0.992	28–48	< 50
Meso	0.195	-7.532	0.995	48–106	50–1,100
Mega	0.1166	0.43	0.990	>106	50–10,000

Figure 4 plots the calculated permeability in Zone 2 versus depth and compared with core measurements. Details of calculations are in an Excel Workbook called calculated permeability based on K_{90} from the NMR log of well 1-32, which is available upon request, and a layout of calculated permeability with log derived lithology, GR, NMR T2 distribution can be seen in Sheet 2 (Graphs) of this Excel Workbook.

Part 2: Determination of Permeability using Maximum Permeability from Core

Permeability Based on K_{Max} in Zone 1 (4,160–4,700 ft)

Correlations between FZI from core using Kmax and 1/ (Swir*phi) from log were used to derive permeability. Maximum permeability and porosity from routine core analysis were used to calculate FZI. Irreducible water saturation and effective porosity from the NMR log were used to calculate 1/ (Swir*phi). The same ranges of FZI and 1/ (Swir*phi) as mentioned in the first part of the report were used for micro, meso, and mega pore size classification. These ranges correspond to permeability ranges of less than 0.5, from 0.5to–25mD, and greater than 25 mD respectively. Table 5 lists the ranges.

Table 5: Ranges of FZI and 1/(Swir*Phi)

	Approx k	FZI	Excel Row	1/(Swir*Phi)	Excel Row
Micro	<0.5	<2.02	4–114	<48.62	4–430
Meso	0.5–25	2.02–10.97	115–218	48.62–106	431–937
Mega	>25	10.97–150	219–318	106–851	938–1,083

Four different correlations were derived for micro, meso, and mega pore size based on max permeability of whole cores. Figures 8, 9, and 10 show these corrections.
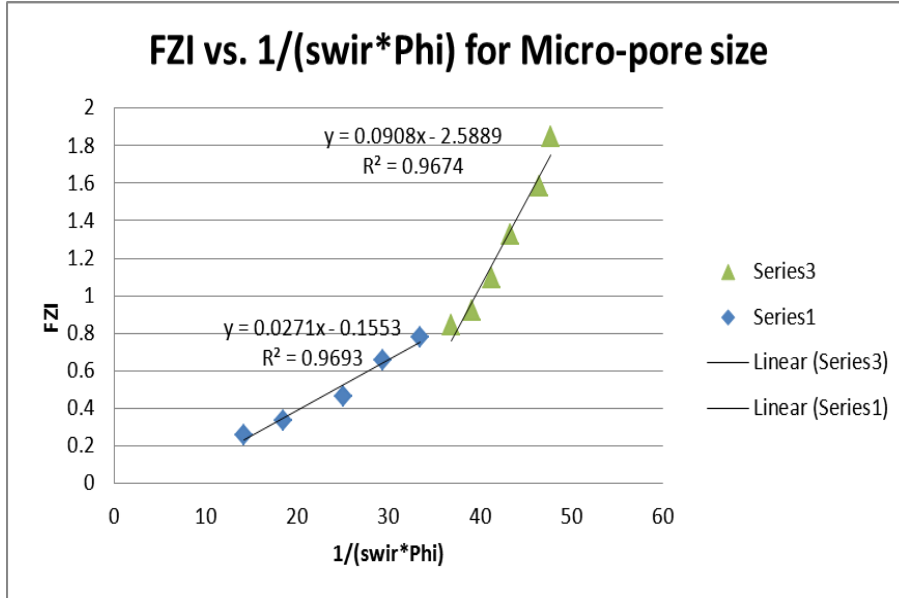

Figure 8: Plot of FZI vs 1/(swir*phi) for micro pore sizes
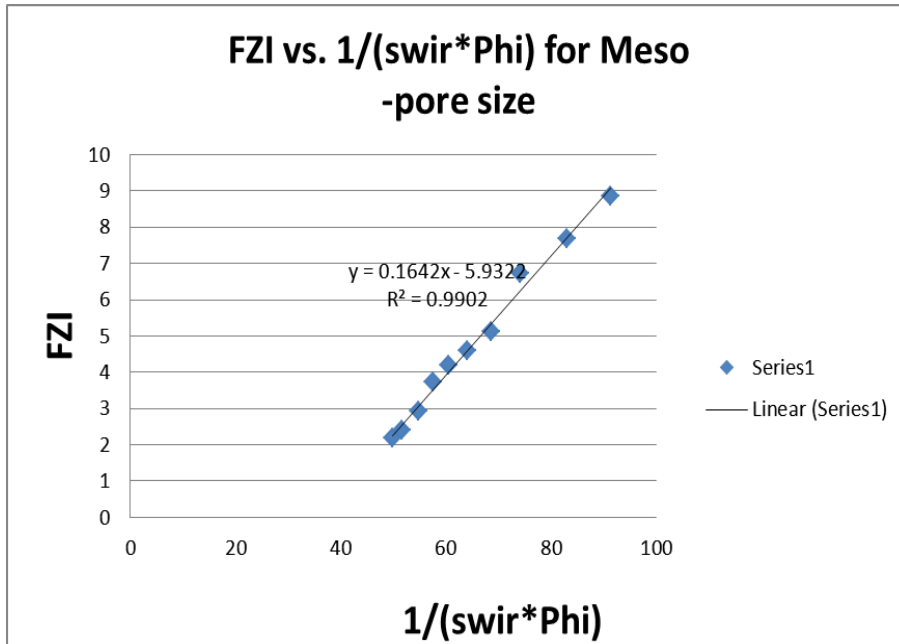

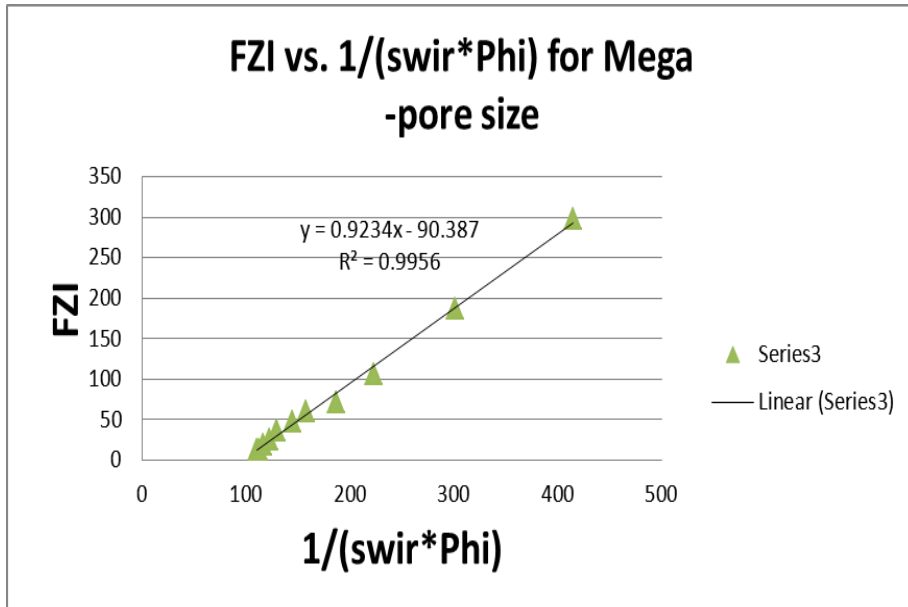Figure 9: Plot of FZI vs 1/(swir*phi) for meso pore sizes

Figure 10: Plot of FZI vs 1/(swir*phi) for mega pore sizes

Permeability was calculated in zone 1 using Equation 3, and coefficients *a* and *b* were derived from figs. 1, 2, and 3. Table 6 lists the coefficients and applied ranges.

Table 6: Coefficients *a* and *b* of Equation 3

	a	*b*	R2	1/(Swir*Phi)	Approx T2
Micro	0.0271	-0.1553	0.9693	<36	<50
Micro	0.0908	-2.5889	0.9674	<48	<50
Meso	0.1642	-5.9322	0.9902	48–106	50–1,100
Mega	0.9234	-90.387	0.9956	>106	50–10,000

Figure 11 plots calculated permeability versus depth where they are compared with core max permeability. Calculated micro pore permeability is shown by brown dots in this plot, and meso and mega pore permeability values are shown by green and blue dots, respectively.

Fig. 11: Permeability vs. depth (micro, meso, and mega pore permeability values)
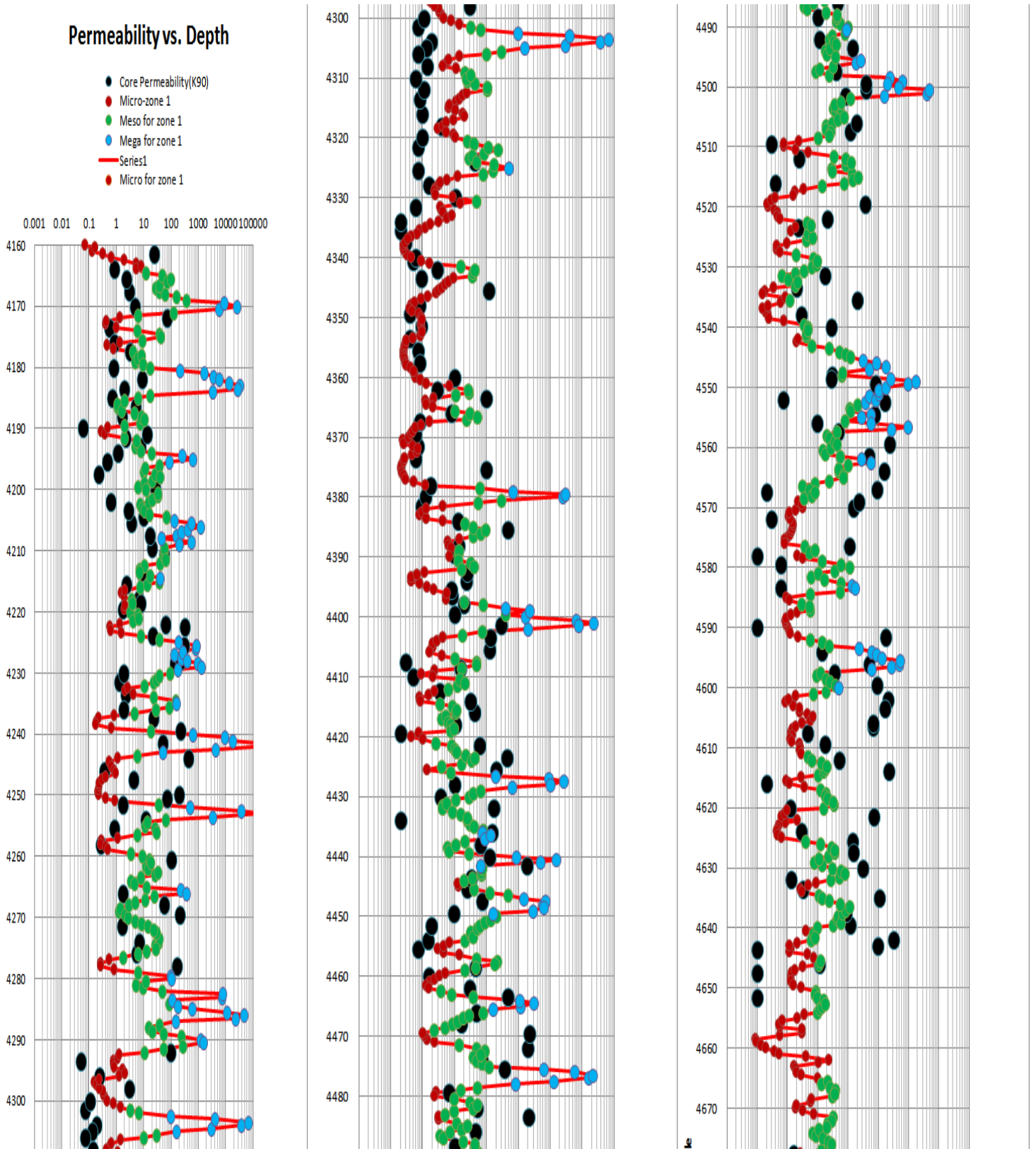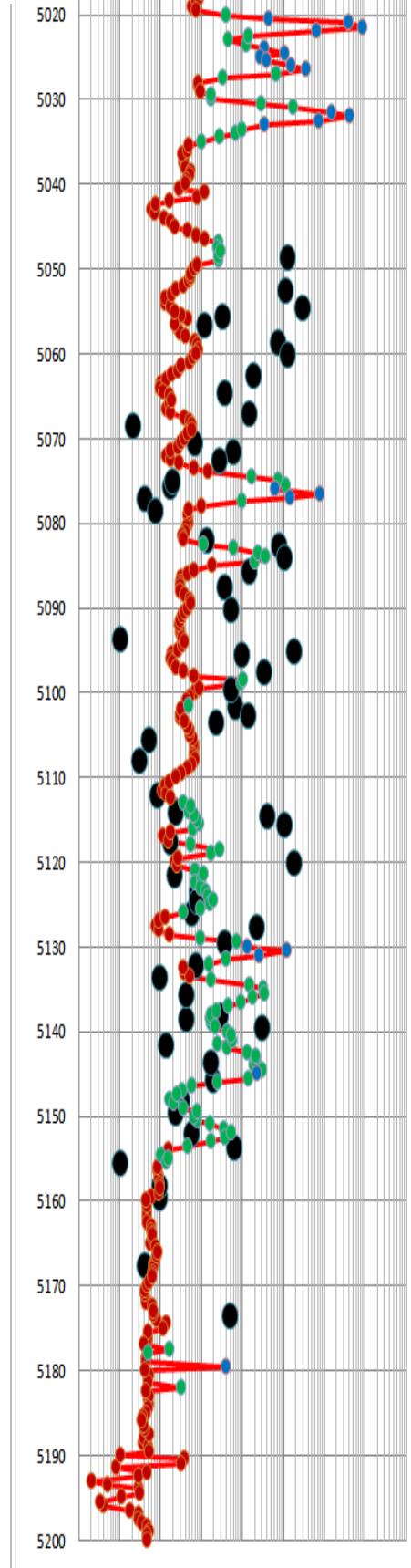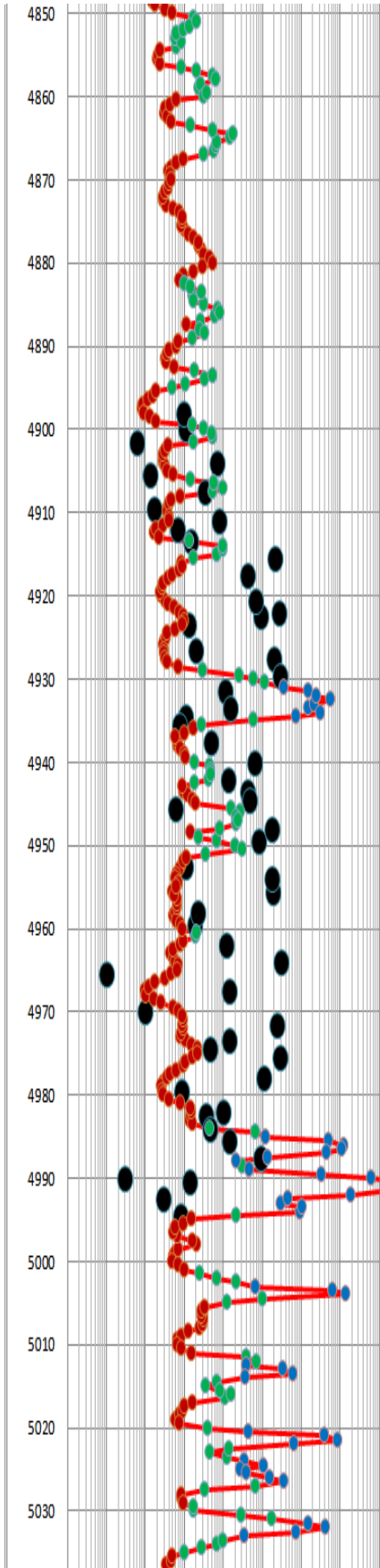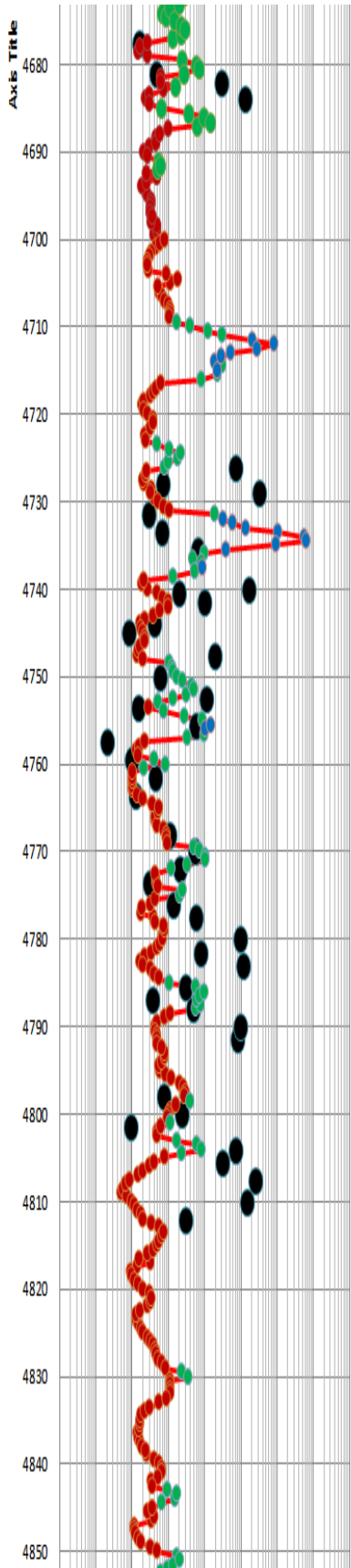
Permeability Based on K$_{Max}$ in Zone 2 (4,700 – 5,200)

The same ranges of FZI and 1/(swir*phi) were considered for micro, meso, and mega pore size classifications in Zone 2, which correspond to approximate permeability range of less than 0.5, from 0.5to –25mD, and greater than 25 mD respectively. Table 7 lists the ranges:

Table 7: Ranges of FZI and 1/(Swir*Phi)

	Approx k	FZI	Excel Row	1/(Swir*Phi)	Excel Row
Micro	<0.5	<2.02	319-348	<48.62	4-430
Meso	0.5-25	2.02-10.97	348-404	48.62-106	431-937
Mega	>25	10.97-150	405-480	106-851	938-1083

Three correlations between FZI and 1/ (swir*phi) were derived in zone 2. Figures 12, 13, and 14 show these correlations.
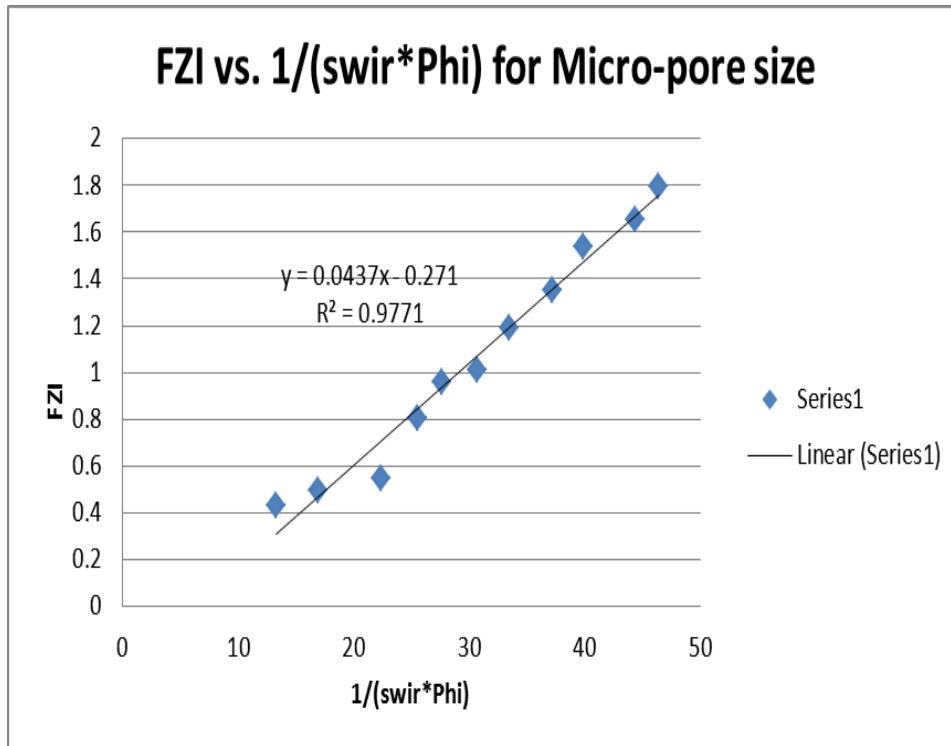

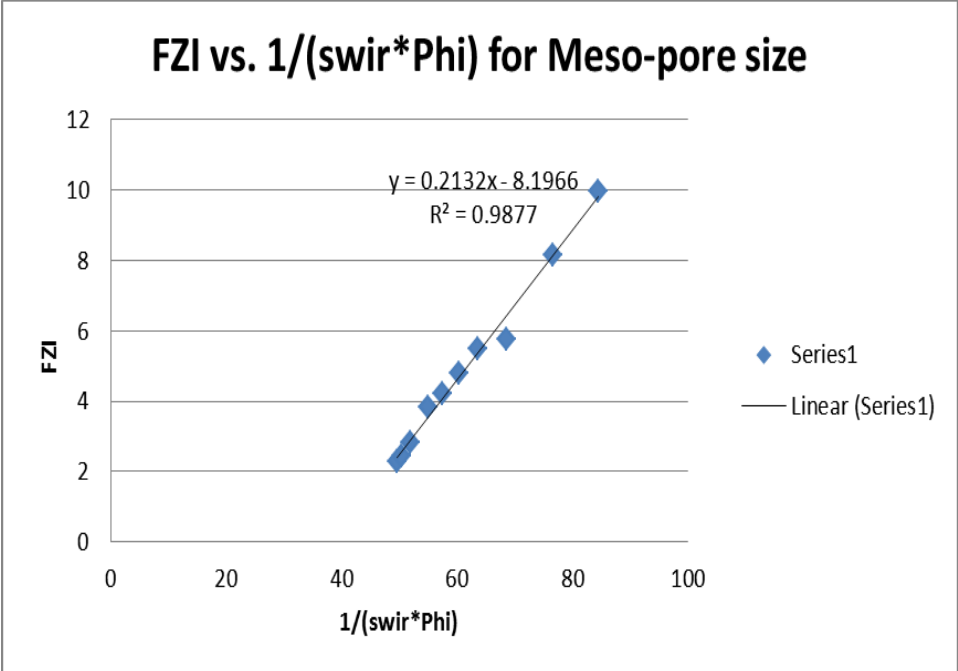Figure 12: Plot of FZI vs 1/(swir*phi) for micro pore sizes

15

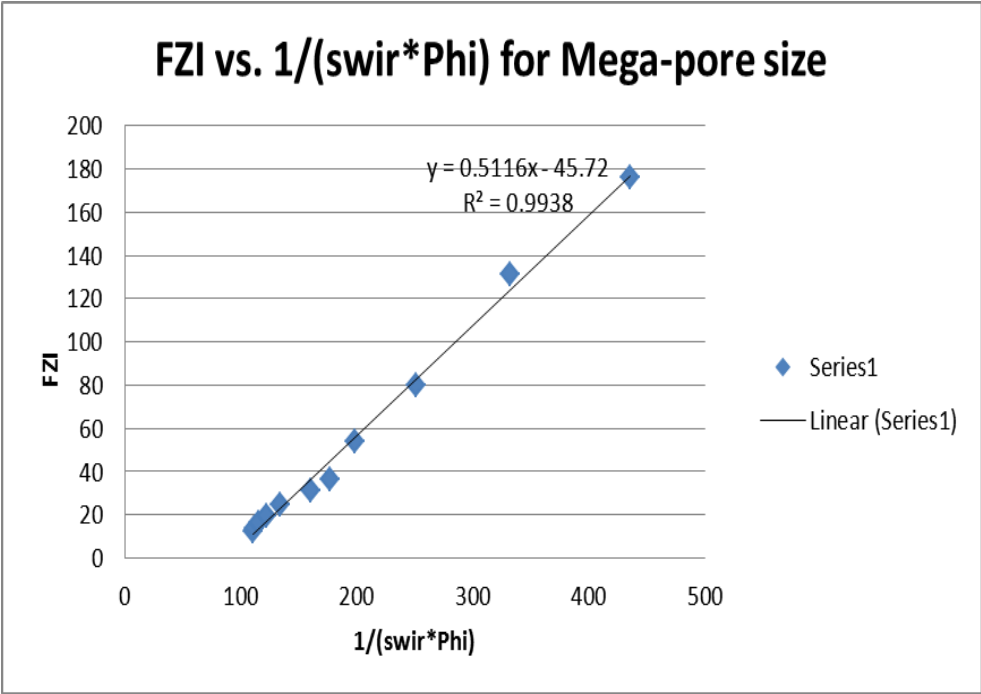Figure 13: Plot of FZI vs 1/(swir*phi) for meso pore sizes

Figure 14: Plot of FZI vs 1/(swir*phi) for mega pore sizes

Permeability was calculated in zone 2 using Equation 3, and coefficients *a* and *b* were derived from figs. 12, 13, and 14. Details of calculations are in an Excel Workbook called calculated permeability based on K_{Max} from the NMR log of well 1-32, which is available upon request, and a layout of calculated permeability with log-derived lithology, GR, NMR T2 distribution can be seen in Sheet 2 (Graphs) of this Excel Workbook. Table 8 lists the coefficients and applied ranges of 1/(Swir*Phi).

Table 8: Coefficients *a* and *b* of Equation 3

	a	*b*	R2	1/(Swir*Phi)	Approx T2
Micro	0.0437	-0.271	0.9771	<48	<50
Meso	0.2132	-8.1966	0.9877	48–106	50–1,100
Mega	0.5116	-45.72	0.9938	>106	50–10,000

Comparison of Predicted Permeability Based on Core Permeability at 90 Degree and Maximum Permeability

Predicted permeability based on max core permeability is almost equal to predicted permeability based on 90-degree core permeability for micro and meso pore intervals. However, higher permeability is predicted for mega pore intervals when core sample max permeability is used. This difference is attributed to differences between max core permeability and 90-degree core permeability for the same porosity when core samples have mega pores. The difference between max core permeability and 90-degree permeability is small when the core samples are micro and meso pore type.

Since 90-degree core sample permeability is more representative of reservoir average permeability, it is suggested to base predicted permeability of the Arbuckle on 90-degree core sample permeability data.