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IMPORTANCE OF POROSITY – PERMEABILITY RELATIONSHIP IN SANDSTONE: PETROPHYSICAL PROPERTIES

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IMPORTANCE OF POROSITY-PERMEABILITY RELATIONSHIP IN SANDSTONES: PETROPHYSICAL PROPERTIES

by

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14962

Dissertation submitted in partial fulfillment of
the requirements for the
Bachelor of Engineering (Hons)
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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
Petroleum Engineering Department
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in partial fulfilment of the requirement for the
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Approved by,

____

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May 2015

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and the original work contained herein have not been undertaken or done by specified sources or persons.

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RAYMOND JOSEFERD

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ABSTRACT

As porosity and permeability relationship becomes more important in the earlier stage of reservoir characterization, it is crucial for the geologist to being able to utilize this unique relationship in formation evaluation. As this project aims to demonstrate the importance of porosity and permeability relationship especially in sandstone reservoir, there are two main applications can be seen throughout the project. The project focuses on rock typing and permeability prediction for 8 wells with permission of Baker Hughes Inc. to disclose most of the well data.

The rock typing is done by using both conventional method and hydraulic flow unit (HFU) method. Conventional method refers to the technique of plotting permeability versus porosity crossplots in semi logarithmic scale. Rock type will be based on the similar pattern of porosity and permeability values with respect to the depth where the core plugs are taken. On the other hand, the HFU method divides the reservoir into different petrophysical types while those distinctive zones will have unique Flow Zone Indicator (FZI) values. Both methods yield the same results which suggest that conventional method and hydraulic flow unit method can be used for XXX-8 Well.

Permeability prediction is done by utilizing Choo's Method and hydraulic flow unit (HFU) method. Choo's Method accounts for the two components of dual rock system which are load bearing matrix and non-load-bearing matrix whereas HFU accounts for the mean value of FZI generated from previous core data to predict permeability value with a given sample value of porosity. Although both methods produce high accuracy results, it is worth to mention that Choo's Method in this case can be used in uncored well with well log data whereas HFU requires core data unless Alternating Conditional Expectation (ACE) is used alongside with FZI. This will be one of the recommendations in order to do further research.

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CHAPTER 1: INTRODUCTION

1.1 Background of Study

A potential reservoir is defined when the rock possesses enough porosity and permeability that enable oil or gas to flow through it. Porosity is a petrophysical parameter which indicates the capability of a rock to contain hydrocarbons (Tarek Ahmed, 2006). In other words, it is a measurement of the void spaces between the grains in a rock (Ma & Morrow, 1996). Permeability, however, is a different parameter which measures the flowing capability of the rock. In more specific terms, Buryakovsky, Chilingar, Rieke, and Shin (2012) claimed that it is the measurement of the rock's ability to transmit fluid under differential pressure. A general trend of permeability increases with porosity can be seen in most of the cases especially in many consolidated sandstone and carbonate formations. Despite that, permeability is actually relying on the interconnectedness of the pore spaces rather than the porosity itself as shown in **Figure 1**.

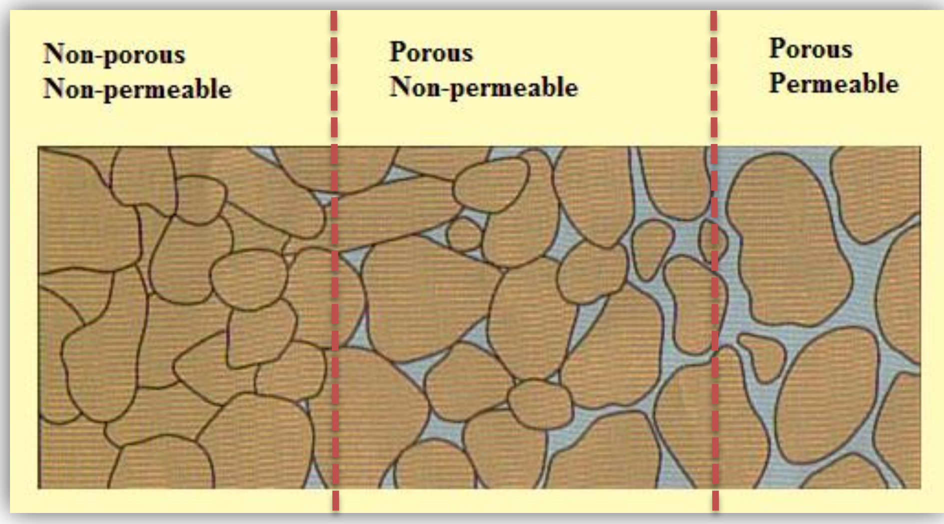


Figure 1. Porosity and permeability illustration.

Subsequently, correlations between porosity, Φ, and permeability, k, has always been very crucial in reservoir characterization and description. In fact, they are also tested for sedimentary rocks in relation to petroleum geology (Ma & Morrow, 1996; Susilo & Permadi, 2009). The unique relationship between both of the petrophysical properties is actually used to estimate the value of permeability from porosity data which is gathered from coring for uncored zone or logging. Costa (2006) mentioned that the prediction of permeability value is a pivotal importance for the explanation of various physical processes such as circulation of fluid in geothermal systems, recovery of hydrocarbon and degassing from vesiculating magmas. However, it is hard for someone to formulate satisfactory theoretical models for estimating permeability due to the complicated geometry of the connected pore space. As a result, Zinszner and Pellerin (2007) concluded in his book entitled "*A Geoscientist's Guide to Petrophysics*" that porosity and permeability relationship is somehow connected to the complexity of the porous space itself.

One of the reason for this relationship to be fully utilized during formation evaluation is because permeability is considered as a "no-logging parameter" as it can only be predicted from measurements on sidewall samples, correlation to wireline logging responses, interpretation of nuclear magnetic resonance (NMR) logs, wireline formation tester pressure responses, and drill stem tests (PetroWiki, 2013b). In fact, the absence of reliable log analysis method to continuously measure the reservoir rocks' permeability in the borehole makes it even more crucial for permeability prediction (Zinszner & Pellerin, 2007). In order to do that, a suitable rock typing method should be used before estimating permeability of each cell of geological model by utilizing unique permeability-porosity relationship of each discrete rock type as mentioned by Babadagli & Al-Salmi (2002). Although discreate hydraulic methods such as mini-test are available but they are still costly to deploy. Therefore, geologists will still prefer to find a relation between permeability and porosity which is easily obtained through log analysis technique. Even though it is easier to deduce, still, it is a risky operation as it is not as accurate as hydraulic method.

There are several applications of porosity and permeability relationship such as saturation height functions, rock typing, permeability prediction, etc. However, in this paper, the importance of porosity and permeability relationship will be demonstrated in the rock typing application and further explanation will be presented in Literature Review.

1.2 Problem Statement

Porosity and permeability relations in rocks become extremely useful and quite common in geological and engineering applications (Ma & Morrow, 1996; Zinszner & Pellerin, 2007). It is a challenge for a geologist or reservoir engineer to identify the rock or formation type within the potential well. Hence, the first problem statement is what will be the significance of porosity and permeability relationship? The second statement will be if it is used for rock typing, what is the other usage of this unique relationship?

1.3 Objectives

Based on the problem statements mentioned in the previous section, the objective of this project is:

- To evaluate importance porosity and permeability relationship.
- To investigate the use of core data with Choo's Method and HFU method for permeability prediction.

1.4 Scope of Study

The main focus of this research project is on the relationship between porosity and permeability particularly in sandstone reservoir. Most of values used are effective porosity and air permeability unless it is stated differently. Methods are chosen based on the most commonly used techniques in the literature reviews.

CHAPTER 2: LITERATURE REVIEW

2.1 Rock Typing

Reservoir characterization is a critical process as they give us a better picture and details of the reservoir potential and flow capacities which ultimately to be used in reservoir simulation models (Shabaninejad & Haghighi, 2011). In order to drive the accuracy of simulation model predictions, the determination of rock type or identification of a bed's lithology plays the most important role in reservoir characterization because the chemical and physical properties of the particular rock which is having hydrocarbon or water containment will most likely affect the measurement of formation properties (PetroWiki, 2013a). This is actually a basic foundation for all petrophysical calculations. At the same time, lithology means the composition or different type of rock such as limestone or sandstone that requires use to use rock typing method to determine. Although lithology is inter-related to rock type, they are in fact representing different attributes of the reservoir. Rock type focuses on pores, while lithology concentrates on only grains. It was said that there are more than 250 classifications for the list of rock types (*The World Wide Rock Catalog*, 1990).

Rock typing is known as a process which divides and classifies reservoir rock distinctively into several units. Burrowes, Moss, Sirju, and Pritchard (2010) said that the decision-making in mature fields for enhancing production and hydrocarbon recovery is highly dependent on rock typing. It is claimed that information such as capillary pressure profiles, set of relative permeability curves and unique porosity-permeability correlation of a given rock will be shown once they are sorted and defined properly (Shabaninejad & Haghighi, 2011). There are two types of rock type determination which are direct determination and indirect determination (PetroWiki, 2013a). Direct determination can be done by obtaining a physical sample of the reservoir. Nonetheless, the process of getting the physical sample is not always easy. Although mud logs most probably the first choice, there might be chances of getting error in exact assignment of a rock fragment due to the fact that the small rock cutting at the surface limited by the size of drill cuttings. As a result, it is difficult to determine the rock type.

On the other hand, rock typing is much more involved in indirect determination whereby the log responses are used simultaneously to determine lithology, porosity and fluid saturations. In this method, one can utilize the available catalogs of analog data to identify petrophysical properties that can be used to refine porosity calculations. Taking an example from PetroWiki (2013c), **Figure 2** shows the four data sets of sands and sandstone depicting the variation of permeability between different types of rock. It can be clearly seen that permeability values of newly deposited beach sands exceeds 30 Darcies whereas permeability of tight gas sandstone is less than 0.01 mD.

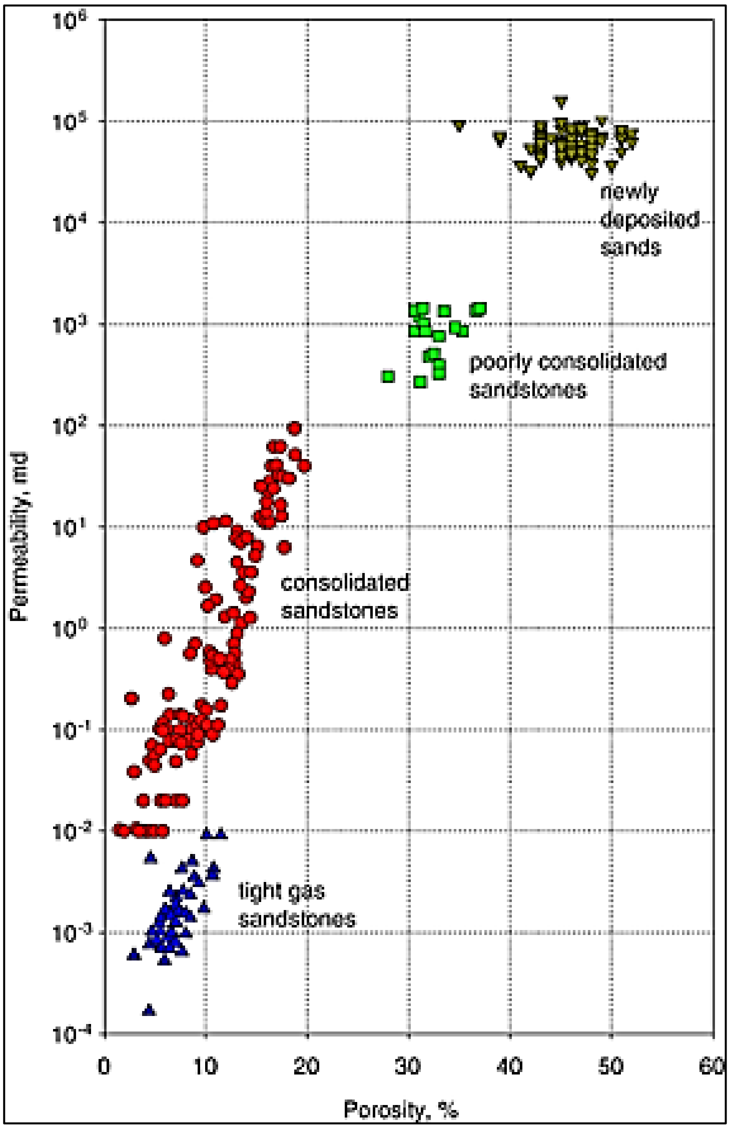


Figure 2. An example of different rock types having different porosity-permeability trend. Adapted from "Rock type influence on permeability," PetroWiki, 2013.

Several quantitative methods of rock typing are actually available in the literature. The pore distribution data is gained through core plugs laboratory analysis and log interpretation of magnetic resonance tools. However, Burrowes et al. (2010) defied the usage conventional method by generating linear porosity and permeability between the logs of permeability and porosity in carbonates. In fact, Xu, Heidari, and Alpak (2012) and Shabaninejad and Haghighi (2011) also disagreed with the usage of classic method as it only works in uniform and homogenous formations such as sandstone reservoirs but not carbonate reservoirs which are often highly heterogeneous. All of the authors agreed with the idea that conventional method log-based rock doesn't account for the dynamic petrophysical properties of rocks, depositional sequences, pore structure and pore throat connectivity in the absence of core measurements (Burrowes et al., 2010; Shabaninejad & Haghighi, 2011; Xu et al., 2012). In simpler terms, permeability based on well log only measured with empirical formulae that correlate permeability to static petrophysical properties. As a result, Burrowes et al. (2010), Shabaninejad and Haghighi (2011) has reviewed other methods which are more reliable such Winland Method and Hydraulic Flow Unit Method (HFU) and to be more specific, Rock Quality Index (RQI).

Al-Ajmi and Holditch (2000) defined a hydraulic flow unit as a representative and distinctive volume of total reservoir rock in which the geological and petrophysical properties that governs the fluid flow are internally consistent. In fact, it is predictably different compared to the properties of the other flow unit. Thomas W. Engler (2010) explains further that the approach has developed a dynamic link which allow the prediction of fluid flow properties by integrating not only macroscopic but also microscopic measurements. Nevertheless, hydraulic flow Unit showed a successful application to predict permeability in uncored wells by using well logs data (Al-Ajmi & Holditch, 2000; Amaefule, Altunbay, Tiab, Kersey, & Keelan; Nooruddin, Hossain, Sudirman, & Sulaimani, 2011; Taslimi, BOHLOLI, KAZEMZADEH, & KAMALI, 2008; Thomas W. Engler, 2010). **Figure 3** shows the basic concept of hydraulic unit in a formation.

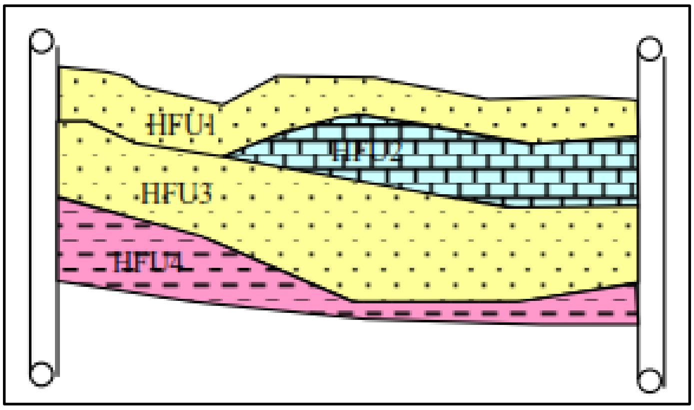


Figure 3. Schematic depicts the concept of hydraulic flow unit. Adapted from "Distribution of Rock Properties," by Thomas W. Engler, 2010.

It is best to describe hydraulic flow unit as distinctive units consists of similar fluid properties that governed by pore geometry which is subsequently affected by mineralogy and textual parameters (Thomas W. Engler, 2010). Mineralogy in this context will be abundance, type and morphology whereas textual parameters are grain size, sorting, shape and packing. One must be clear that although one formation falls under the same flow unit with others, it does not necessarily mean that they are having the same geologic unit. Even so, there should not be an issue for Petroleum Engineers since they are more concerned with the fluid flowing behaviors rather than the geologic units or facies.

To improve the current HFU technique, Shabaninejad and Haghighi (2011) were able to develop new method which is improved generalized permeability and porosity relationship by using the concept of HFU. On the other hand, Permadi and Kurnia (2011) found out there is similarities between pore geometry and the structure which is the foundation for rock typing. Therefore, they have suggested to use pore geometry – pore structure cross plot (PGS plot) in order to examine the pore attributes relationship. Rasaei and Nabavi (2007) conducted rock typing with different methods such as conventional porosity and permeability, mercury injection and relative permeability, etc. However, they mentioned that the method of RQI/FZI is not applicable on the Iranian Oil Reservoir due to the inconsistency of data. The methods shown in **Table 1** are the compilations of the techniques used by different authors in order to determine the rock type before proceed for permeability prediction.

Table 1. Comparison of methods used by different authors.

Authors	Title	Rock Typing Methods
Burrowes et al. (2010)	*Improved Permeability Prediction In Heterogenous Carbonate Formations.*	• Winland Method • HFU Method (RQI)
Shabaninejad and Haghighi (2011)	*Rock typing and Generalization of Permeability - Porosity Relationship for an Iranian Carbonate Gas Reservoir.*	• Conventional Method • Winland Method • HFU Method (RQI) • Generalized Porosity-Permeability correlation
Rasaei and Nabavi (2007)	*Systematic Rock Typing in an Iranian Oil Reservoir*	• Conventional Method • Mercury Injection • HFU Method (RQI)
Permadi and Kurnia (2011)	*Rock Typing and Permeability Prediction for Water-Wet and Oil-Wet Rocks*	• Pore Geometry-pore structure cross-plot
Thomas W. Engler (2010)	*Distribution of Rock Properties.*	• HFU Method (RQI)
Taslimi et al. (2008)	*Determining Rock Mass Permeability In A Carbonate Reservoir, Southern Iran Using Hydraulic Flow Units And Intelligent Systems.*	• HFU Method (RQI)

Nooruddin et al. (2011)	*Field Application of a Modified Kozeny-Carmen Correlation to Characterize Hydraulic Flow Units*	• HFU method (RQI) • Modified Kozeny Carmen Correlation
Al-Ajmi and Holditch (2000)	*Permeability Estimation Using Hydraulic Flow Units in a Central Arabia Reservoir*	• HFU method (RQI)
Abed (2011)	*Hydraulic flow units and permeability prediction in a carbonate reservoir, Southern Iraq from well log data using non-parametric correlation*	• HFU method (RQI)

CHAPTER 3: METHODOLOGY

3.1 Project Workflow

In order to ensure that the objective of this project to be successfully achieved, there are four stages of procedures should be conducted as shown in **Figure 4.** The first stage – **Case Study** is done throughout the whole progress of the project. Case studies from different oil fields and rock typing methods used by other authors are carefully studied and compared to each other. Besides that, the general definition of porosity and permeability are also acquired for the background study purposes. The next stage, **Data Collection** is performed by acquiring real field data from oil service company – Baker Hughes Inc with their permission to keep all well details confidential. The third most important stage which is **Data Analysis** comprised most of the project activities involving core porosity- permeability crossplots, permeability prediction, and hydraulic flow unit crossplots for rock typing. The final stage of this project will be the evaluation of the results obtained from the analysis. Hence, conclusion will be made whether the initial hypothesis is accepted or rejected.

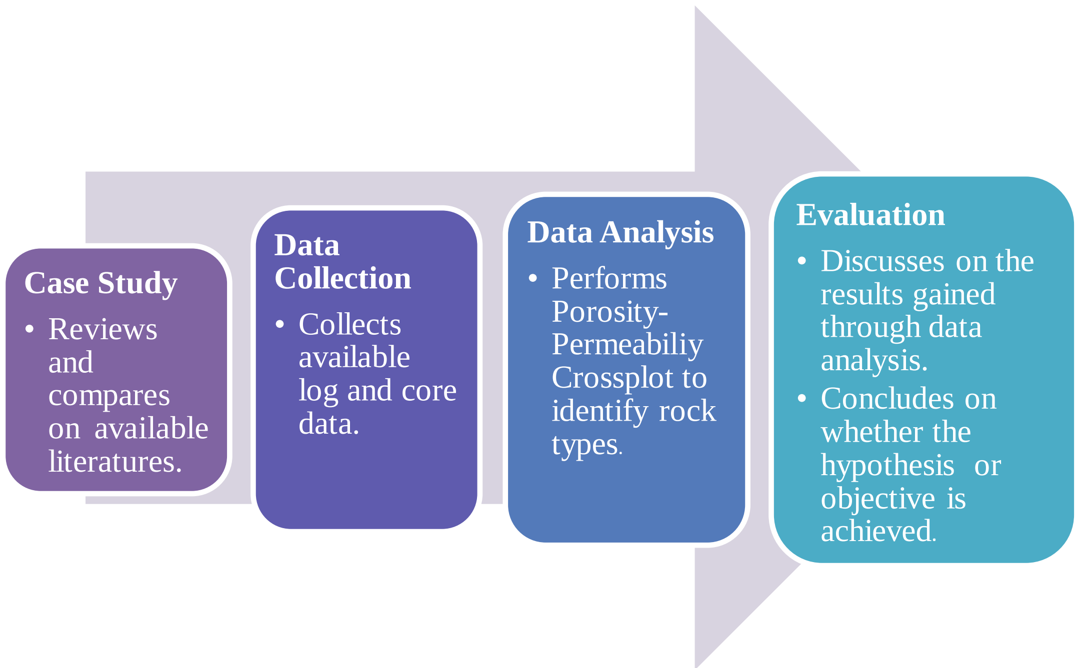


Figure 4. Flow chart for the process of the current project.

3.2 Project Activities

The activities for this project can be divided into five parts as shown in **Figure 5.** Firstly, the core porosity and permeability data is obtained through routine core analysis or special core analysis. The permeability data is comprised of both air permeability and brine permeability. By using the core porosity and permeability data, a core poroperm cross plot is constructed and porosity to permeability transforms for each rock-type is also derived for use in further studies, so that permeability could be predicted without the need for clay and silt volume estimates as input. This transformation is known as core based classification for Reservoir Quality Index (RQI). The results between the two methods are compared. The next part is to predict the log permeability by utilizing Choo's Permeability Prediction Method. This is applied in all 8 wells to derive a continuous permeability log using the clay and silt volume output from Sand-Silt-Clay (SSC) model. The subsequent part is permeability prediction by using HFU method. Finally, both cross plots for core data and predicted log data will be compared to each other to justify the good match between the two data.

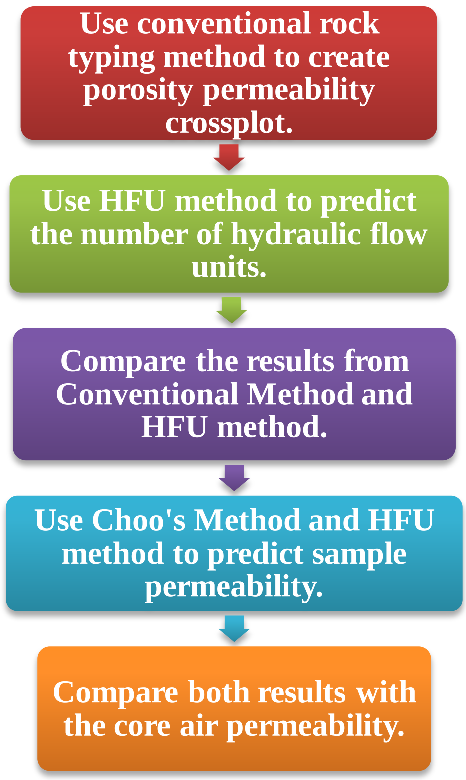


Figure 5. Flow chart for project activities.

3.3 Conventional Method

Conventional method for rock typing is basically done by evaluating regressed permeability value from log derived porosity or porosity data obtained from core (Burrowes et al., 2010; Shabaninejad & Haghighi, 2011). Nearly in most cases, we can obtain a linear relationship between permeability and porosity. However, it is said that conventional method does not really depicting the actual relationship between the two petrophysical properties and this project will compare this method and hydraulic method in order to obtain more accurate rock typing.

There are several steps need to be done in order to obtain a proper relationship of porosity-permeability cross plots:

1. Firstly, the depth for every single values of porosity and permeability of the core plugs must be in the correct ascending order as we need to recognize which of the plugs come first.
2. The relationship between porosity and permeability is then plotted in a semi log graph.
3. Next, the trend of the subsequent points after the first point should be observed either it falls under the same rock type. If it does, it will be assumed as the same rock type and if it does not fit in, it will be categorized as another rock type. The usual trends that will be observed are increase in both porosity and permeability or decrease in porosity and increase in permeability or vice versa.
4. To display the accuracy or the linear relationship between the two petrophysical parameters, the R squared functions of the Microsoft Excel are displayed alongside the equation of the linear gradient.

Table 2 shows a set of porosity and permeability points for a sample well with an ascending order of depths. Each single points is marked numerically to ease the job of identify which data point on a cross plot. **Figure 6** shows the plotted points whereby point 1 is not connected to point 3 as the trend of porosity and permeability is different. However, point 2 is not connected to point 4 although they can be on the same trend. This is due to the depth of point 2 and point 4 is not interconnected.

Table 2. A set of porosity and permeability data in an ascending order of depths.

Well	Depth ft	Core Porosity %	Core Permeability mD
XXX-2	5301.917	23.7	298
XXX-2	5311.600	25.5	404
XXX-2	5312.517	24.0	237
XXX-2	5313.433	25.3	239

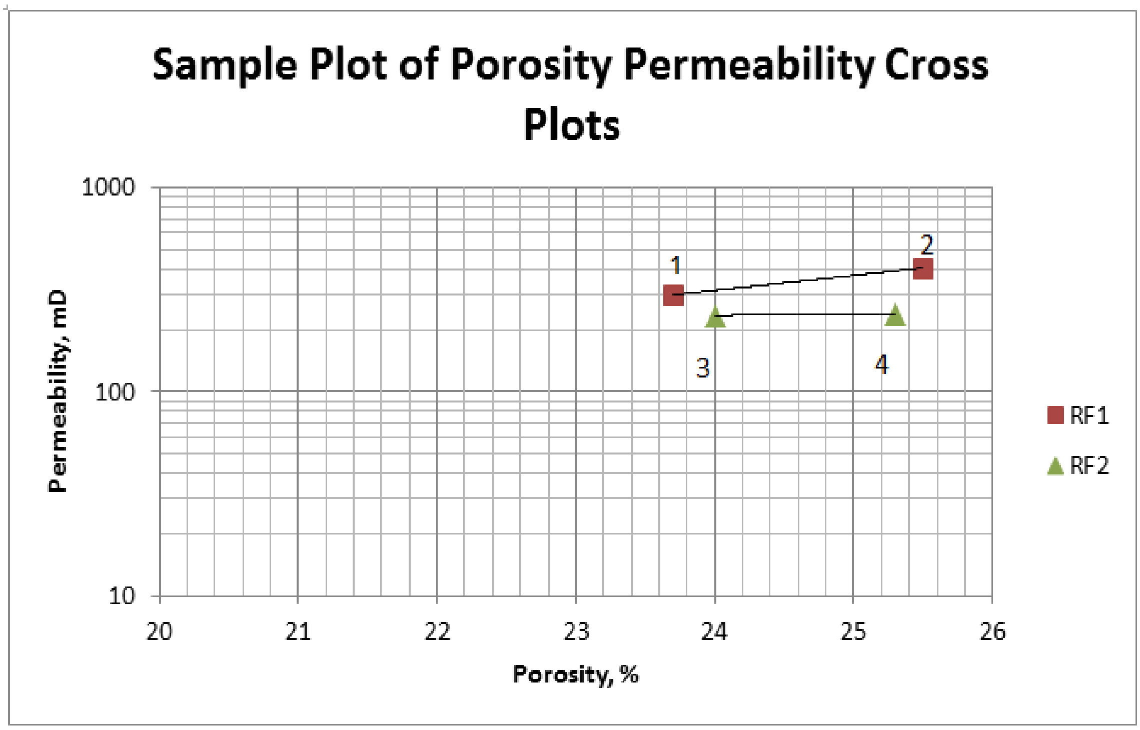


Figure 6. Porosity permeability cross plots shows two different rock types.

3.4 Hydraulic Flow Unit Method & Permeability Prediction

This method is based on geological parameters and the science behind the flow in pore scale (Burrowes et al., 2010). In fact, it is a special parameter which has taken all the geological attributes of texture and mineralogy into account. As different diagenetic process and depositional environments control the pore geometry, RQI will vary in different types of rock. This method is actually modified based on Kozeny Carmen equation with the concept of mean hydraulic radius. Therefore, in this project, rock types are classified according to **Equation 3**. Permeability prediction, on the other hand, can be done by utilizing **Equation 4.**

Equation 1

$$RQI = 0.0314\sqrt{\frac{k}{\emptyset_e}}$$

Equation 2

$$\emptyset_z = \frac{\emptyset_e}{1-\emptyset_e}$$

Equation 3

$$FZI = \frac{RQI}{\emptyset_z}$$

Equation 4

$$k = 1014 * (FZI_{mean})^2 * \frac{{\emptyset_e}^3}{(1-\emptyset_e)^2}$$

Where,

k : Permeability , md

$\emptyset_e$: Effective porosity, fraction

RQI : Rock Quality Index, μm

$\emptyset_z$: Normalized porosity

FZI : Flow zone indicator

3.4 Choo's Permeability Prediction

Choo (2010) presented a new reliable method of determining permeability particularly from well logs in clastic rocks by incorporating Kozeny- Carman equation, Kozeny Carman capillaric model and the derived load bearing rock equation from the formation factor equation. By implementing this method, one can utilize log data and compare it core data to increase confidence level for the permeability prediction. The final calculated permeability actually represents the degradation of permeability by the pore filling sediments that create the non-load-bearing matrix. **Figure 7** shows the ability of Choo's permeability prediction equation which takes account of the degradation of permeability as a result of the presence of silt and clay subsequently can be seen in **Equation 5**.

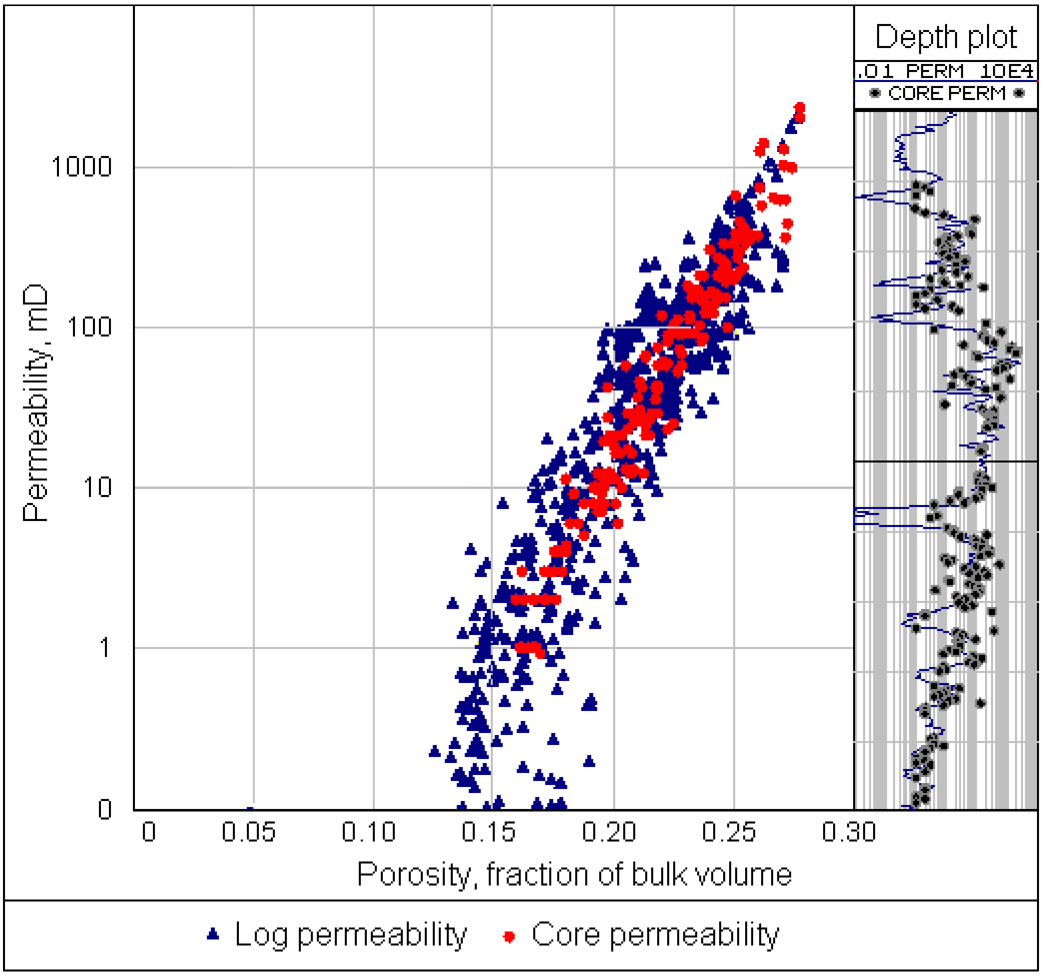


Figure 7. The semi empirical formula fitting with log permeability and core permeability overlying to each. Adapted from "State-Of-The-Art Permeability Determination From Well Logs To Predict Drainage Capillary Water Saturation In Clastic Rocks," by Choo, 2010.

Choo's Method of permeability prediction is done by utilizing **Equation 5**.

Equation 5

$$k = \frac{A\emptyset^{B}}{10^{(6Vcl+3Vsilt)}}$$

Equation 6

$$A = \frac{0.125r_g^2}{10}$$

Equation 7

$$B = m\left(\frac{2}{c} + 1\right) + 2$$

Equation 8

$$c = \frac{\log(\frac{1}{\emptyset^{m}})}{\log(\frac{r_g}{r_{eff}})}$$

Where,

A : Choo constant

B : Choo exponent

C : Reservoir compaction factor

k : Permeability, mD

m : Cementation exponent

$\emptyset$: Porosity, fraction

r_g : Dominant rock-grain radius, μm

r_{eff} : Effective pore-throat radius, μm

Vcl : Relative total clay (wet) volume

$Vsilt$: Relative silt volume

3.5 Key Milestones (FYP 1)

Project Start Date: 6 October, 2014 Project End Date: 22 November, 2014

Week 1-2

- Selection of topic: "Importance of Porosity-Permeability Relationship in Sandstones: Petrophysical Properties."

Week 3-5

- Preliminary case studies and research.
- Literature review on application of poroperm relationship and its apoplication.

Week 6

- Submission of Extended Proposal report.

Week 7-9

- Research on the conventional methods being used by different authors and compare their methods for the results accuracy.
- Preparation for Proposal Defence Presentation.
- Presenation for Proposal Defence.

Week 10 -12

- Revised on the unavailability of carbonate reservoir data and change scope to sandstone reservoir.
- Obtain data from Baker Hughes Inc. and sign for data confidentiality agreement.

Week 13

- Submission of Interim Draft report and obtain stamps from coordinator.

Week 14

- Submission of Interim Report.

Figure 8. Key milestones for FYP 1.

3.6 Key Milestones (FYP 2)

Project Start Date: 12 January, 2015 Project End Date: 13 April, 2015

Week 1-4

- Perform conventional method for rock typing for all the 7 wells.
- Discuss on the finding of each wells and compare the rock typing with the log data.

Week 5-7

- Prepare progress report and additonal data added for literature review .

Week 8

- Submission of Progress Report.

Week 9-11

- Transform log porosity to get log permeability.
- Compare log predicted permeabilty and core permeability
- Apply Hydraulic Flow method and compare with conventional method.

Week 12

- Revised on current data and acquire water saturation data from company to perform saturation height function.

Week 13

- Submission of draft report.

Week 14

- Submission of Final Report and Viva.

Figure 9. Key milestone for FYP 2.

3.7 Gantt Chart for FYP 1

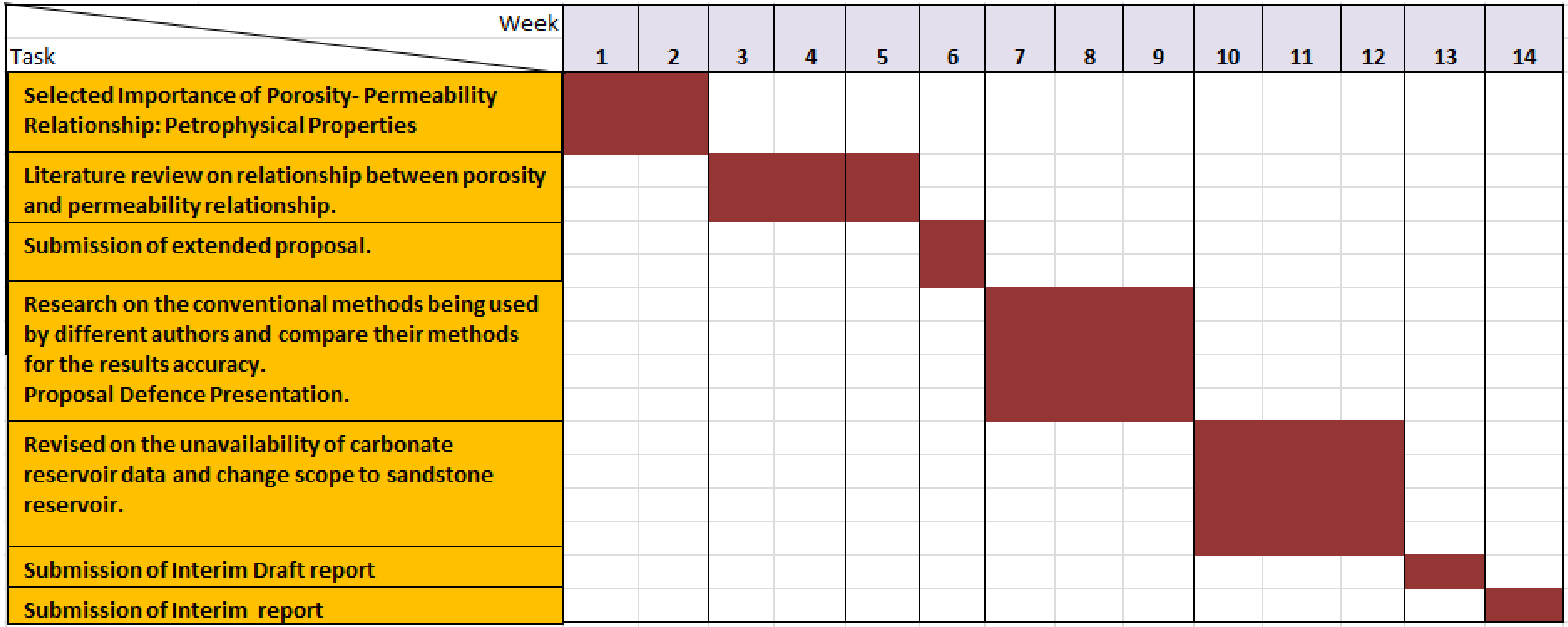


Figure 10. Gantt Chart for FYP1.

3.8 Gantt Chart for FYP 2

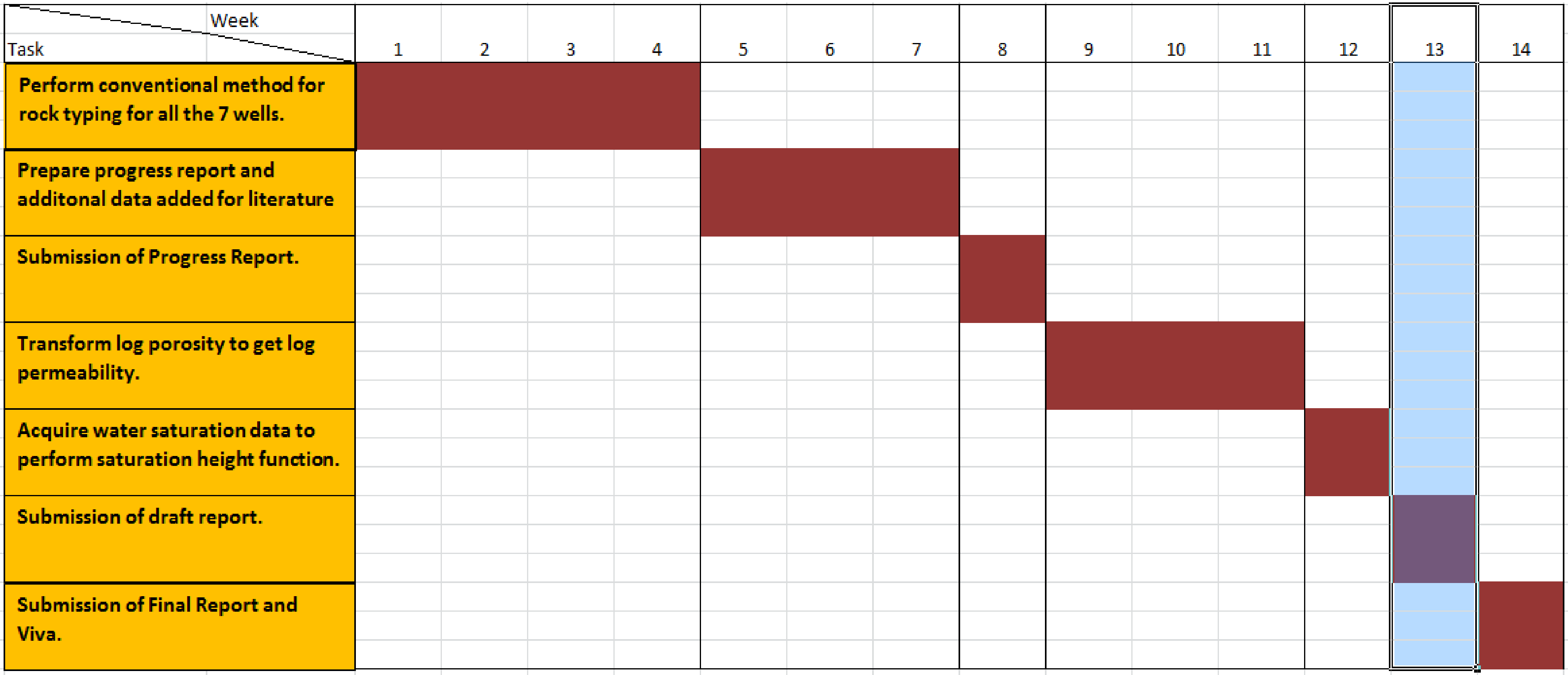


Figure 11. Gantt Chart for FYP 2.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Data Availability

Cores were taken in a total of eight XXX wells and both Routine Core Analysis (RCA) and Special Core Analysis (SCAL) data were available for integration. However, due to the fact that one of the well has only sidewall core data from the formation which is not being analysed in this study, the core data has been excluded. Following a review of existing RCA and SCAL data, it was decided that a short core analysis program be performed, while there was a window of opportunity, to address shortcomings and strengthen the existing database. 11 pairs of plugs (22 individual plugs) were cut and supplied to Core Laboratories in Aberdeen, along with one rock sample. **Table 3** shows the summary of plug data and results from core analysis.

Table 3. Summary of core data.

Well ID	Depth, feet	Air Permeability md	Brine Permeability md	Porosity, fraction
XXX-2	5304.25	228.56	151.00	0.249
XXX-2	5304.43	234.50	160.00	0.247
XXX-2 ST1	5519.20	94.23	39.00	0.214
XXX-2 ST1	5519.50	90.04	46.00	0.216
XXX-2 ST1	5636.10	97.21	43.00	0.211
XXX-2 ST1	5636.30	103.74	65.00	0.210
XXX-2 ST1	7682.50	4.52	1.05	0.147
XXX-2 ST1	7682.70	6.07	1.46	0.149
XXX-5	4047.80	221.57	123.00	0.259
XXX-5	4047.10	261.48	137.00	0.261
XXX-5	4648.45	388.49	173.00	0.232
XXX-5	4648.60	262.66	119.00	0.232
XXX-5	4792.45	978.38	440.00	0.259
XXX-5	4792.62	1107.17	455.00	0.256
XXX-6	3904.10	461.22	311.00	0.267
XXX-6	3905.00	129.80	47.00	0.264
XXX-6	3979.50	3306.74	1641.00	0.294
XXX-6	3979.70	2414.36	1717.00	0.290
XXX-7	4090.25	1361.55	786.00	0.299
XXX-7	4090.25		n/a	0.292
XXX-103	4822.70	627.50	338.00	0.242
XXX-103	4822.85	528.45	269.00	0.244

The most common permeability data obtained from a routine core analysis (RCA) program is the air permeability which will be used to construct the cross plot in this paper. The air permeability data provided by core lab shown in **Table 3,** has been corrected by utilizing the following equation:

$$k_{air} = k_a(1 + \frac{b}{P})$$

Where,

k_{air} : air permeability of core sample

k_a : absolute permeability of the core sample

b : Klikenberg constant for a given gas in a specific core sample

P : average flowing pressure upon the measurement of gas permeability is taken

The main reason of correcting the air permeability is to account the for the "slippage" effect of the gas due to the interactions between gas molecules and the walls of the pore spaces (Ezekwe, 2010). The effect can significantly increase the the gas permeability at low pressures which is even greater than the absolute permeability itself (Barker & Tellam, 2006). To ease the study of the porosity and permeability relationships in this paper, data availability is checked and shown in **Table 4.** Due to the fact that only XXX-8 well has a complete profile, it is the only well that will be investigated for permeability prediction and saturation height function other than the conventional rock typing. The full details of porosity and permeability data for all of the seven wells are attached in the **Appendix** future use.

Table 4. Data availability check for 7 wells.

Data \ Wells	XXX-2	XXX-2ST1	XXX-7	XXX-8	XXX-103	XXX-6	XXX-5
Porosity	√	√	√	√	√	√	√
Permeability	√	√	√	√	√	√	√
Log				√			
Water Saturation				√			

4.2 Conventional Rock Typing

Figure 11 depicts the uncorrected cross plots of porosity and permeability relationship of XXX-2 well. The cross plot is done without taking the arithmetic, geometric or harmonic averaging of the permeability value. It is shown that there are five different rock types based on the various trend of increments or decrements of permeability correspond to the increasing porosity. All the rock types in this well show exponential relationship between the two petrophysical parameters. However, in this uncorrected cross plot, Rock Type 2 shows the least correlation as the R squared value is only 0.2276 while Rock Type 1 and 3 has R squared values of 0.86 and 0.85. Rock Type 5 has no R squared value as it is a standalone point. In order to improve the exponential correlation between porosity and permeability values, some corrections has been done towards the cross plot such that the points are correlated to the one has more similarity with it in a way that they follow the ascending order of the depth. With the new corrected cross plot shown in **Figure 12**, all the Rock Type are perfectly matched with the R squared value of 1 while only Rock Type 1 still having the 0.86 R squared value. This suggests that the correlation has slightly improved and more accurate.

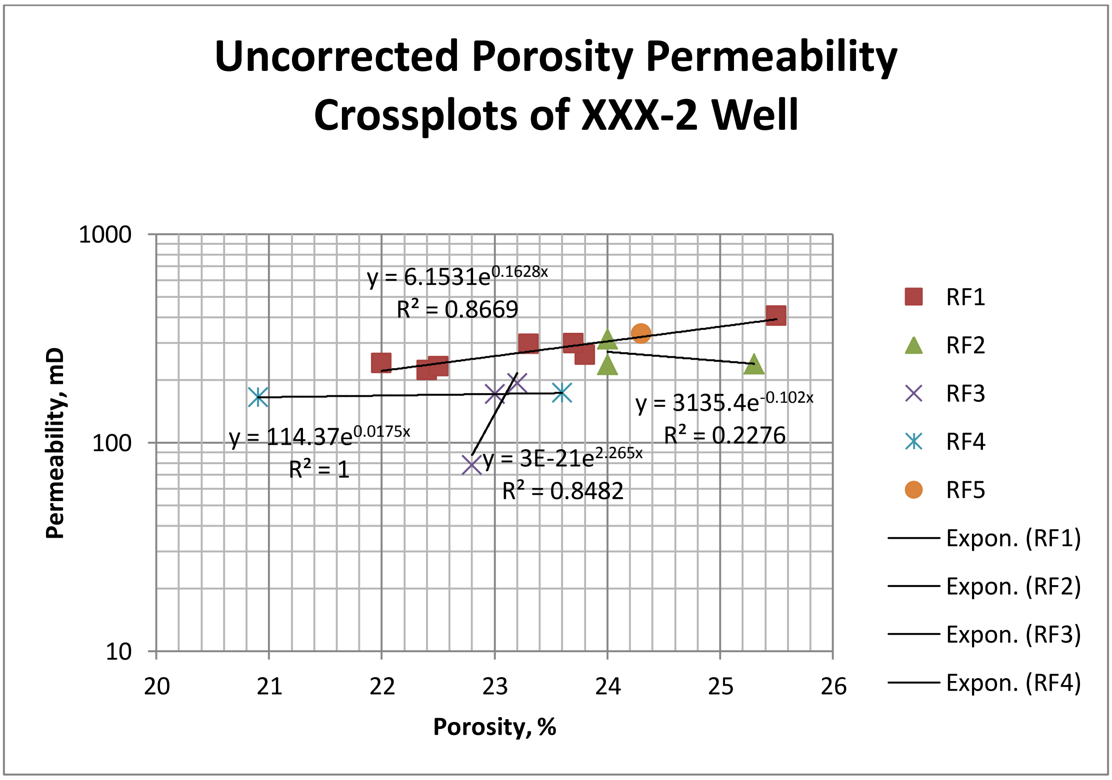


Figure 12. Uncorrected cross plot for XXX-2 Well.

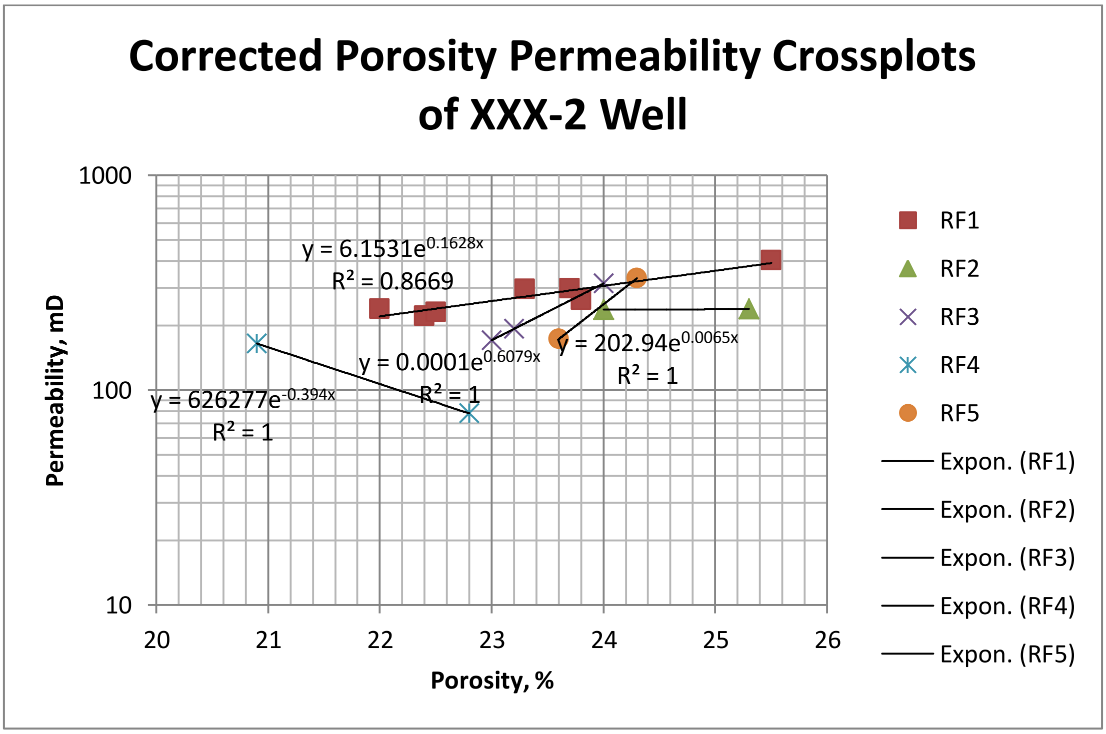


Figure 13. Corrected cross plot for XXX-2 Well.

As XXX-8 well is the only well that having both core and well log data, the results for the rock typing is compared with the lithofacies generated by the well log as shown in **Figure 14** and **Figure 15.** The output from crossplot is indeed matched with the lithofacies in the well log as we identified there are 4 rock types in this well. **Table 5** shows the porosity and permeability value corresponding to the depth taken and classified into different rock types.

Table 5. Results from XXX-8 well rock typing.

Depth, ft	Porosity, %	Permeability, mD	Rock Typing
1176.55	15.5	9.441	Rock Type 1
1176.84	20.4	47.35	
1176.97	14.8	2.968	
1177.11	23.4	172.4	Rock Type 2
1177.50	23.9	243.9	
1177.64	24.0	144.1	Rock Type 3
1177.74	24.7	154.4	
1177.80	21.0	91.11	
1177.94	19.8	98.60	Rock Type 4
1178.11	17.5	23.53	
1178.55	18.8	47.30	
1178.77	14.6	9.544	
1179.10	14.1	4.499	
1180.93	14.3	2.661	
1181.69	17.3	13.73	

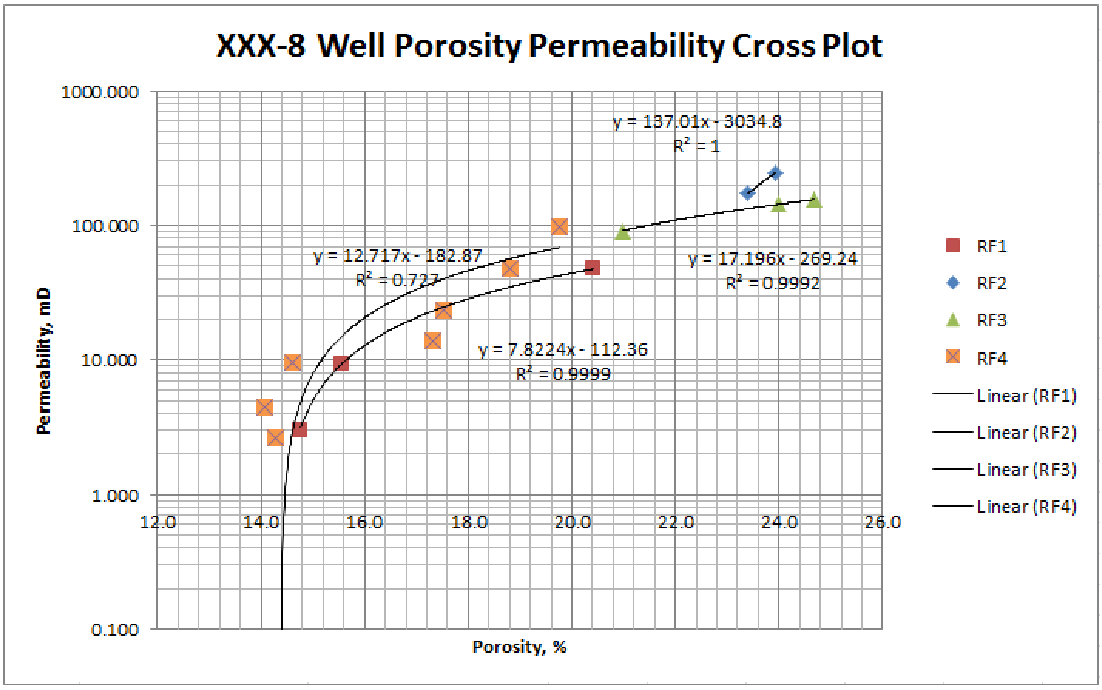


Figure 14. Porosity permeability crossplot for XXX-8 well.

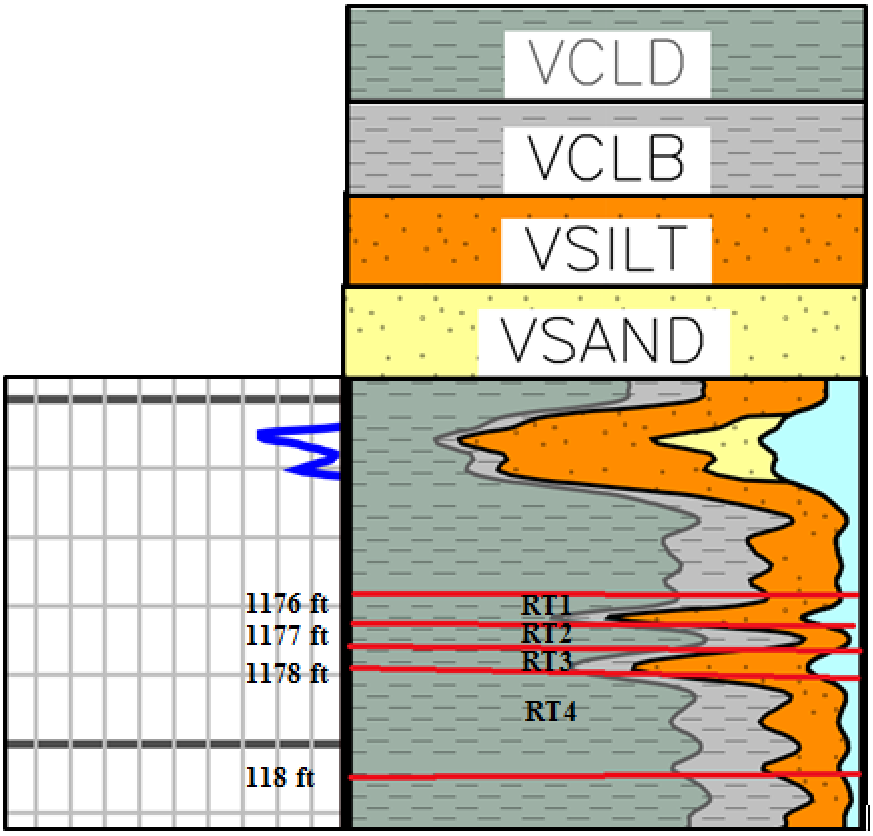


Figure 15. Well log data indicates the four rock types matched the crossplot analysis.

4.3 Hydraulic Flow Unit Method

To boost the confident of the conventional rock typing method or to increase the accuracy of the result, hydraulic flow unit method is used for the rock typing in XXX-8 well. Prior to the finding of the mean value of FZI, the number of hydraulic flow units should be determined first. Two approaches which are histogram analysis and probability plot which are also known as graphical clustering methods have been used in this project for clustering core data into different HFU groups. By utilizing **Equation 1, 2** and **3,** FZI values for each core data is obtained and tabulated in **Table 6. Table 7** shows the frequency of log FZI for each core data and which is to be used for histogram analysis.

Table 6. FZI values for each core data.

Porosity, %	Air Permeability, mD	RQI	Normalized Porosity	FZI	log FZI
15.546	9.441	0.24469738	0.184076539	1.3293241	0.123631
20.42	47.35	0.47814737	0.256597135	1.8634166	0.27031
14.764	2.968	0.14078604	0.173213196	0.8127905	-0.09002
23.409	172.4	0.85218385	0.305636432	2.7882273	0.445328
23.931	243.9	1.00251467	0.314595959	3.1866737	0.503338
23.976	144.1	0.76967158	0.315374092	2.4405035	0.387479
24.683	154.4	0.78528045	0.327721497	2.3961823	0.37952
20.967	91.11	0.65454537	0.265294244	2.467243	0.392212
19.764	98.60	0.70134691	0.246323346	2.8472612	0.454427
17.518	23.53	0.36390592	0.212385733	1.7134198	0.233864
18.818	47.30	0.4978371	0.231800153	2.1476996	0.331974
14.604	9.544	0.25383935	0.171015036	1.4843101	0.171525
14.082	4.499	0.17748247	0.163900463	1.0828674	0.034575
14.28	2.661	0.1355464	0.166588894	0.8136581	-0.08956
17.309	13.73	0.27960816	0.20932145	1.3357836	0.125736

Table 7. Frequency of log FZI.

Numbering	Description for Log (FZI)	Frequency
1	From -0.09 till -0.08	2
2	From 0- 0.1	1
3	From 0.1 till 0.2	3
4	From 0.2 till 0.3	2
5	From 0.3 till 0.4	4
6	From 0.4 till 0.5	3

The data of the flow zone indicator is plotted in the form of histogram, the n, number of hydraulic flow units is obtained through the normal distribution. A histogram of log FZI should be able to indicate the number of normal distributions for n, number of hydraulic flow unit because FZI distribution itself is a superposition of many log-normal distributions. However, the drawback if this method is that it is very hard to separate the overlapped individual distributions from the histogram as shown in **Figure 16.** It is clearly difficult to determine number of HFU's for this well from histogram alone due to the superposition nature of the histogram plot. In fact, histogram method is not really reliable for most field application since identification of the HFU can be confused with the transition zones between different HFU.

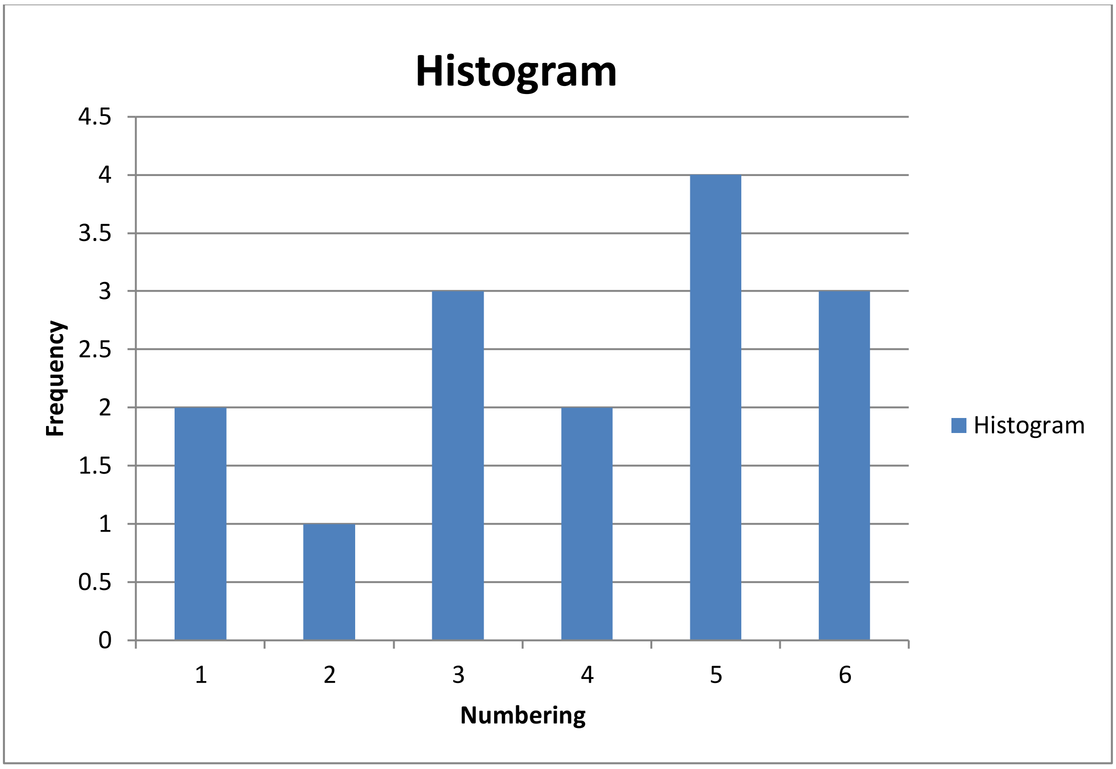


Figure 16. Histogram for FZI values for number of hydraulic unit determination.

Since histogram analysis doesn't show clearly the number of hydraulic flow unit, the normal probability analysis (the cumulative distribution function) has been carried out since it is smoother than the histogram and the scatter in the data can be reduced in which the identification of the cluster will be easier. In fact, probability plot is the integral of the histogram. A distinct straight line is formed by the normal distribution in a probability plot. Hence, the number of the hydraulic flow units of the well is indicated by the number of lines in the plot itself.

Figure 17. shows a probability plot of the logarithm of FZI for XXX-8 well. **Table 8** shows the probabilities of each sample data. Based on the straight lines, there are a total of 4 HFU were identified in this reservoir.

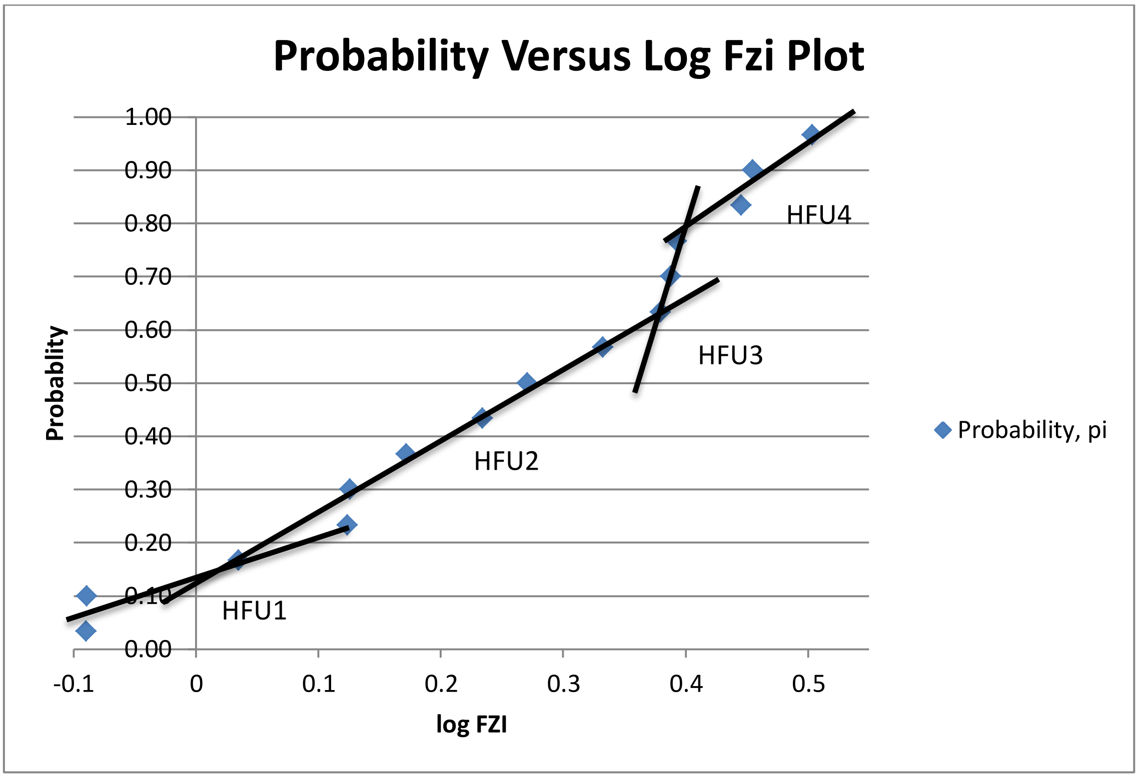


Figure 17. Probability plot for XXX-8 Well.

Table 8. Probabilities for each sample point.

Number of core point, n	log FZI	Probability, pi
1	-0.090021398	0.03
2	-0.089558063	0.10
3	0.034575294	0.17
4	0.123630876	0.23
5	0.125736102	0.30
6	0.171524656	0.37
7	0.233863783	0.43
8	0.270309968	0.50
9	0.331973541	0.57
10	0.379519858	0.63
11	0.387479438	0.70
12	0.392211929	0.77
13	0.445328175	0.83
14	0.45442731	0.90
15	0.503337595	0.97

With the idea of having at least 4 HFU in the well, the least square regression method can now be implemented to find the most optimal number of the HFU. The basic concept of least square regression method is by plotting RQI versus normalized porosity on a log-log plot and a straight line with a unit slope will be produced. The y intercept will represent the mean value of FZI for each HFU as shown in **Figure 18** based on the values in **Table 6**. The following steps were used to construct the plot:

1. Reservoir quality index (RQI) and normalized porosity ($\emptyset_z$) is calculated using **Equation 1** and **2** from core data.
2. A graph of RQI versus $\emptyset_z$ is plotted in logarithmic scale.
3. Initial guess for the intercept of the straight line equation is made which carries the mean FZI value of each HFU.
4. Core sample data is assigned to the nearest constructed straight line.
5. The intercept of each HFU which is the mean value of FZI is recalculated using least squares regression equations.

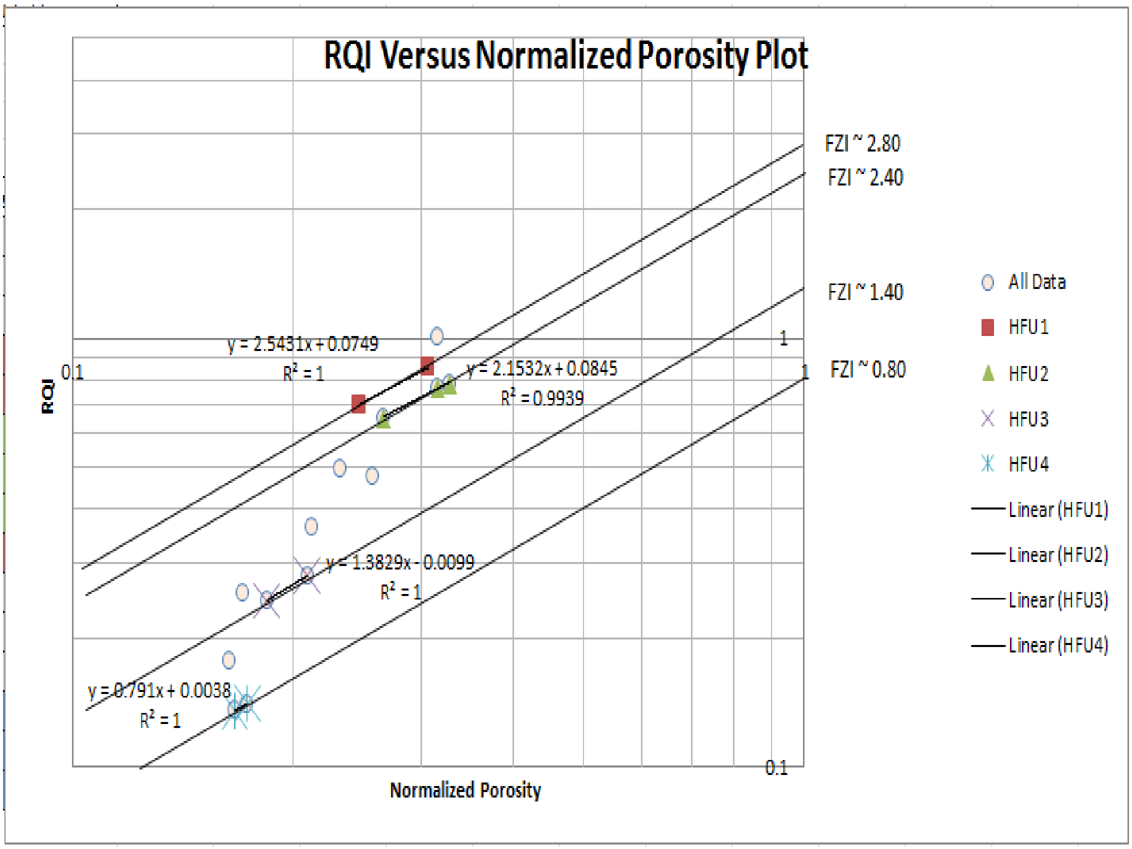


Figure 18. RQI Versus Normalized Porosity Plot.

4.4 Comparison between HFU Method and Conventional Method

Both of the techniques have determined that XXX-8 well is having four different flow units of rock type. However, there is a slight different in the results whereby one of the data point is actually belongs to the same group of rock in RT1 which was obtained by using HFU technique. The weakness of using conventional method is that it is more based on the pattern of porosity and permeability with respect of their depth. However, HFU technique takes into account that same flowing unit (rock type) might exist in between the layers which suggest the rock type in different depth might actually be the same formation. **Table 9** shows the comparison of HFU and conventional method.

Table 9. Comparison of rock type and the hydraulic flowing unit.

Depth, ft	Porosity, %	Permeability, mD	Rock Typing	HFU
1176.55	15.5	9.441	Rock Type 1	HFU1
1176.84	20.4	47.35		
1176.97	14.8	2.968		
1177.11	23.4	172.4	Rock Type 2	HFU2
1177.50	23.9	243.9		
1177.64	24.0	144.1	Rock Type 3	HFU3
1177.74	24.7	154.4		
1177.80	21.0	91.11		
1177.94	19.8	98.60	Rock Type 4	HFU1
1178.11	17.5	23.53		HFU4
1178.55	18.8	47.30		
1178.77	14.6	9.544		
1179.10	14.1	4.499		
1180.93	14.3	2.661		
1181.69	17.3	13.73		

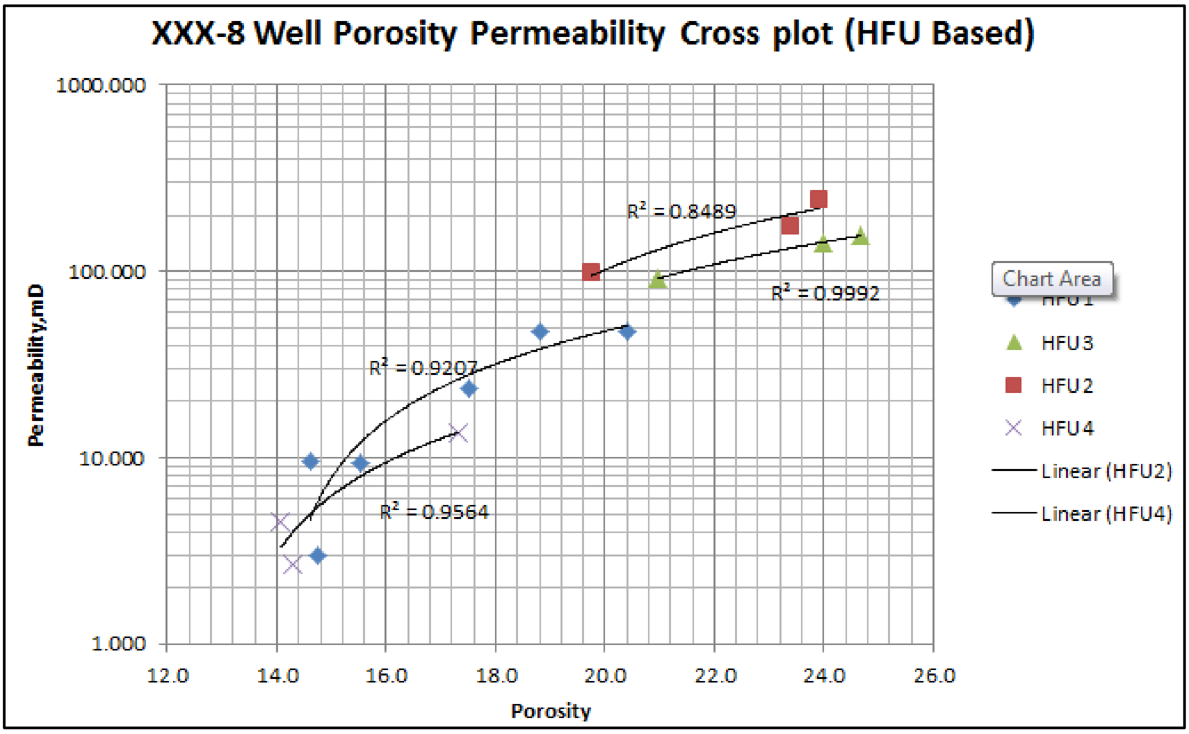


Figure 19. Porosity permeability cross plot based on HFU.

Figure 19 shows the plot of permeability against porosity which is based on the mean value of FZI of hydraulic flow unit. By comparing it to the initial plot of conventional method in **Figure 14**, it yields greater average value of R squared.

4.5 Choo's Permeability Prediction

Based on the Field Development Project report of XXX field, the Choo constant (A) of 16,500,000 was used for all wells, which represented a dominant rock grain radius of ~36 µM. This size was corroborated using thin sections and the SEM data from the 2011 petrology work done by Baker Hughes Inc, but unfortunately no sieve analysis data is available for full quality control. The Choo exponent (B) was initially defined separately for each cored well to obtain the best match between predicted and core permeability. The average B value was ~6; hence this was applied to all wells which including XXX-8 well. Using the maximum observed core porosity of 0.30 p.u., the "B" of 6 represents an effective pore throat radius of ~9.8 µM, which is confirmed by high pressure mercury injection data, again, obtained from the Field Development Project report of XXX field. **Table 10** shows the predicted value of permeability by utilizing **Equation 5. Figure 20** shows how accurate the predicted permeability with the actual core permeability, bears the R squared value of 0.9323. This proved that Choo's method is reliable for this well.

Table 10. Predicted permeability values by using Choo's Permeability Prediction.

Depth, ft	Porosity, %	Predicted Permeability, mD	Air Permeability, mD
1176.55	15.546	10.40389414	9.441
1176.84	20.42	53.43408423	47.35
1176.97	14.764	7.633226746	2.968
1177.11	23.409	121.2777452	172.4
1177.5	23.931	138.4359945	243.9
1177.64	23.976	140.0052508	144.1
1177.74	24.683	166.6754374	154.4
1177.8	20.967	62.61836379	91.11
1177.94	19.764	43.92714883	98.60
1178.11	17.518	21.30056269	23.53
1178.55	18.818	32.72839661	47.30
1178.77	14.604	7.150145672	9.544
1179.1	14.082	5.747380949	4.499
1180.93	14.28	6.249613919	2.661
1181.69	17.309	19.82055503	13.73

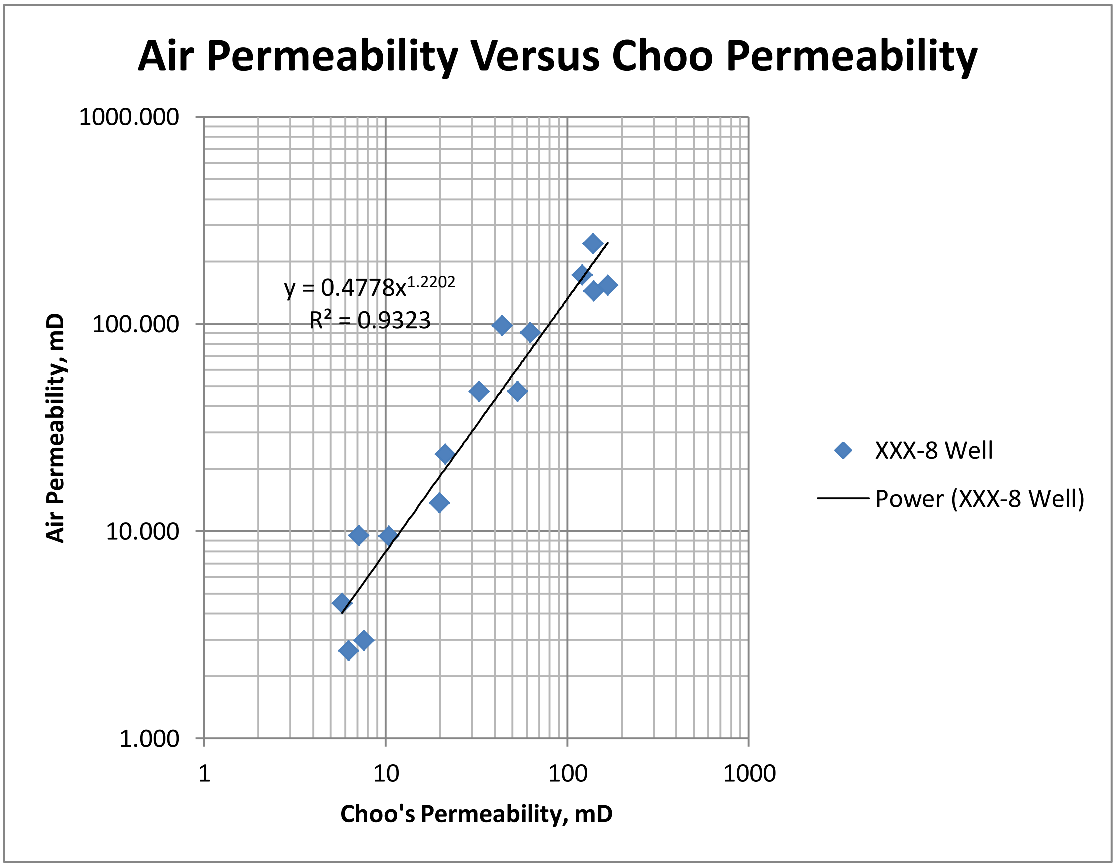


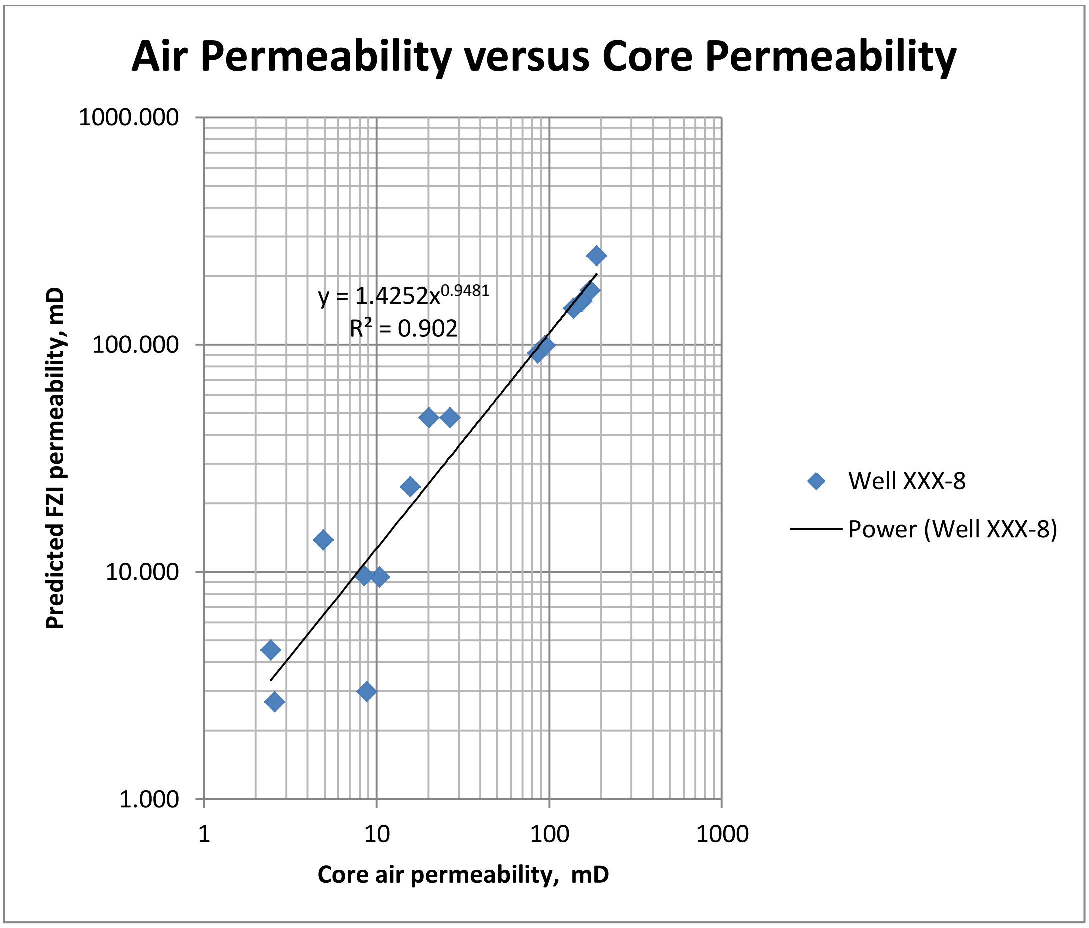
Figure 20. Air permeability is matched with Choo's predicted permeability.

4.6 HFU Permeability Prediction

HFU has also been used as a permeability prediction method. In this report, the method will be demonstrated by utilizing core date and unlike Choo's Method, this technique can be applied for cored well. Additional steps are required to use well log data to predict permeability value and this will be discussed in the **Conclusion and Recommendation** section. **Table 12** shows the tabulated results by utilizing **Equation 4** and comparison between the core permeability is shown in **Figure 21.** The mean values of FZI are the results obtained during the rock typing. Although it is not as accurate Choo's method to predict permeability, it is still a reliable method to boost the confidence of the results obtain from core lab or other prediction method.

Table 11. Predicted permeability based on HFU formula.

Porosity, %	FZI Mean	Predicted Permeability	Air Permeability, mD
0.15546	1.4	10.46910531	9.441
0.2042	1.4	26.72104079	47.35
0.14764	1.4	8.803594177	2.968
0.23409	2.8	173.8389631	172.4
0.23931	2.8	188.2873503	243.9
0.23976	2.4	139.2801403	144.1
0.24683	2.4	154.8346804	154.4
0.20967	2.4	86.18910856	91.11
0.19764	2.8	95.33228748	98.60
0.17518	1.4	15.70468487	23.53
0.18818	1.4	20.09531999	47.30
0.14604	1.4	8.488568196	9.544
0.14082	0.8	2.454949885	4.499
0.1428	0.8	2.571806127	2.661
0.17309	0.8	4.92172535	13.73



4.6 Other Information from Porosity Permeability Relationship

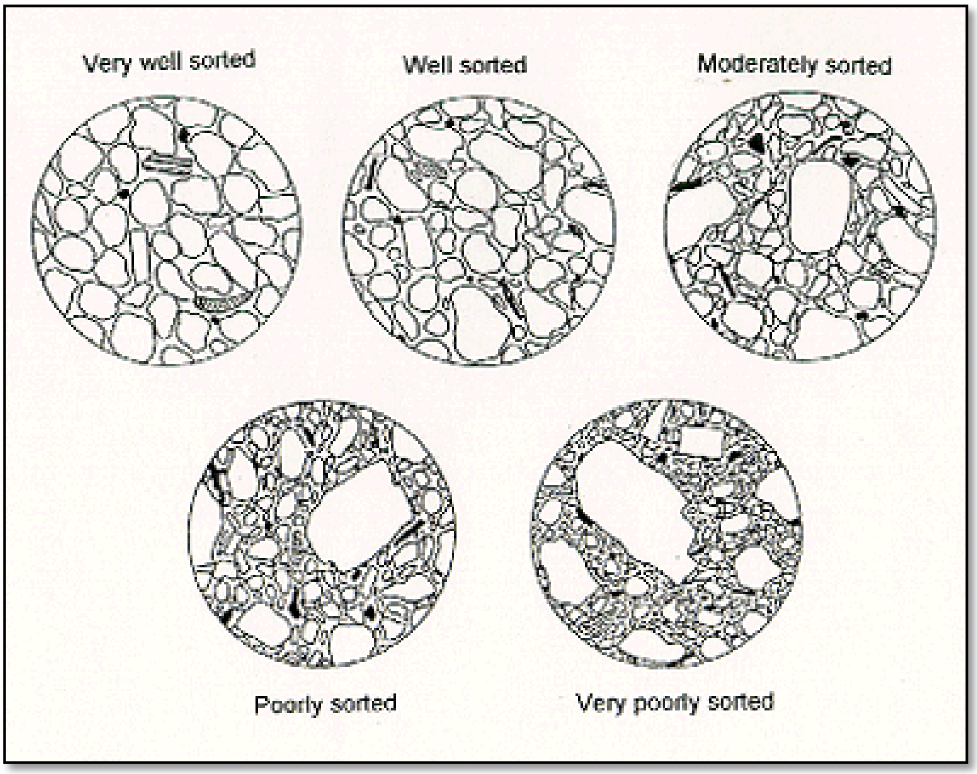


Figure 21. Sorting of the grain might have greatly impact the relationship of porosity and permeability. Adapted from, "Sediment," by Ezekwe, 2010.

In fact from **Figure 12 or Figure 13**, we can deduce the lithologies of the particular well apart from knowing the amount of rock type in it. The increase in both porosity and permeability in Rock Type 1, 3 and 5 might suggest that they are related to increase in depositional energy. This can be caused by the better grain sorting or associated to decrease in amounts of fine-grained sediments which lies within the pore spaces or pore throat as shown in **Figure 14**. Apart from that, it might indicates greater vertical or lateral communication between porous and permeable beds. Some other causes that can result in the increment of both porosity and permeability will be thinner mudstone layers or other permeability barriers and reduction of low permeability calcite-cemented sandstone in the formation. With the relationship of porosity and permeability being established, we can also estimate how the pore geometry, pore type and fluid properties are closely related to permeability itself. It is undeniable fact that, sandstone texture has a direct impact on these elements. Pore type which is determined by the pore throat size affects the rock permeability directly by limiting the flow capacity. Pore geometry affects permeability as well bu not as much as pore throat does. As the surface of the pore gets rougher, the harder for the fluid to pass through the pore and hence, lower the permeability. In short, sandstone texture can affect permeability such that:

- Permeability increases with grain sorting.
- Permeability increases with grain rounding.
- Permeability decreases with grain size.

As mentioned by (Hartmann, Beaumont, and Coalson (2000)) in **Figure 15** that the porosity and permeability relationship can indicate the grain size of the formation, we can deduce the grain size of formation in XXX-2 well too. The red circle in Figure 14 shows the range of values for Rock Type 1, 2, 3 and 5 for XXX-2 well which indicates that they might consists of fine grains or crystals. However, the findings is uncertain as there are no other data such as CT scan to prove the results.

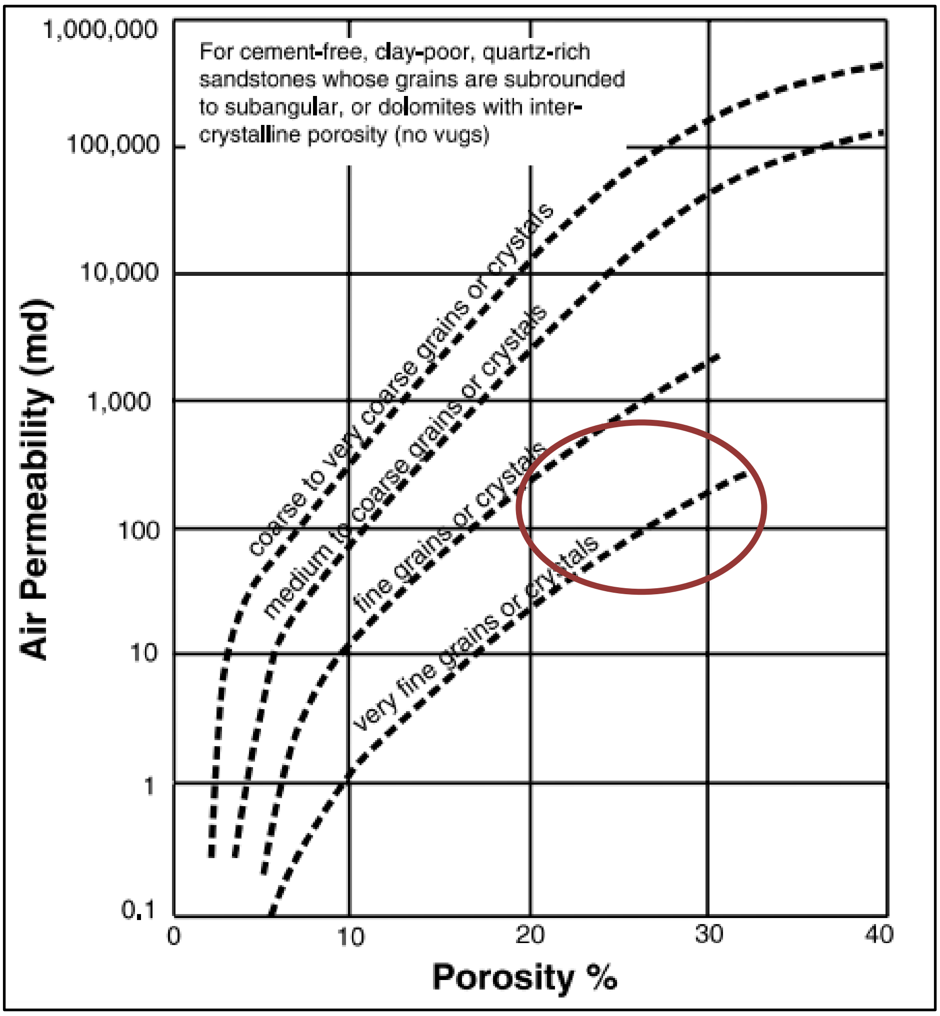


Figure 22. Grain size affects porosity and permeability. Adapted from "Predicting Sandstone Reservoir System Quality and Example of Petrophysical Evaluation. " by Hartmann, Beaumont, and Coalson, 2000.

CHAPTER 5: CONCLUSION & RECOMMENDATIONS

5.1 Conclusion

In a nutshell, the objectives of this project have been achieve. Porosity and permeability relationship can be demonstrated in the application of rock typing. Although **conventional cross plots method** is one of the techniques to be used for rock typing, it is however, **cannot be depended solely** as it might mislead the flow properties of a reservoir such as what happened in XXX-8 well. **Greater improvements** can be seen when using the **hydraulic flow unit** for rock typing as it is able to distinguish between different rock types and correlates the flow unit although it is in between of other hydraulic flow units. However, one must determine the number of hydraulic flow units correctly before correlates the flow unit. In this project, **histogram analysis does not provide much information** on number of flow units whereas **probability plot** has indicated a total of **4 flow unit** in XXX-8 well.

Another significant application of porosity and permeability relationship will be permeability prediction. Only two methods are shown in this paper for the sake of demonstrating this application which are **Choo's Permeability Prediction** which is commonly used in PETRONAS and also **hydraulic flow unit** method. Both of them showed reliable results as it is close to the actual core data.

Apart from that, porosity and permeability crossplots can actually tell us the type of pore geometry of the particular formation. With experience and previous data collection, petrophysicist and geologist can actually construct the porosity and permeability crossplot which defined the pore geometry corresponding to the rock type in a particular field.

5.2 Recommendations

Other than conventional method and hydraulic flow method, another famous method for rock typing will be **Winland Method** (Shabaninejad & Haghighi, 2011)**.** This method links the relationship between some of the petrophysical properties such as porosity, permeability and capillary pressure to the pore throat r35. This is actually the pore throat radius which is measured with a mercury saturation of 35% in a mercury-injection capillary pressure experiment.

Although it is to be said that graphical clustering analysis which is including the histogram analysis and permeability plot might not be able to accurately indicate the number of low unit, it can be improved by comparing to other analytical method. **Some of the recommendations** to determine the number of flow units are **hierarchical cluster analysis** and **sum of square errors**, SSE. Hierarchical cluster analysis such as **Ward's algorithm** is done by calculating the distances between data point points, in this case, it would be FZI values and each sample data is treated as a cluster (Al-Ajmi & Holditch, 2000). The next step is merging two clusters which are closest in distance and the new cluster's distance with the other clusters are calculated again. These processes are continued until the required number of clusters is obtained. However, the number of clusters shall be known prior to the calculation as it is an input to the hierarchical cluster analysis. Sum of square errors (SSE), on the other hand, is done by assuming the initial number of HFU is 1 and Matlab software will be used to perform the cluster analysis (Taslimi et al., 2008). Next, linear regression analysis is performed for a numbers of HFU and finally the number of HFU against the sum of square errors is plotted. Usually, the sum of square errors will decrease with the increment of HFU number but stop after a certain number of HFU. The point where it stops will be the optimal number of HFU.

For the permeability prediction, HFU method can be used to correlate FZI correlation with well logs by using **Alternating Conditional Expectation (ACE).** This method extends the concept of hydraulic flow unit in which only well log data are provided. The well log data needed are gamma ray, deep resistivity to shallow resistivity, effective porosity and sonic travel time (Abed, 2011).

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APPENDIX

Appendix A: 7 wells core data

WELL	DEPTH	CPOR	CPERM
	FT	%	mD
XXX-2	5297.417	23.8	263
XXX-2	5298.417	23.3	296
XXX-2	5299.417	22.4	222
XXX-2	5300	22	240
XXX-2	5301.083	22.5	231
XXX-2	5301.917	23.7	298
XXX-2	5311.6	25.5	404
XXX-2	5312.517	24	237
XXX-2	5313.433	25.3	239
XXX-2	5314.517	24	314
XXX-2	5316.767	23	171
XXX-2	5317.85	23.2	193
XXX-2	5318.767	22.8	78
XXX-2	5319.6	20.9	165
XXX-2	5320.517	23.6	173
XXX-2	5326	24.3	332
XXX-2ST1	5439	16.8	3
XXX-2ST1	5440.083	17.2	4
XXX-2ST1	5441.25	18.6	5
XXX-2ST1	5442.083	17	2
XXX-2ST1	5443	18.6	6
XXX-2ST1	5444.083	18	7
XXX-2ST1	5445	18.3	5
XXX-2ST1	5446.083	18.4	5
XXX-2ST1	5447	16.5	3
XXX-2ST1	5448.083	16.4	3
XXX-2ST1	5449	17	4
XXX-2ST1	5450.083	17	4
XXX-2ST1	5455.467	12.9	1
XXX-2ST1	5464.967	20	8
XXX-2ST1	5466.633	20	13
XXX-2ST1	5469.467	20	19
XXX-2ST1	5470.383	20	10
XXX-2ST1	5471.633	18.7	5
XXX-2ST1	5476.883	16.4	4
XXX-2ST1	5481.217	13.9	1

XXX-2ST1	5482.3	17	3
XXX-2ST1	5483.3	11.8	1
XXX-2ST1	5484.3	13.1	2
XXX-2ST1	5486.3	17	14
XXX-2ST1	5487.383	11.7	5
XXX-2ST1	5488.967	18.6	54
XXX-2ST1	5503	13.7	1
XXX-2ST1	5515	14.3	1
XXX-2ST1	5518.083	10.1	1
XXX-2ST1	5519	20	72
XXX-2ST1	5520.333	20.6	111
XXX-2ST1	5521.083	19.5	36
XXX-2ST1	5523.25	21	128
XXX-2ST1	5524	20.8	186
XXX-2ST1	5526	20.2	56
XXX-2ST1	5532.583	21.6	140
XXX-2ST1	5533.5	19.2	39
XXX-2ST1	5534.583	20.6	92
XXX-2ST1	5535.5	20.1	92
XXX-2ST1	5536.667	19.7	50
XXX-2ST1	5537.5	19.2	42
XXX-2ST1	5538.583	18.9	40
XXX-2ST1	5539.5	18.6	36
XXX-2ST1	5540.583	20.2	88
XXX-2ST1	5541.5	17.2	20
XXX-2ST1	5542.583	17.6	24
XXX-2ST1	5543.75	17.8	70
XXX-2ST1	5561.167	18.7	31
XXX-2ST1	5561.917	19.2	91
XXX-2ST1	5563.083	20.1	93
XXX-2ST1	5565.5	17.3	9
XXX-2ST1	5567.583	19.8	106
XXX-2ST1	5568.5	17.8	4
XXX-2ST1	5569.75	18.5	10
XXX-2ST1	5576.667	18.3	14
XXX-2ST1	5585.583	17.4	5
XXX-2ST1	5583.417	19	30
XXX-2ST1	5584.583	20.7	66
XXX-2ST1	5587.583	20.7	27
XXX-2ST1	5590.75	21.8	133
XXX-2ST1	5592.083	20.1	89
XXX-2ST1	5593	19.7	62
XXX-2ST1	5594.083	18.7	9
XXX-2ST1	5595	20.3	27
XXX-2ST1	5596.083	19.7	18

XXX-2ST1	5597	19	19
XXX-2ST1	5599	20.7	67
XXX-2ST1	5600	19.9	55
XXX-2ST1	5628.833	20.6	57
XXX-2ST1	5635.25	20.9	121
XXX-2ST1	5636	21.1	116
XXX-2ST1	5637.083	21.4	113
XXX-2ST1	5668.2	21.1	110
XXX-2ST1	5639.083	21.5	129
XXX-2ST1	5640	21.6	125
XXX-2ST1	5641.083	21.3	125
XXX-2ST1	5642	21.5	122
XXX-2ST1	5643.083	19.9	99
XXX-2ST1	5644.25	18	20
XXX-2ST1	5645.083	15.7	6
XXX-2ST1	5646	15.6	10
XXX-2ST1	5647.25	17.5	11
XXX-2ST1	5648	19.8	46
XXX-2ST1	5649.167	19.9	
XXX-2ST1	5650	18.5	21
XXX-2ST1	5651.167	18.3	38
XXX-2ST1	5652	17.9	22
XXX-2ST1	5653	20.7	84
XXX-2ST1	5654	21.2	142
XXX-2ST1	5655.167	19.8	48
XXX-2ST1	5658.333	21.4	111
XXX-2ST1	5659.083	20	61
XXX-2ST1	5660	18.8	64
XXX-2ST1	7654	9.2	1
XXX-2ST1	7668.583	13	1
XXX-2ST1	7669.917	15.5	1
XXX-2ST1	7670.833	11.8	5
XXX-2ST1	7672	12.1	1
XXX-2ST1	7673	14.9	4
XXX-2ST1	7673.917	12.9	4
XXX-2ST1	7675.083	14.2	1
XXX-2ST1	7676	15	3
XXX-2ST1	7677.25	14.4	2
XXX-2ST1	7685.833	11.4	1
XXX-2ST1	7689.167	9.4	1
XXX-2ST1	7699.417	11.7	2
XXX-2ST1	7702.833	10.2	1
XXX-2ST1	7703.833	10.3	1
XXX-2ST1	7615.783	10.2	1
XXX-2ST1	7708.75	10.3	1

XXX-5	3793.9	11.8	1
XXX-5	3796.5	16.8	2
XXX-5	3799.6	18.4	1
XXX-5	3800.5	25	25
XXX-5	3801.8	23	5
XXX-5	3803.1	23.6	6
XXX-5	3804	21.4	8
XXX-5	3815.5	22.5	7
XXX-5	3816.8	20.5	2
XXX-5	3827.5	19.3	18
XXX-5	3829.9	23	34
XXX-5	3831.2	24.7	59
XXX-5	3832	20.4	1
XXX-5	3857.3	18.9	33
XXX-5	3858.8	22.1	8
XXX-5	3863.8	22.7	1273
XXX-5	3865.8	12.4	4
XXX-5	3908.6	13.9	1
XXX-5	3909.3	13	4
XXX-5	3945.3	26.4	158
XXX-5	3959.3	30.3	3225
XXX-5	3960.4	24.9	1213
XXX-5	3997.3	26.6	167
XXX-5	3998	21.9	43
XXX-5	3999	24.1	162
XXX-5	3999.9	30.2	2456
XXX-5	4001	28.3	484
XXX-5	4003.4	28.8	1379
XXX-5	4005.4	27.5	163
XXX-5	4044.8	27.6	183
XXX-5	4045.8	26.4	286
XXX-5	4046.8	26.6	138
XXX-5	4048	25.7	206
XXX-5	4048.9	24.7	120
XXX-5	4050.1	26.1	204
XXX-5	4051	23.8	94
XXX-5	4052.3	27.2	290
XXX-5	4053.6	25.6	160
XXX-5	4054.6	26.4	640
XXX-5	4056.1	25.9	740
XXX-5	4057.1	14.9	117
XXX-5	4058.1	22.9	164
XXX-5	4059.8		
XXX-5	4060.8	22.1	221
XXX-5	4062	16.8	51

XXX-5	4062.9	21.7	31
XXX-5	4562.8	12.5	1
XXX-5	4563.7	12.8	1
XXX-5	4576	11.1	1
XXX-5	4576.9	14.4	1
XXX-5	4578	17.7	10
XXX-5	4579	17.1	5
XXX-5	4580	16.1	3
XXX-5	4580.9	25.7	1275
XXX-5	4582	22.7	142
XXX-5	4589.2	21.9	1612
XXX-5	4629.9	19.4	143
XXX-5	4630.8	27.7	158
XXX-5	4632.7	20.5	45
XXX-5	4633.7	23.3	920
XXX-5	4635	26.8	2249
XXX-5	4636	26.2	1386
XXX-5	4637.2	26.4	1681
XXX-5	4638.3	22.8	160
XXX-5	4639.4	23.7	197
XXX-5	4640.3	23.8	559
XXX-5	4641.8	24.5	481
XXX-5	4643.2	24.6	603
XXX-5	4644	23.2	178
XXX-5	4645	23.9	588
XXX-5	4646	23.2	156
XXX-5	4646.9	22	169
XXX-5	4648	22.9	186
XXX-5	4649	23.9	467
XXX-5	4650	24.5	654
XXX-5	4651	26.2	1978
XXX-5	4652	26	1517
XXX-5	4653	25.3	998
XXX-5	4654	25.7	1191
XXX-5	4655.5	23	229
XXX-5	4656.5	23.7	188
XXX-5	4657.5	23	321
XXX-5	4658.5	24.8	224
XXX-5	4659.5	24.4	225
XXX-5	4660.5	26	711
XXX-5	4663.2	26.5	1585
XXX-5	4664.2	22.9	168
XXX-5	4665.3	26.3	1327
XXX-5	4666.4	27.7	3938
XXX-5	4667.5	26.8	1948

XXX-5	4668.5	25.7	945
XXX-5	4669.6	26.2	1427
XXX-5	4670.5	25.5	1309
XXX-5	4671.5	22.6	102
XXX-5	4673.8	24.8	1327
XXX-5	4674.8	24.2	260
XXX-5	4786	26.7	3393
XXX-5	4787.1	27.1	955
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XXX-5	4792	24.2	208
XXX-5	4793	26.1	862
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XXX-5	4799	25.9	830
XXX-5	4800	25.4	607
XXX-5	4801	23.9	191
XXX-5	4802	26.8	2140
XXX-5	4803	27.4	1351
XXX-5	4804	25.6	986
XXX-5	4805	29	5193
XXX-5	4806	28.8	5924
XXX-5	4807	29.6	6658
XXX-7	3982.6	19.8	29
XXX-7	3988.8	16.62	2
XXX-7	3990.8	27.3	447
XXX-7	3992.6	21.1	74
XXX-7	3994	21.8	100
XXX-7	3995.3	23.1	440
XXX-7	3996.4	17	5
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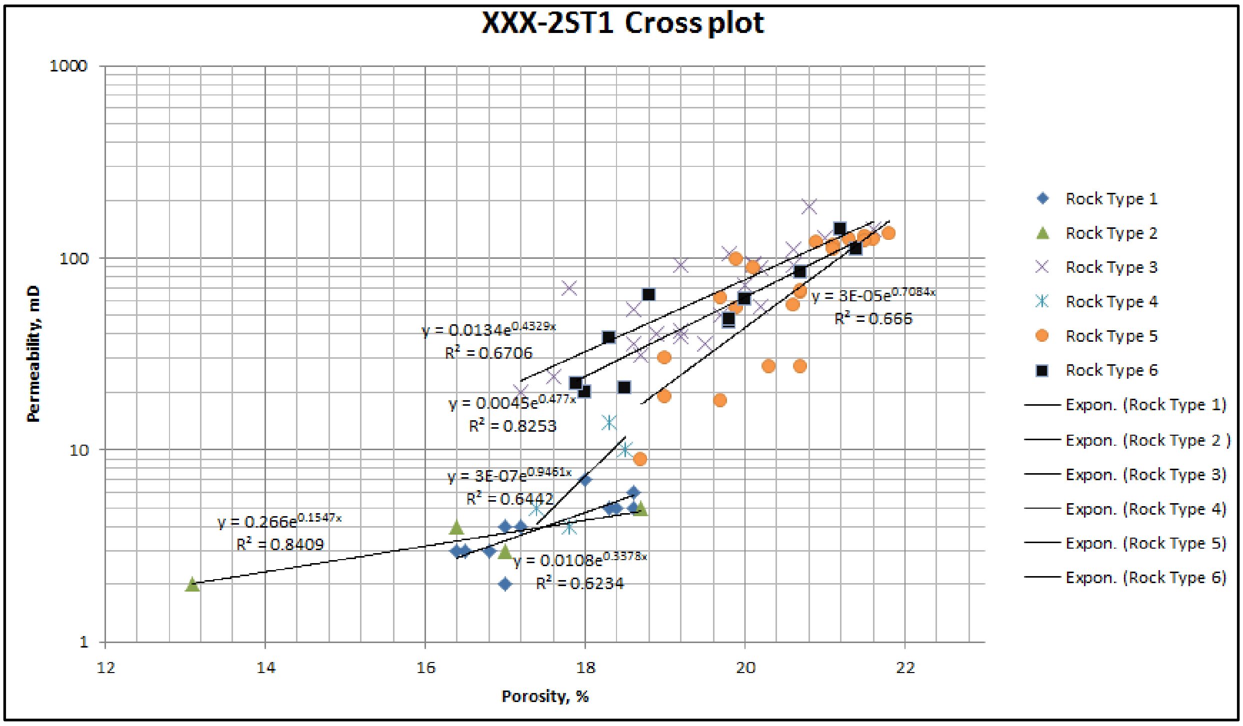
XXX-7	4004.7	29	527
XXX-7	4048.9	18.6	5
XXX-7	4051.7	11.9	1
XXX-7	4057.9	13.3	1
XXX-7	4058.8	14.7	1
XXX-7	4060.9	14.7	26
XXX-7	4077.3	21.7	108
XXX-7	4078.3	17	446
XXX-7	4079.5	24.3	826

XXX-7	4081	25.7	687
XXX-7	4090.5	28.7	888
XXX-7	4091.6	26.2	441
XXX-7	4093.4	12.4	1
XXX-7	4094.5	25.9	794
XXX-7	4095.2	27.9	1435
XXX-7	4096.1	26.1	886
XXX-7	4100	27.8	1290
XXX-7	4101.7	28	1649
XXX-7	4102.7	27.8	458
XXX-7	4105.6	28.1	569
XXX-7	4106.4	27.6	968
XXX-7	4109	26.3	457
XXX-7	4109.9	25.1	453
XXX-7	4117.5	23.5	435
XXX-7	4118.7	25.9	808
XXX-7	4121.5	27.7	971
XXX-6	3877.1	24.8	167
XXX-6	3892.5	23.5	78
XXX-6	3893.5	23.4	132
XXX-6	3894.6	24.4	144
XXX-6	3895.7	25.1	177
XXX-6	3896.7	23.5	57
XXX-6	3899.8	125.2	264
XXX-6	3901	24.9	367
XXX-6	3902.5	27.4	1604
XXX-6	3905.3	23.1	72
XXX-6	3907.4	29.9	3140
XXX-6	3908.4	27.6	2543
XXX-6	3909.4	26	187
XXX-6	3910.4	25.5	447
XXX-6	3911.4	29.6	3989
XXX-6	3912.4	27.3	1675
XXX-6	3913.4	25.5	919
XXX-6	3914.4	28.6	2023
XXX-6	3922.8	26.5	616
XXX-6	3925.7	22.2	35
XXX-6	3963.4	22	267
XXX-6	3968.7	28.3	1530
XXX-6	3969.7	28.1	1770
XXX-6	3970.65	28.7	3077
XXX-6	3971.65	28.4	2453
XXX-6	3973.8	28.8	3081
XXX-6	3974.8	28.6	2713
XXX-6	3975.8	22.1	1356

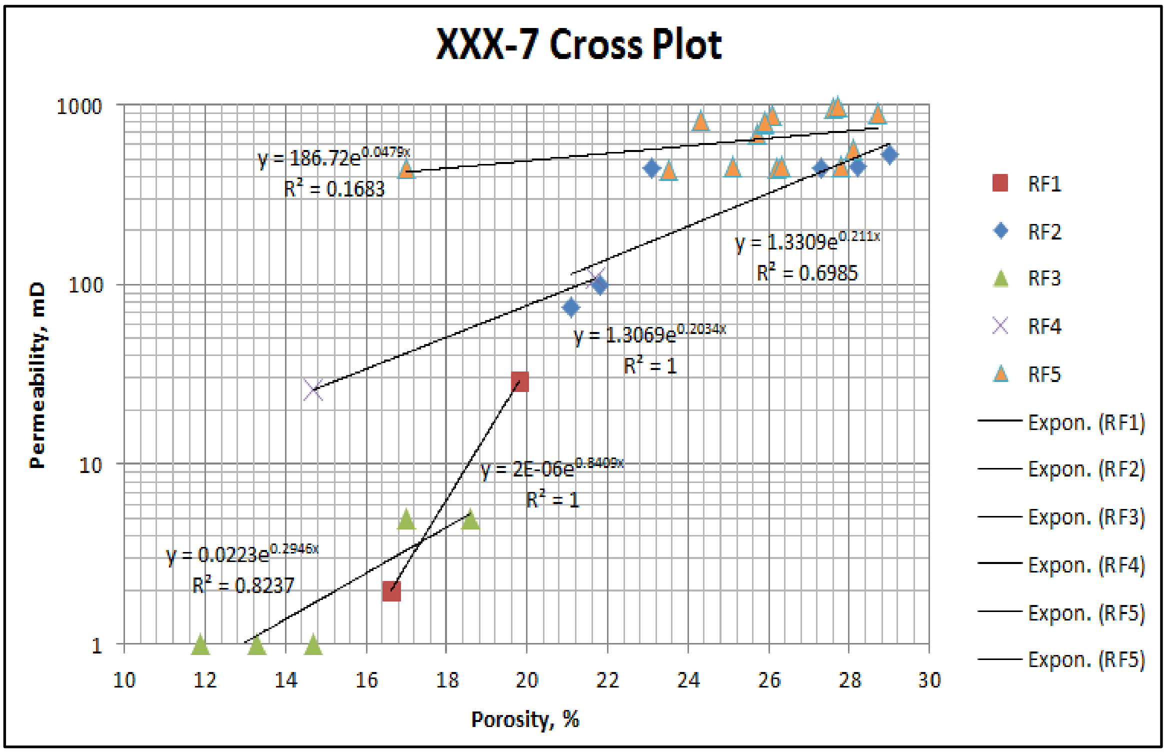
XXX-6	3976.8	29.4	2884
XXX-6	3977.8	27.4	1223
XXX-6	3978.8	25.8	731
XXX-6	4005.3	28.3	1224
XXX-6	4006.5	27.6	788
XXX-6	4007.5	28	826
XXX-6	4009.4	26.7	768
XXX-6	4010.4	25.1	368
XXX-6	4011.4	26.7	631
XXX-6	4013.3	18.8	512
XXX-6	4014.3	26.5	465
XXX-6	4015.6	26.6	1147
XXX-6	4017.4	25.6	1185
XXX-6	4019	25.6	769
XXX-6	4020.2	21.2	40
XXX-6	4021.2	23.6	909
XXX-6	4022.2	21.1	173
XXX-6	4024	25.3	691
XXX-6	4033.4	10.1	1
XXX-6	4034.8	23.4	12
XXX-6	4035.8	24.8	500
XXX-6	4037.2	20	63
XXX-6	4038.3	12.1	1
XXX-6	4039.3	20	15
XXX-6	4087.3	26.7	2764
XXX-6	4110.8	12.5	1
XXX-6	4112.2	22	531
XXX-6	4114.5	23.7	541
XXX-6	4118.4	23.1	267
XXX-6	4133.4	18.8	1
XXX-6	4138	11.5	1
XXX-6	4144.5	24.3	68
XXX-6	4145.5	25.7	44
XXX-6	4149.4	24.4	49
XXX-6	4150.5	23.5	36
XXX-6	4151.5	23.4	42
XXX-6	4154.3	23.5	47
XXX-103	4767	24.2	58
XXX-103	4767.5	27.1	2321
XXX-103	4792	26.4	1290
XXX-103	4797	22.2	142
XXX-103	4797.5	26.7	1261
XXX-103	4798.5	27.2	1932
XXX-103	4799.5	27.1	1906
XXX-103	4803	26.4	1087

XXX-103	4803.5	25.8	453
XXX-103	4822	23.6	1578
XXX-103	4823	23.8	123
XXX-103	4823.5	17.1	37
XXX-103	4824	23.8	531
XXX-103	4825	25.1	851
XXX-103	4831.5	22.3	850
XXX-103	4832.5	24	210
XXX-103	4834	15	3.7
XXX-103	4905	22.5	114
XXX-103	4906	22.8	144.1
XXX-103	4916	26.4	623
XXX-103	4922	23.2	105
XXX-103	4978	26.4	1735

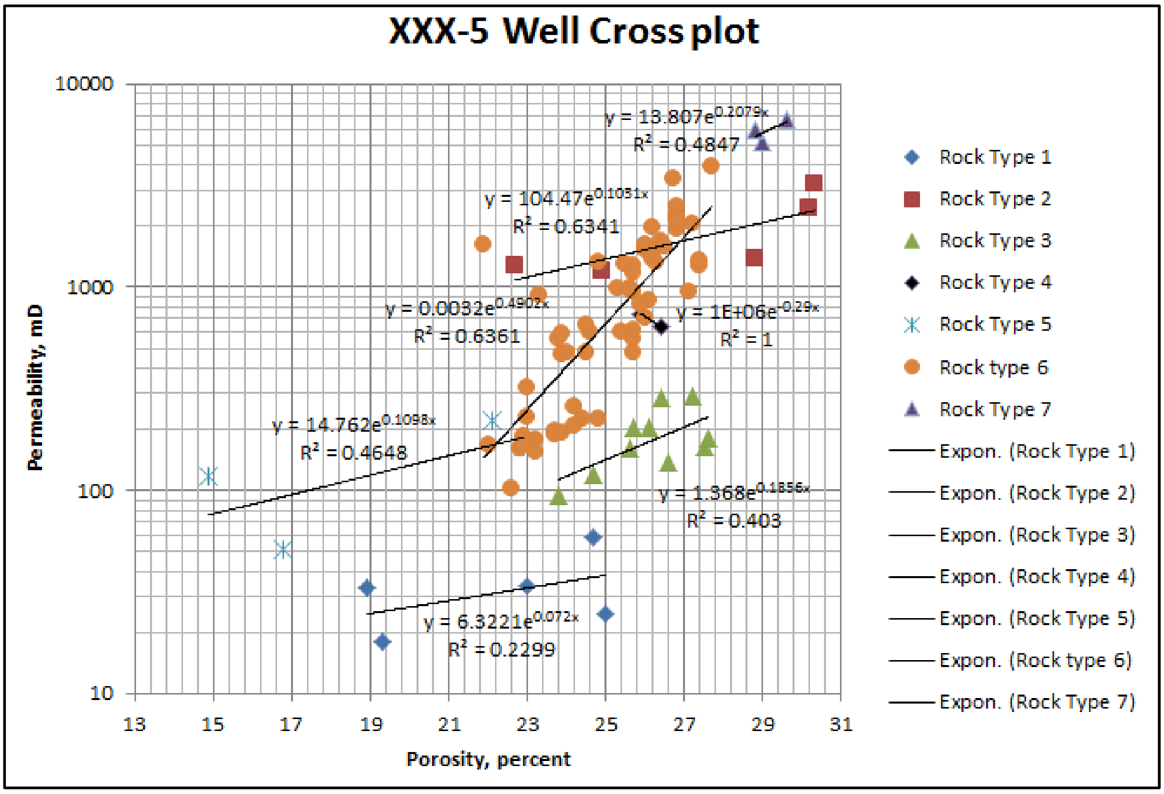
Appendix B: XXX-2ST1 Cross Plot



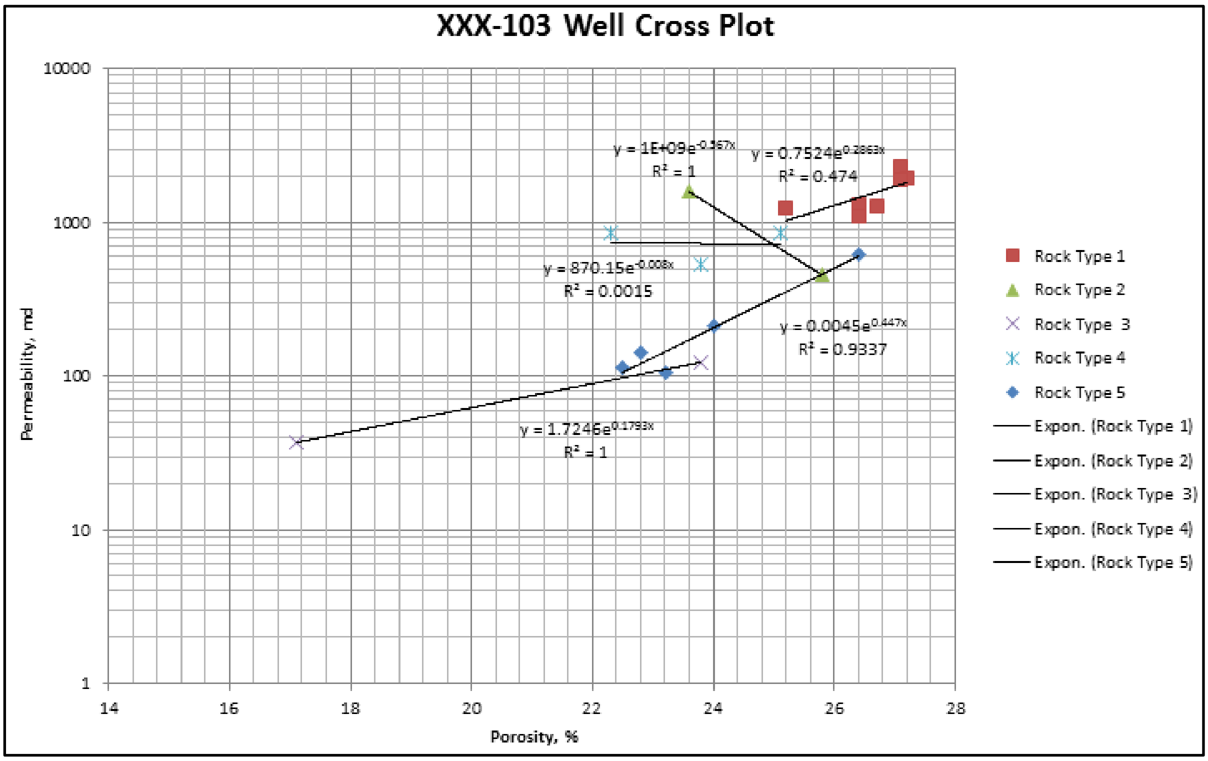
Appendix C: XXX-7 Cross Plot



Appendix D: XXX-5 Well Cross Plot



Appendix E: XXX-103 Well Cross Plot



Appendix F: XXX-106 Well Cross Plot