UNIVERSITI TEKNOLOGI PETRONAS

FYP DISSERTATION

SCALE & CHARACTERISTICS OF HETEROGENEITIES IN SANDSTONE RESERVOIR – MIRI FORMATION (HOSPITAL ROAD OUTCROP)

Scale & Characteristics of Heterogeneity in Sandstone Reservoir – Miri Formation (Hospital Road Outcrop)

by

Nurul Nadhira binti Idris

Dissertation submitted in partial fulfillment of
the requirements for the
Bachelor of Engineering (Hons)
(Petroleum Engineering)

JANUARY 2011

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CERTIFICATION OF APPROVAL

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Approved by,

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(AP Dr. Abdul Hadi Abdul Rahman)

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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 that the original work contained herein have not been undertaken or done by unspecified sources or persons.

NURUL NADHIRA BINTI IDRIS

Contents

ABSTRACT

This project is about a study of sedimentological and certain petrophysical properties of Miri Formation specifically at Miri Hospital Road Outcrop. The objective of this study is to characterize and quantify the reservoir heterogeneities. The objective can be achieved by identifying and analyzing facies characteristics, certain petrophysical properties (porosity & permeability), and certain grain characteristics (size distribution & sorting). The outcrop thickness ranges between 9.8 to 11m and it comprises of seven (7) layers. Among all those layers, five (5) of them are sandstone layers while the other two (2) are shale layers. The best sandstone reservoir lies in Facies F which has largest layer thickness (1.84 – 2.40 m), less permeability barriers and it has good grain sorting.

ACKNOWLEDGEMENT

I would like to take this opportunity to express my utmost gratitude to the individuals who have taken the time and effort to assist me in completing this project. Without the cooperation of these individuals, I would undoubtedly have faced complications throughout the course.

First and foremost my utmost gratitude to my supervisor, AP Dr. Abdul Hadi b. Abdul Rahman, for his invaluable support, encouragement, supervision and useful suggestions throughout this research work. His moral support and continuous guidance enabled me to complete my work successfully.

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To friends which have continuously assisted me throughout the project especially during field trip. To parents and friends, thank you for the moral supports. Last but not least, to all individuals who have helped me in any way, but whose name is not mentioned here, I would like to thanks to all of you.

1. INTRODUCTION

1.1. Project Background

Reservoir heterogeneity is defined as rock properties variability within a single reservoir that affects the flow of hydrocarbons. It exists at all scale of formations, whether in grain, laminae, bed, or sandbody. The two (2) most important parameters in hydrocarbon production are porosity which to store the hydrocarbon inside the rock and secondly; the permeability which provide mobility to the hydrocarbon to production wells. In heterogeneous reservoir, these two parameters are also affected.

Generally the reservoir heterogeneity is dominantly controlled by the process at depositional level. Different depositional environment will result in different heterogeneity of reservoir. However, diagenetic and structural compartmentalization also plays an importance role in determining the heterogeneity of the reservoir.

As this project is focusing on sandstone reservoir, the report will concentrate more on the heterogeneity in sandstone. Sandstones are detrital sedimentary rocks with grains range from 0.05mm to 2mm in diameter. There are generally three (3) types of sandstones which are quartz arenite, arkose, and graywacke. Both arkose and graywacke are poorly sorted and angular which make them high in heterogeneity level. While quartz arenite are majorly dominant by quartz and the matrix are very little.

There are three (3) major levels of heterogeneity in a clastic reservoir which are megascopic, macroscopic, and microscopic. Megascopic level of scale ranges between height of ten (10) to hundreds of meters with length of hundreds to ten (10) kilometers. Meanwhile for macroscopic level of scale ranges between heights of ten (10) meters to ten (10) millimeters. The smallest scale of heterogeneity is microscopic which ranges from size of hundreds to ten (10) micrometers.

1.2. Problem Statement

As in 2010, studies that have been made by the experts reported that there are six (6) trillion barrels of oil remaining in the world reserves yet to be recovered. However, as it is one of the challenges in future oil and gas industry, 70% of the reserves consist of unconventional oil, and only 30% of the reserves are conventional oil. Unfortunately, among the 30% of the reserves, there is very much of them that are in thin formation (<30ft) with low porosity, low permeability, low temperature (7°C), and deep (>3000ft). These are called difficult oil.

The industry now has entered tertiary recovery phase which includes Enhanced Oil Recovery (EOR) method. The EOR method can be used to recover that difficult oil. However in using EOR techniques, several considerations have to be made to choose the most suitable techniques to be applied. The considerations include the reservoir heterogeneity. In evaluating the heterogeneities of the chosen formation, a detail and thorough study is needed.

1.3. Objectives

The primary objective of doing the study is to characterize and quantify the heterogeneities of the chosen formation (Miri Formation – Hospital Road Outcrop). This objective can be achieved by:

- Identify and analyze facies characteristics of sandstone in the outcrop.
- Identify petrophysical properties (porosity, permeability) and grain characteristics (grain size distribution, sorting) of the formation.

1.4. Relevancy and Feasibility of the Project

The project involves a major percentage of geosciences and reservoir geosciences field and that would be relevant for a Petroleum Engineering student. A Petroleum Engineering student should have sufficient knowledge of Geoscience and Geology to enhance the hydrocarbon productivity.

This project is a study to characterize the heterogeneities of the formation. It is a relevant study as the objective is to analyze whether it is a low or highly varied formation. This project is feasible to be done in UTP since all equipment needed is available in UTP laboratories.

1.5. Scope of Work

The scope of study involved would be on geosciences and reservoir geosciences field, with specification on reservoir characterization. This study scope includes gathering information on clastic rock characteristics, its heterogeneity, and the effect of different types of heterogeneities to the production performance. There is mapping and certain critical petrophysical properties estimation works. There will be also sample analyzing works to obtain reservoir properties data such as porosity and permeability.

1.6. Study Area

The area of study was around Miri Town, which is located at northeast of Sarawak, Malaysia. There are several best outcrops located at Miri, however the interested one is Miri Hospital Road Outcrop (Latitudes N 04°22’35.7” & N 04°22’47.1”, Longitudes E 113°59’31.5” & E 113°59’39.1”). Geologically, it is an extended part of Baram Delta Province. It is located behind a residential area along the road way to Miri Hospital. The outcrop is exposed to hot weather and rain throughout the year.

Figure 1.1: *Location of Miri on Malaysia map.*

Source: *http://malaysiamap.org*

1.7. Structure of Dissertation

This report consists of eight (8) chapters. The first chapter is the introduction part which where the project background, the problem statement, the objective of doing the project, the relevance and the feasibility of the project, and the job scope are written. The second chapter presents the literature review on several related subtopics. The third chapter which is the Methodology presents about the workflow of the project, how the project can be run, and the equipment that is used for the project. The next chapter, chapter four (4) will be the presents the results of the project. In chapter five (5), discussions on results are presented. There will be also some recommendations for further plan in the future. The next chapter which is chapter six (6) will conclude the whole project. All references are written in chapter seven (7). The appendices will be presented in chapter eight (8).

2. LITERATURE VIEW

2.1. Reservoir Characterization

As described by Kelkar and Perez (2002), reservoir characterization is defined as describing various reservoir characteristics by using all available data. The reservoir characteristics can be grain size distribution and the mineral sorting, reservoir permeability and porosity, depositional environment, and others. In obtaining the data, there are lots of methods those can be used according to the reservoir scales. Some of the methods are by analyzing core plugs, well logging data, well testing, outcrop studies, and also seismic.

The reservoir description will be better if more data are available. However, in real case usually not all data available at the same time. As the operation has been developed to further stages, more data could be obtained. With limited data, a good interpretations and judgments are required to describe a reservoir.

2.1.1. Porosity

From Abhijit Y. Dandekar (2006), even though a reservoir rock looks solid to the naked eye, a microscopic examination reveals the existence of tiny openings in the rock. The openings, which are called pore space stores an amount of hydrocarbon. The storage capacity of a rock is called porosity. In producing hydrocarbon, porosity is one of the most important parameter and it helps determine how much hydrocarbon can be produced.

2.1.2. Permeability

(Crain's Petrophysical Handbook) Having pore spaces inside rocks to store hydrocarbon is not sufficient to produce those hydrocarbon. An effective pathway is needed so that the hydrocarbon can flow towards the production well.

The production capacity of a rock is called as permeability. Permeability of a rock is a function of absolute permeability and fluid viscosity. Heterogeneity determines whether the permeability is effective or not. For example, a poor grain sorting rock will result low permeability.

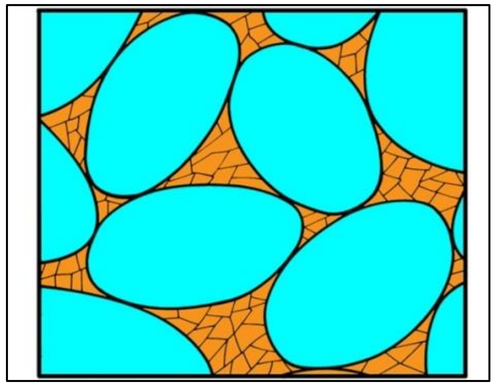


Figure 2.1: *Porosity in a rock. Turquoise body shows grain while the orange figure shows pore space of the rock.*

Source: *http://sepmstrata.org.*

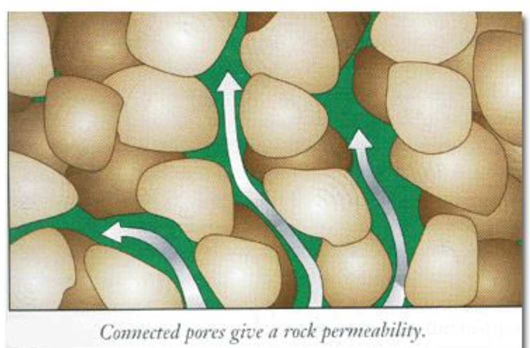


Figure 2.2: *Permeability in a rock. Brown body shows grain while the green figure shows pore space of the rock. The connected pore space provides permeability to a rock.*

Source*: http://www.mpgpetroleum.com.*

2.2. Reservoir Heterogeneities

Reservoir heterogeneity is defined as rock properties variability within a single reservoir that affects the flow of hydrocarbons (Crain's Petrophysical Handbook, 2010). If a reservoir is homogeneous, the reservoir characterization would be easy since measuring at any point will give description of the whole reservoir. However due to some occurrences and natural causes such as various types of depositional environments of rocks, heterogeneities occur in the reservoir and affect the performance. Therefore for a proper reservoir description, those variations must be predicted and taken into account.

Reservoir heterogeneities exist at all scale of formations, whether in grain, laminae, bed, or sandbody. The degree of the variations varies from pore scale to field scale. The scales are classified into five (5) scales which are microscopic, macroscopic, mesoscopic, megascopic, gigascopic.

The most important properties that are affected from the heterogeneities are porosity and permeability because these two properties indicate the storage and production capacity of a rock. Both porosity and permeability are geometric properties of a rock and both are the result of its lithologic composition. The texture and diagenesis of the rocks are strongly affecting porosity and permeability.

There are many factors can affect porosity and permeability of rocks which are grain size, grain shape, sorting, shale content, compaction, and cementation.

2.2.1. Sorting

(Crain's Petrophysical Handbook) Permeability decrease with decreasing grain size because pore diameter decreases and then the capillary pressure increases. However, having coarse grain size will not change the porosity if the other grains have smaller or larger size. This is called grain sorting. If all the grains have same large size, then it will be well sorted and the porosity and permeability will be high. This is because as sorting decreases, the pores between the larger grains are filled by the smaller particles which thus decrease the porosity.

2.2.2. Packing

Grain packing also play important role in determining porosity and permeability. Cubic packing of grains will give higher porosity than rhombohedral packing. For a cubic packing grain, the porosity will be as high as 40%, while for a rhombohedral packing grain, the poosity is 26%. There is difference in porosity value because in rhombohedral packing, the grain manage to fill in the spot between two (2) grains so they are stacked up closer than in cubic packing.

2.2.3. Angularity

Increase in the angularity of the grain shape will also increase the porosity and permeability. Angularity is a function of weathering and mineral types.

The porosity of sandstone is often quite high. Round grains and a high content of grain cement gives high porosity. The higher porosity of sandstone results in a lower heat transmission than in granite or dense limestone.

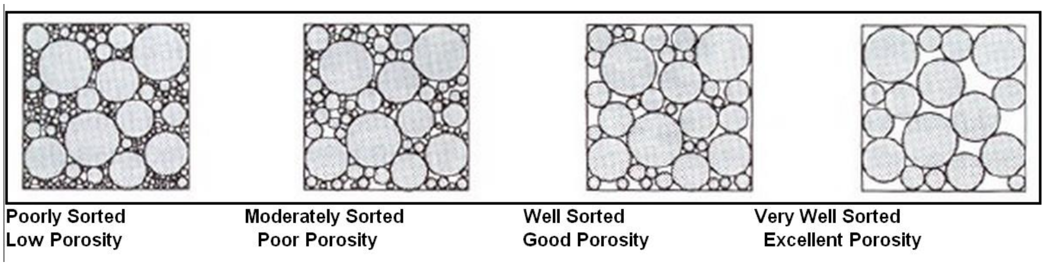


Figure 2.3: *Grain sorting and porosity relationship.*

Source: *http://spec2000.net*

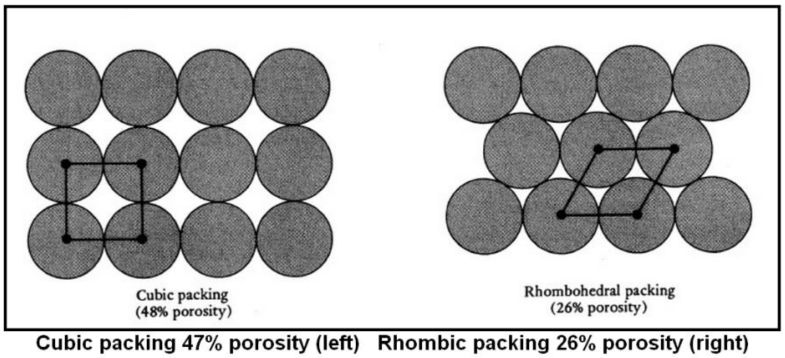


Figure 2.4: *Grain Packing and porosity relationship.*

Source*: http://spec2000.net*

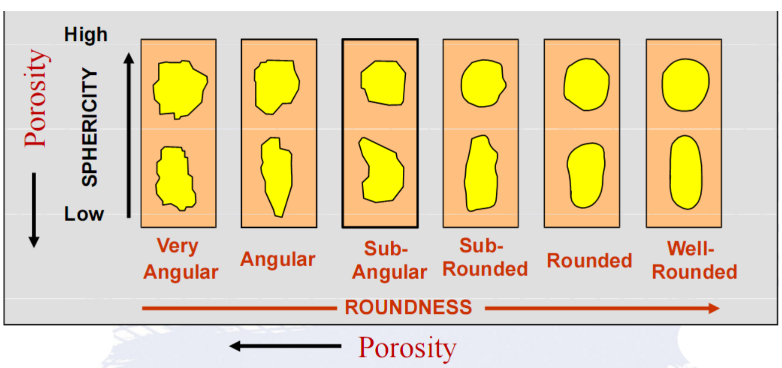


Figure 2.5: *Grain angularity and porosity relationship.*

Source: *http://spec2000.net*

However, those grain textures not the only heterogeneities occur in a reservoir. There are other factor such as vugs, dissolution, and fractures. Vugs are the isolated pores in a reservoir. As known, isolated pore space is totally not contribute to production. Usually vugs have irregular shape which disturbs the reservoir in a whole. In contrast, fractures help to have good permeability. The cracks created a path or channel for fluid to transmit.

2.3. Definition of Scales

As described by Ringrose et. al.(1996), reservoir heterogeneities can be measured on different scales which are:

2.3.1. Microscopic

Microscopic heterogeneities are the heterogeneities measured at micro level. They are also called pore-level heterogeneities. It represents the scale volume at which the rock properties are determined by grain size, pore size, grain and pore shape, grain distribution and etc. The major control of the varieties in the scale is compaction, cementation, and sedimentation process.

2.3.2. Macroscopic

Macroscopic heterogeneities are the heterogeneities those are measured at core level. They are also called core level heterogeneities. Measurement of permeability, porosity, fluid saturation, capillary pressure, and wettability are usually done at this scale. The measured rock and fluid properties are very useful for well testing analyzing and reservoir simulation.

2.3.3. Mesoscopic

The data at mesoscopic scale is obtained from well logging data. This data is usually used for reservoir simulation since it is represented at grid block. In reservoir simulation, the reservoir is represented in grid block so that average properties values can be determined in order to find the whole reservoir properties.

2.3.4. Megascopic

Megascopic heterogeneities are heterogeneities that have same order of magnitude as a reservoir simulator grid block, which is typically several feet in breadth and width. The properties measured on this scale include some log data; pressure transient, such as repeat formation test (RFT); and residual oil saturation measurements with single well tracer test. Some seismic data can also be considered to be on this scale. At this scale, the internal architecture becomes critical in identifying the spatial distribution of reservoir flow units.

2.3.5. Gigascopic

Gigascopic heterogeneities are heterogeneities those are measured at an interwell reservoir scale. It represents the whole reservoir and is the largest scale. The properties measured on this scale include permeability measurement from well test data and interwell tracer tests. In addition, surface seismic data and major fault locations also can be considered part of gigascopic heterogeneities.

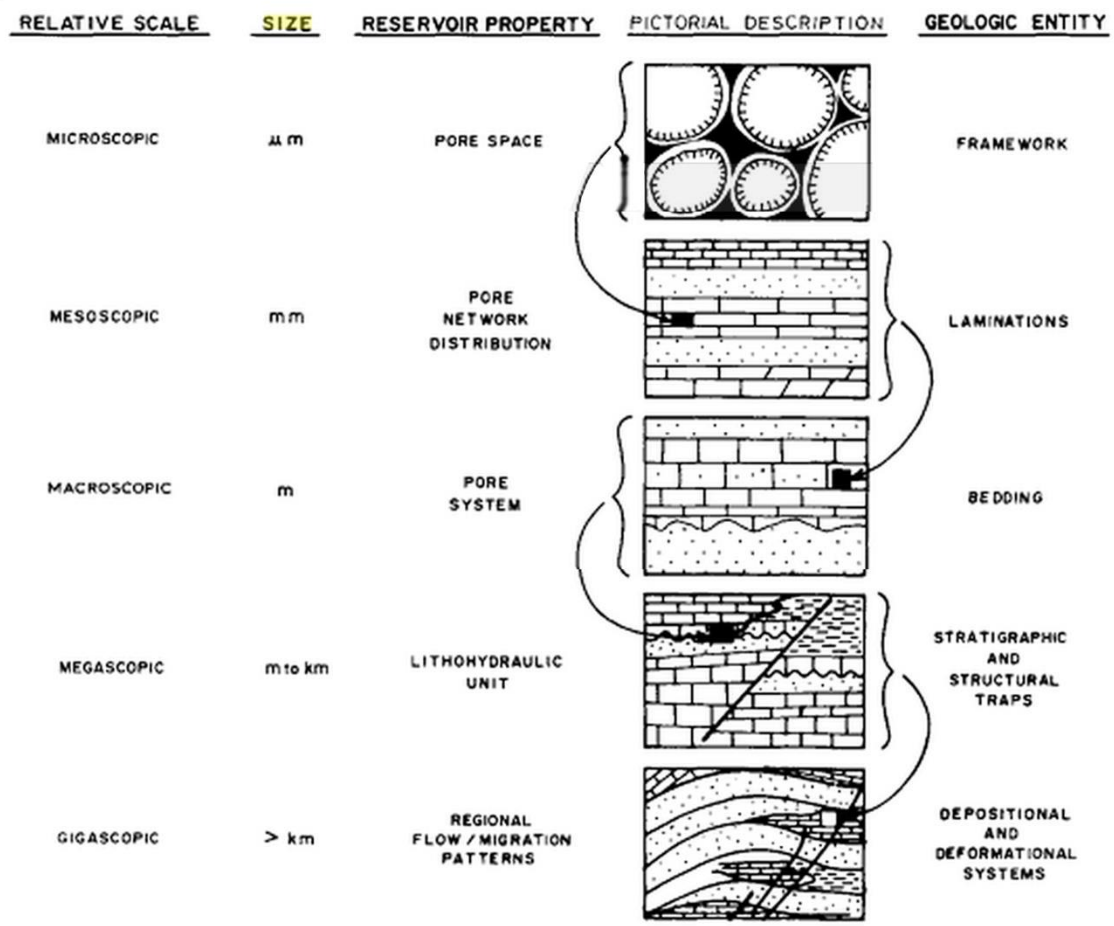


Figure 2.6: *Different scales in a field*

Source: *Carbonate Reservoir Characterization: A Geologic – Engineering Analysis*

2.4. Effect of Scales

Type	**Level**	**Measurement scale**	**Measurements**	**Geologic observations**	**Flow performance effect**	**Flow process effect**
Micro	Pore	µm	• Pore geometry • Grain size • Mineralogy	• Texture • Mineralogy • Fractures	Displacement efficiency (trapped oil)	Complex EOR process
Macro	Core	inch	• Permeability • Relative permeability • Porosity • Capillary pressure • Wettability • Saturation	• Lamination • Crossbedding baffles within genetic units	Sweep efficiency (bypassed oil)	Secondary process (waterflooding)
Mega	Grid block	foot	• Logs • RFTs • Single well tracer • Seismic	• Boundaries of genetic units • Permeability zonation within units	Sweep efficiency (bypassed oil)	Secondary recovery (waterflooding)
Giga	Inter well	mile	• Well test • Surface seismic	• Sealing / nonsealing faults	Extraction efficiency (untrapped oil)	Primary recovery

Table 2.1: *Scales of Reservoir Heterogeneities*

Table 2.1 describes the varieties of the reservoir properties at different scales and their effect on flow performance. As can be seen at column measurement scale it varies at different scales of reservoir. The measurements are also varied and it is very important to consider the varieties. For example, at microscopic, the porosity measurement will give a value of one or zero (either in pore space or grain), however at macroscopic, it will give the average porosity in a rock. In addition, the permeability calculated from core is much smaller than permeability yielded from well test analysis. That shows how the scales vary the properties.

Therefore the heterogeneities have to be defined correctly in reservoir characterizing so that the properties can be used to represent the whole reservoir. However, not all data is available at all scale. For example, permeability can only be measured at core scale or reservoir scale. So the permeability in grid block is unknown.

2.5. Effect on Reservoir Performance

Heterogeneities in different scales affect reservoir performance differently. In microscopic scale, preferential flow path channels are created, and these channels are pore scale heterogeneities. Therefore, during fluid displacement, the fluid displacement preferred to flow along these channels and leave some residual hydrocarbons at the other path. This situation will decrease the displacement efficiency thus reduce the recovery. The residual or trapped hydrocarbon can only be displaced by modifying the capillary forces between hydrocarbon and displacement fluid.

At macroscopic and megascopic, the same cases happen but in a larger scale. From the injector well, not all the displaced hydrocarbon can reach producer well because of the creation of the preferential flow paths. The hydrocarbon left will remain as trapped oil or residual oil. More to the point, at gigascopic scale, there will be some reservoirs that are not contacted a bit. This is because there are lots of hydrocarbons which are isolated from the others.

3. METHODOLOGY

3.1. Introduction

As to make sure the research and project works run smoothly and keep track with the department's schedule, a plan was made during earlier stage of the project. The plan includes a project flow, a Gantt chart, and planning on several suitable research methods. This whole chapter will present the plan of the project which is one of the important elements in a study or project done.

3.2. Project Flow

The attachment below showed the flow diagram of the project flow. It describes all important works done to complete the study.

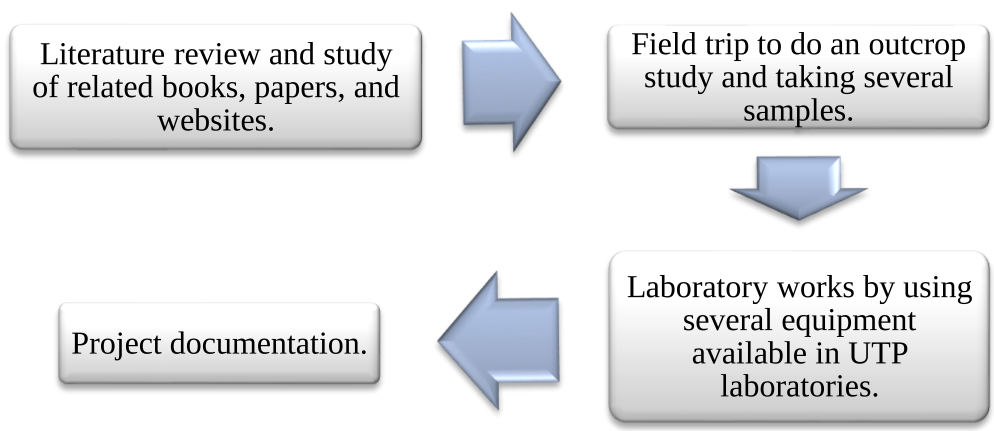


Figure 3.1: *Project flow from the beginning of literature review phase until documentation of the result.*

3.3. Gantt Chart

NO	ACTIVITY	2010					2011			
		AUG	SEPT	OCT	NOV	DEC	JAN	FEB	MAR	APR
1	Preliminary research work									
2	Project work (literature review)									
3	Field Trip									
4	Laboratory Work									
5	Documentation & Report Making									
6	Progress report submission									
7	Pre-EDX (Seminar & Poster presentation)									
8	Oral Presentation									

***Table 3.1**: Gantt Chart for the whole project*

The above Gantt chart shows the early plan for the whole project flow. It started with preliminary research work which is the first study of the project background to determine whether the project is relevant and feasible or not. Continuously, project work is done throughout the whole two semesters. During the second semester, a field trip is done to have the samples taken, so that those samples can be then tested. Finally, the project will be documented and presented.

3.4. Research Methodology

3.4.1. Outcrop Study

A field trip has been done in order to study the chosen outcrop which is Miri Hospital Road Outcrop. Two days have been spent to complete the study. The first that was done is to limit the study area to 30 meters length and 10 meters height. The measurement was done by using measuring tape. It was then followed by layers identification based on rough looking to the surface structure, color, and rock type. Once the layers have been identified, the outcrop including the identified layers was sketched. Every layer's thickness was measured by using measuring tape and was then recorded. Several photographs of each layer and the overall view of the outcrop were taken and labeled.

3.4.2. Sampling

Several samples have been taken from the outcrop which will be then tested in the laboratories. One (1) to two (2) rock samples for grain size analysis were taken at each layer and they were labeled accordingly in plastic bags. Several samples were also taken for porosity and permeability measurement. However the sampling was only done in clean sand layer. In each layer, three (3) samples were taken along the layer and for each location, three (3) samples were taken vertically. The samples were labeled according to which layer they belong and to which direction were they located in the outcrop. The sampling works were done by using hammer and chisel.

3.4.3. Sieving

Sieving works have been carried out to obtain the grain size distribution in each layer. The sieving works have been conducted by using Sieve Shaker Endecott's EFL 2000 **(See section 3.5)**. Sieves' diameters that have been used were ranged from 0.063mm to 2.0mm. Prior to start the tests, the samples' mass and empty sieves' mass were measured. The tests were conducted for ten (10) minutes for each sample. The output of the test was mass of the sample that was retained in the sieve. **Appendix 8.1** shows the example of the result sheet. The total number of samples that were completed for the tests is ten (10).

3.4.4. Porosity and Permeability Measurement

Porosity and permeability measurements were done by using Mercury Porosimeter PASCAL 240 Series **(See section 3.5.1)**. The experiment was done with aid of the laboratory technician. In each experiment, a sample will be cut to a small fragment. The mass, volume, and density of the sample was measured before starting the experiment in order to estimate mercury volume that will be injected. The sample was then put into a dilometer to start the mercury injection. The experiment took about one hour to be completed. Only two (2) samples can be tested due to lack of equipment and expertise to run the test.

3.5. Equipment

Below is the equipment that has been used in the project works.

3.5.1. Porosimeter Pascal 240

This Pascal 240 Porosimeter porosity measurement basically used rock fragmentation to calculate the certain critical parameters by usage of mercury injection. The output that can be obtained from this system includes porosity, bulk density, particle size distribution, and the analysis of pore shape. The technique used is based on the mercury properties to behave as a non-wetting liquid with a lot of solid materials. Therefore, mercury will penetrate through the open pores of a solid sample under the effect of an increasing pressure. In using this machine, four assumptions have been made:

- The mercury surface tension and contact angle with the solid material are constant during the analysis.
- The intrusion pressure must be on equilibrium.
- Pores are considered as being of cylindrical shape.
- Solids are not subject to deformation under effect of pressure.

Figure 3.2*: The Pascal 240 Porosimeter*

Figure 3.3: *The Endecott's EFL 2000 Series Sieve Shaker.*

4. RESULT

This section presents all results obtained from allworks done. The results are separated into two (2) sections; Field Study result and Laboratory Analyses result.

4.1. Field Study

4.1.1. Outcrop Description

The studied outcrop is 30 meters in length and about 10 meters of height. The base and top of the outcrop is not visible due to lots of gravel downfall from above of the outcrop. The outcrop surface is exposed to sunlight which results in erosion and oxidation of sandstone layers. Generally, the formation consists of clean sandstone, laminated sand, and laminated shale layers. Most of the rocks show trace of marine life and there is also oil stain detected at some rocks. The outcrop display apparent horizontal beds.

The variation of the layers is quite clear because sandstone layers are mostly weathered and eroded compared to shale layers. The outcrop shows huge variation of layer thickness. However, the thickness variation is not as much along a layer. There are many thin horizontal layers of shale and sandstone.

4.1.2. Identification of Facies & Sedimentological Logging

There are about twenty (20) layers have been identified from the whole outcrop. Since there are too many layers, therefore they were group into seven (7) groups of layers. All the layers were divided and labeled. The outcrop is quite steep and flat.

4.1.3. Facies Description

All layers were measured for thickness and the data were recorded and tabulated. The overall thickness of the outcrop is ranged between 9.8 to 11 meters. The outcrop is observed for layers' lateral continuity.

Figure 4.1*: Photograph shows part of the Miri Hospital Road Outcrop. The view shows about 10m of the whole length.*

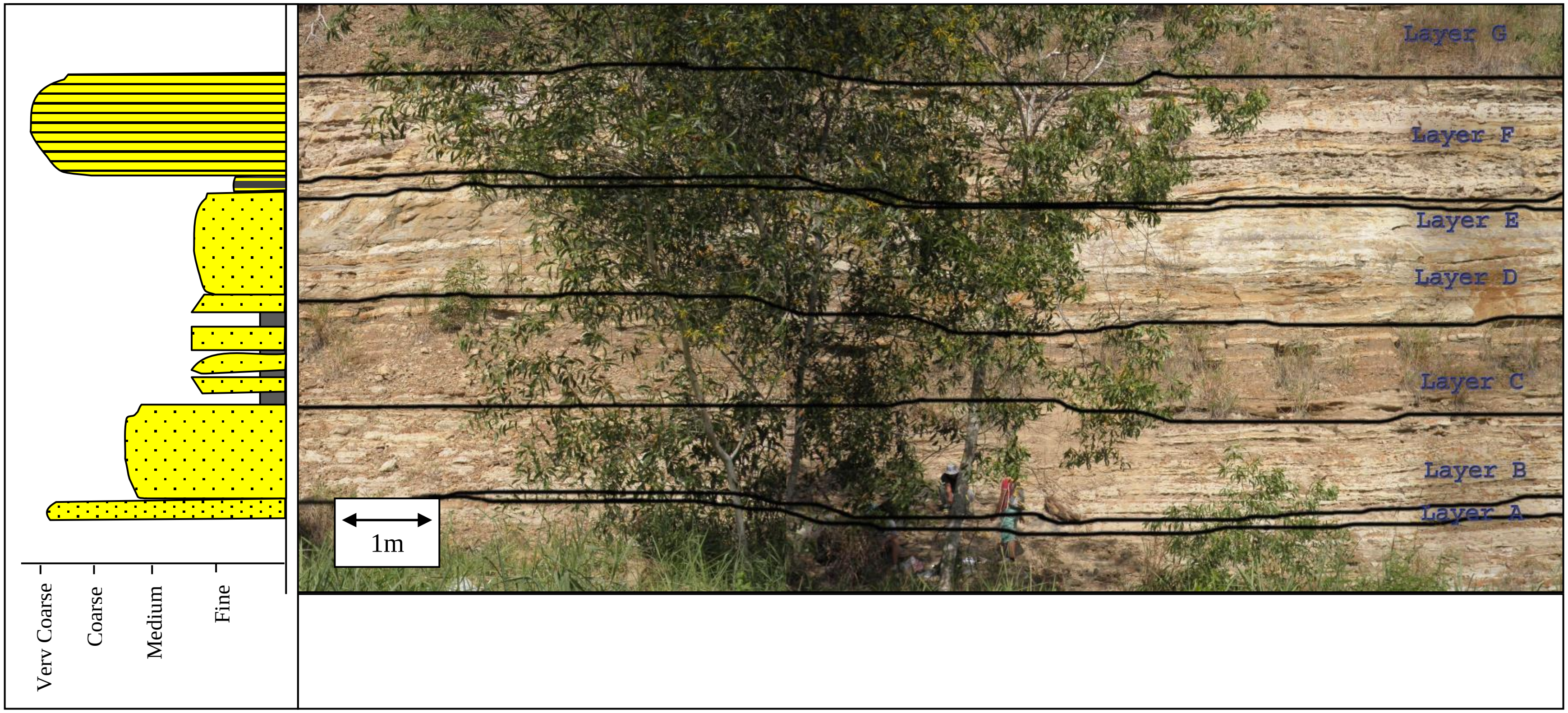


Figure 4.2: *Facies Identification and Sedimentological Logging of Hospital Road Outcrop, Miri.*

LAYER	PICTURE	SKETCHES	THICKNESS (m)	DESCRIPTION
A			0.24 – 0.32	• Consists of whitish clean sandstone. • There is trace fossils detected on the sandstone surface.
B			1.60 – 2.00	• Consists of whitish sandstone. However there are rust-colored in several spots. • There are trace fossils detected on the rock surface. • There are very thin shale layers along the facies. • There are also thin mud layers along the facies.
C			1.20 – 2.00	• Consists of yellowish sandstone. • There are thick shale layers interbedding the whole layer. • The differences between layers are clear due to high differences in color and erosion of sandstone by weathering.

D			1.60 – 2.40	• Consists of whitish sandstone, however the surface has gone through oxidation and cause the appearance of red color surface. • There are also thin shale layers along the whole layer.
E			0.16 – 0.40	• Consists of a group of very thin shale layers. • The rock structure is very strong.
F			1.84 – 2.40	• Consists of whitish sandstone. • There are several spots of rust-colored. • The layer consists of many sandstone layers stacked onto each other which are very brittle.
G			± 3.00	• Unreachable layer of sandstone layer with thin shale layers.

Table 4.1: *Facies Description in each layer. Included in the table are the layer thickness and hand sketches of each facies.*

LAYER	LATERAL CONTINUITY
A	Starts at length of 7.6 m and ended at length of 30m
B	Continuous
C	Continuous
D	Continuous
E	Almost disappear at length of 17 to 20 m
F	Continuous
G	Continuous

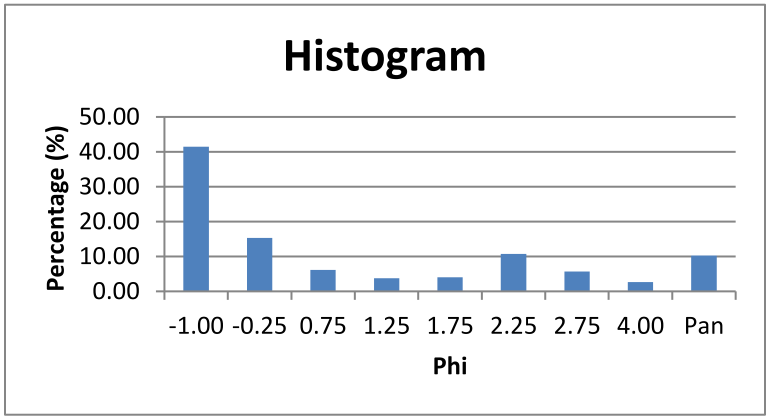
Table 4.2*: Table shows the lateral continuity in every layer.*

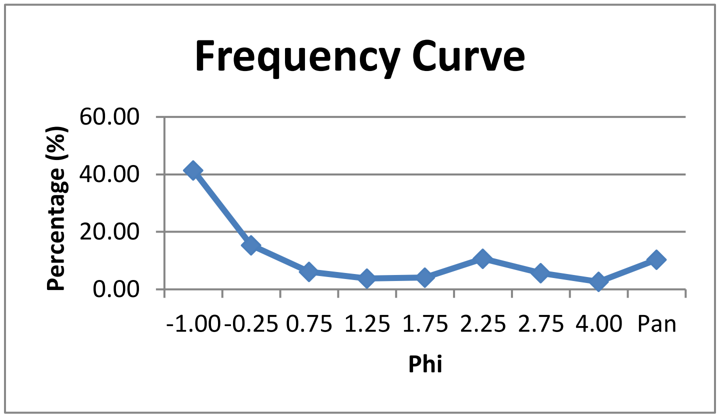
4.2. Laboratory Analyses

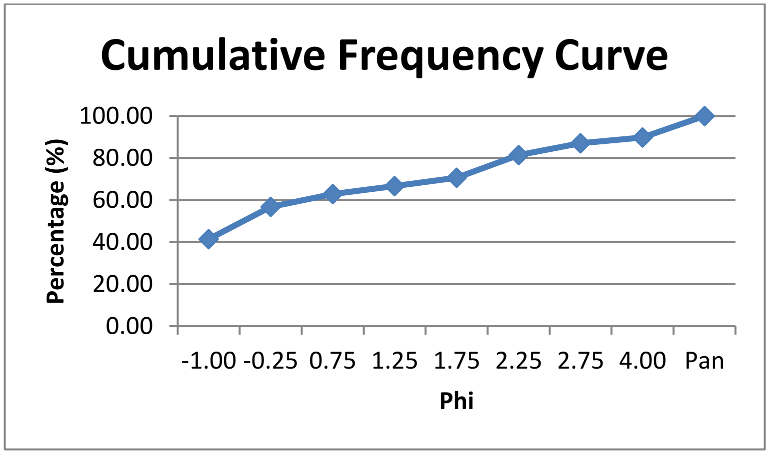
4.2.1. Grain Size Distribution

An experiment of sieving the samples has been carried out prior to analyze the grain size distribution of the formation. Mass of the retained soil in each sieves for every layers are recorded. Primary results of the experiment are attached as **Appendix 9.1**. The following diagrams show histogram, frequency curve, and cumulative frequency curve for every layer. The mode, mean, median, and standard deviation for each layer are also calculated and tabulated.

LAYER A



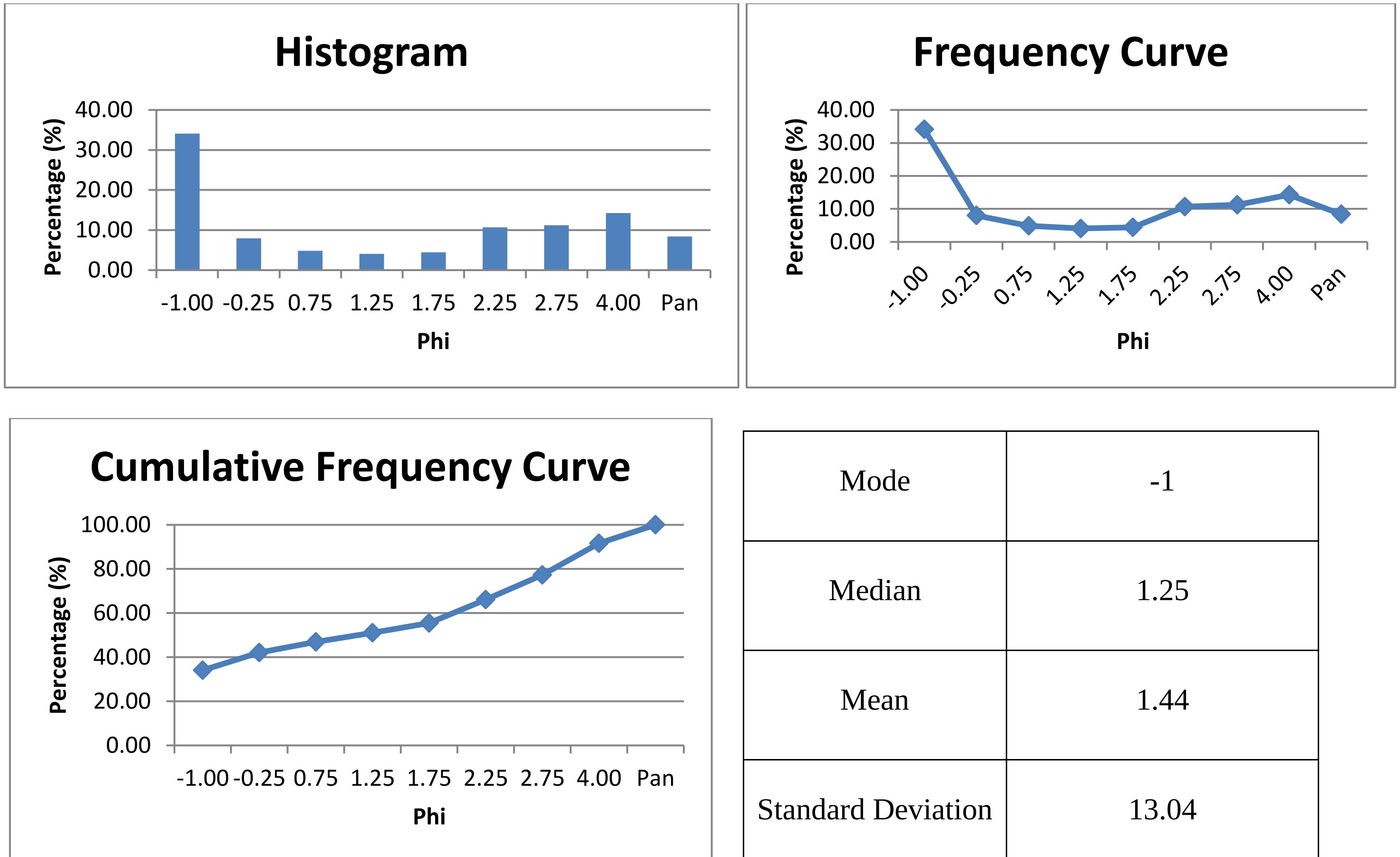




Mode	-1
Median	-0.63
Mean	1.444
Standard Deviation	14.94

Figure 4.3: *Grain Size Distribution Diagram for Layer A*

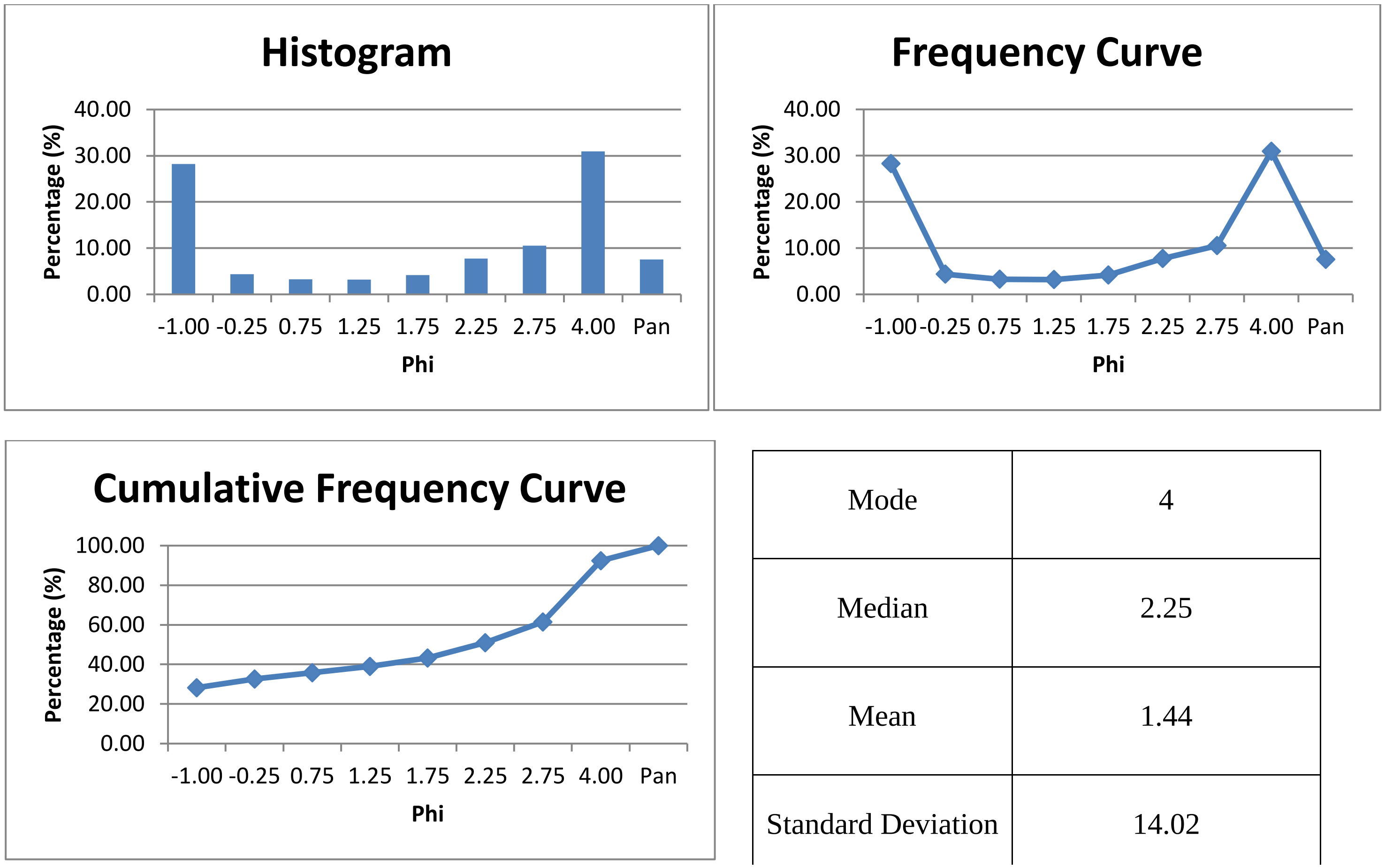
LAYER B



Mode	-1
Median	1.25
Mean	1.44
Standard Deviation	13.04

Figure 4.4: *Grain Size Distribution Diagram for Layer B*

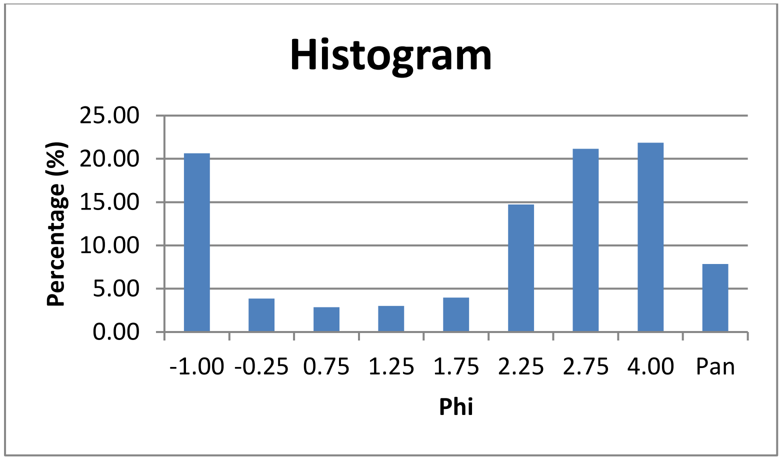
<u>LAYER C</u>

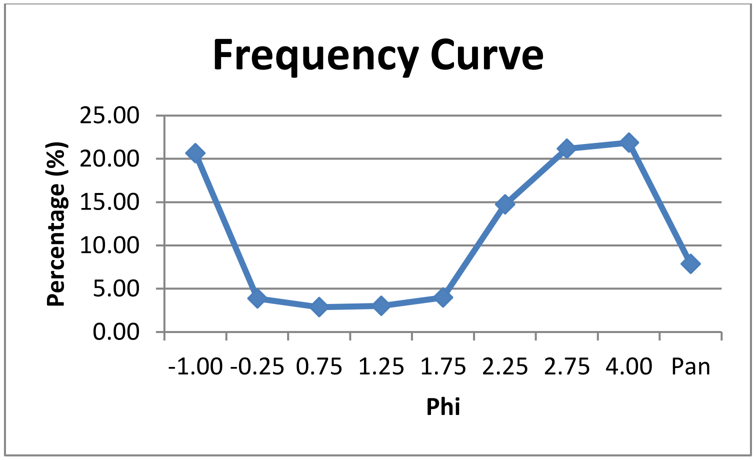


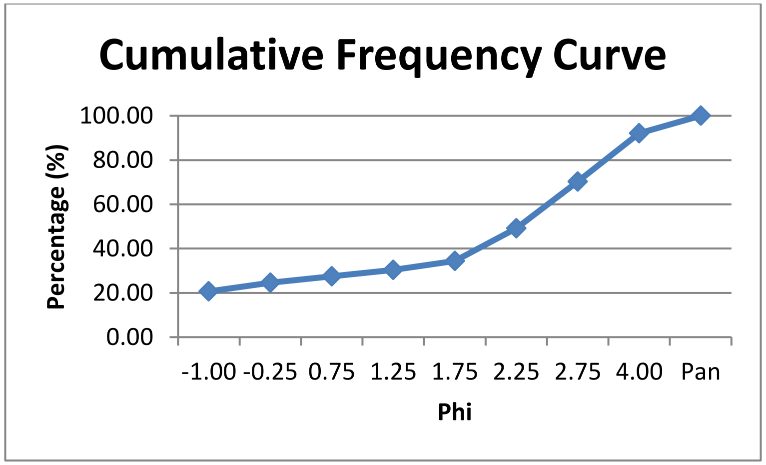
Mode	4
Median	2.25
Mean	1.44
Standard Deviation	14.02

Figure 4.5: *Grain Size Distribution Diagram for Layer C*

LAYER D



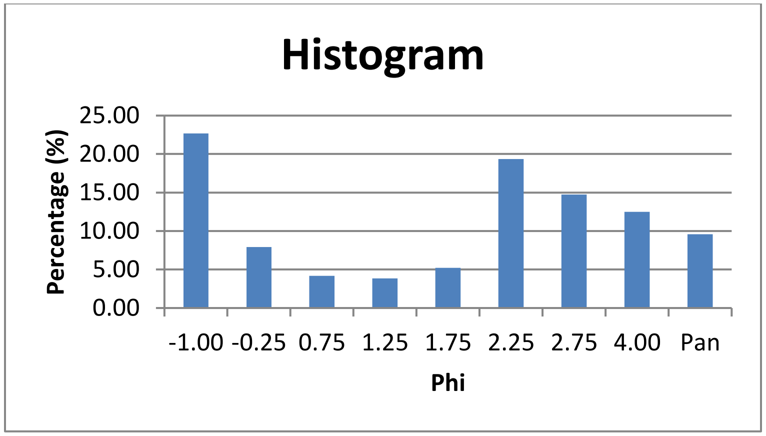


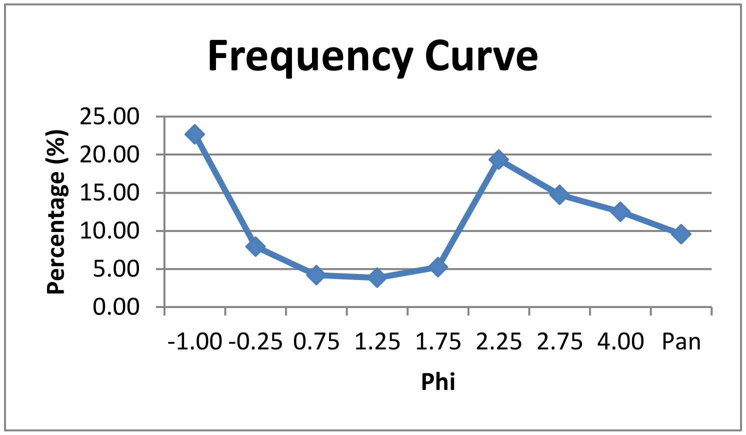


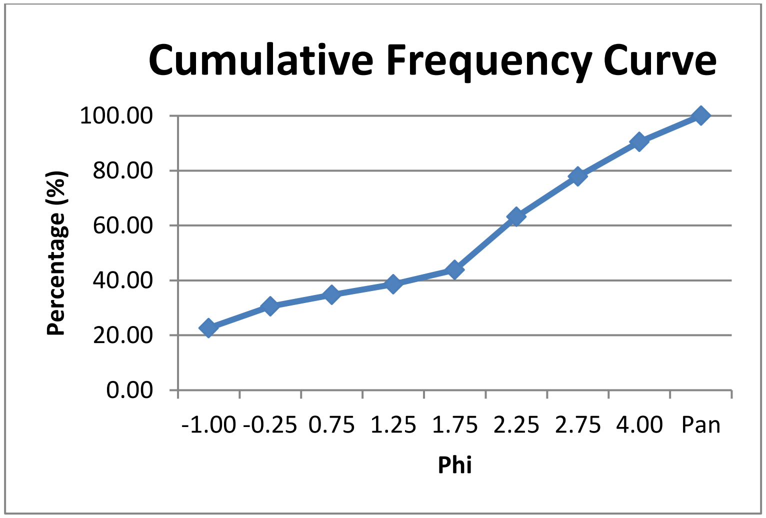
Mode	4
Median	2.25
Mean	1.44
Standard Deviation	12.52

Figure 4.6: *Grain Size Distribution Diagram for Layer D*

LAYER E



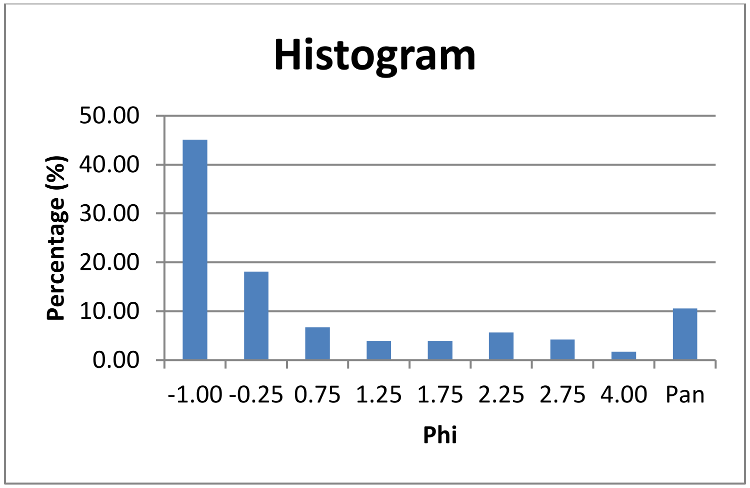


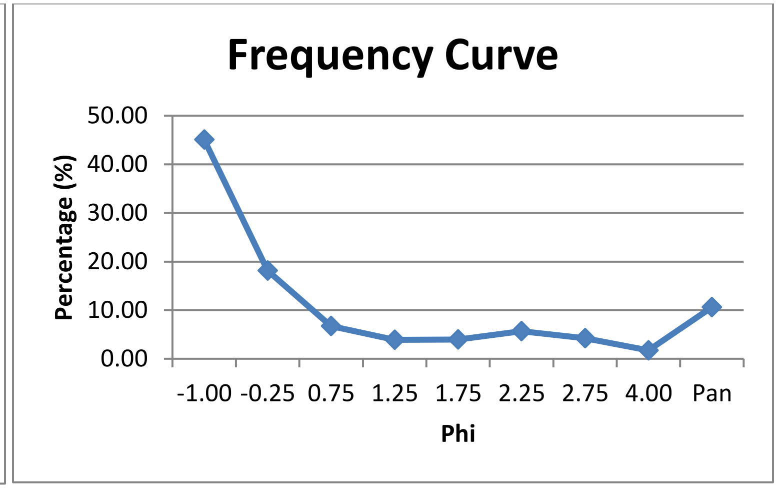


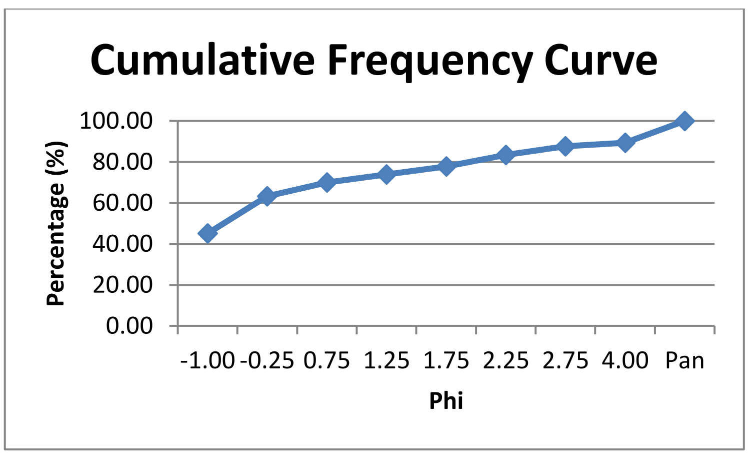
Mode	-1
Median	2
Mean	1.44
Standard Deviation	11.57

Figure 4.7: *Grain Size Distribution Diagram for Layer E*

LAYER F







Mode	-1
Median	-0.63
Mean	1.44
Standard Deviation	16.09

Figure 4.8: *Grain Size Distribution Diagram for Layer F*

4.2.2. Porosity & Permeability

Porosity and permeability measurement have been carried out for two samples and following are the result from the test:

LAYER	POROSITY (%)	PERMEABILITY (mD)
B	22.77	19.51
D	21.53	1.63

Table 4.3: *Porosity and permeability result in Layer B & D*

5. DISCUSSION

5.1. Facies Description

Facies	Description	Thickness (m)	Grain size	ϕ (%)	k (md)	Lateral continuity	Picture
A	• Consists of whitish bioturbated sandstone. • There is trace fossils detected on the sandstone surface.	0.24 – 0.32	• Mode: -1(2mm) • Median: -0.63 • Mean: 1.44 • S. Deviation: 14.94 • Sorting: Good			Not continuous. Only traceable up to 22.4m.	
B	• Consists of whitish sandstone. However there are rust-colored in several spots. • There are trace fossils detected on the rock surface. • There are very thin shale layers along the facies. • There are also thin mud layers along the facies.	1.60 – 2.00	• Mode: -1(2mm) • Median: 1.25 • Mean: 1.44 • S. Deviation: 13.04 • Sorting: Good	22.77	19.51	Continuous along 30m	
C	• Consists of yellowish sandstone. • There are thick shale layers interbedding the whole layer. • The differences between layers are clear due to erosion of sandstone by weathering.	1.20 – 2.00	• Mode: 4(0.063mm) • Median: 2.25 • Mean: 1.44 • S. Deviation: 14.02 • Sorting: Good			Continuous along 30m	

D	• Consists of whitish sandstone; however the surface has gone through oxidation and causes the appearance of red color surface. • There are also thin shale layers along the whole layer.	1.60 – 2.40	• Mode: 4(0.063mm) • Median: 2.25 • Mean: 1.44 • S. Deviation: 12.52 • Sorting: Medium to poor	21.53	1.63	Continuous along 30m	
E	• Consists of a group of very thin silty sandstone layers. • Contain mud laminations.	0.16 – 0.40	• Mode: -1(2mm) • Median: 2.00 • Mean: 1.44 • S. Deviation: 11.57 • Sorting: Medium to poor			Not continuous. The layer is not traceable at length of 17 to 20m.	
F	• Consists of whitish sandstone. • There are several spots of rust-colored. • The layer consists of many sandstone layers stacked onto each other which are very brittle.	1.84 – 2.40	• Mode: -1(2mm) • Median: -0.63 • Mean: 1.44 • S. Deviation: 16.09 • Sorting: Good			Continuous along 30m	
G	• Unreachable layer of sandstone layer with thin shale layers.	± 3.00				Continuous along 30m	

Table 5.1: *Summary of all facies' descriptions.*

ϕ = Porosity

k = Permeability

5.2. Sandstone Layers

This section presents explanation of the above table. There are seven (7) columns with different parameters and characteristics. The facies' surface structure is shown in description column. The estimated thickness of each layer is shown in third column. The values are ranged between the minimum and maximum thickness of each layer. The thickness also reflects the uniformity of the layer.

The fourth column presents the grain size distribution of each layer. Inside the column includes mode, median, mean, and standard deviation for each layer. Mode shows the grain diameter that is dominating the rock. Median shows grain diameter that separates the distribution into 50% coarser grain and 50% finer grain. The standard deviation shows the sorting of the grain size. The higher the value means the value is more further from mean value, and in the study aspect, it means the better the sorting will be.

The fifth and sixth column will be the porosity and permeability presentation which are obtained from Porosimeter tests. The porosity is the accessible porosity in the rock, while the permeability is the general permeability in the rock.

The seventh column shows the lateral continuity of the layer, whether they are continuous along the 30m study area, or just cover a portion of the whole length of the outcrop. Meanwhile the last column shows the picture of the facies.

The detail characteristics and parameters of each layer are explained in the following sections:

Millimeters (mm)		Micrometers (µm)	Phi (ϕ)	Wentworth size class		Rock type
	4096		-12.0			
				Boulder	Gravel	Conglomerate/ Breccia
	256		-8.0			
				Cobble	Gravel	Conglomerate/ Breccia
	64		-6.0			
				Pebble	Gravel	Conglomerate/ Breccia
	4		-2.0			
				Granule	Gravel	Conglomerate/ Breccia
	2.00		-1.0			
				Very coarse sand	Sand	Sandstone
	1.00		0.0			
				Coarse sand	Sand	Sandstone
1/2	0.50	500	1.0			
				Medium sand	Sand	Sandstone
1/4	0.25	250	2.0			
				Fine sand	Sand	Sandstone
1/8	0.125	125	3.0			
				Very fine sand	Sand	Sandstone
1/16	0.0625	63	4.0			
				Coarse silt	Silt	Siltstone
1/32	0.031	31	5.0			
				Medium silt	Silt	Siltstone
1/64	0.0156	15.6	6.0			
				Fine silt	Silt	Siltstone
1/128	0.0078	7.8	7.0			
				Very fine silt	Silt	Siltstone
1/256	0.0039	3.9	8.0			
				Clay	Mud	Claystone
	0.00006	0.06	14.0			

Figure 5.1: *Grain size classification.*

Source: *http://www-odp.tamu.edu*

5.2.1. Layer A

Facies A consists of whitish bioturbated sandstone with trace fossils detected on the surface. From the facies identification, Layer A only exists at length of 7.6m from the left of the whole outcrop and the thickness is almost uniform along the layer with small range (0.24 – 0.32m).

From Table 5.1 in Grain Size section, the obtained mode value is -1φ (2mm) while the median is -0.63φ (1.18mm). Mean is 1.44φ (0.4mm) and the standard deviation is 14.94. Therefore the most frequent occurring particle class is size of 2mm which is categorized as very coarse sand. Large standard deviation (14.94) shows the sorting of the grain is good. This statement can be supported by the histogram that shows only one (1) higher value (-1φ). Generally, rocks with good grain sorting will provide good porosity.

(McIlroy et. al., 2010) Bioturbated layers usually have lower porosity due to anisotropy. No porosity and permeability measurement was carried out for Layer A.

5.2.2. Layer B

Facies B consists of whitish to yellowish sandstone. It is possibly caused by rusty water flows from the above part of the outcrop. There are also trace fossils detected at several spots on the rock surface. There is also a group of very thin shale and mud layers occupied the whole layer. Layer B shows good lateral continuity along the 30m of the studied area. The thickness ranges between 1.60 to 2.00m.

From Table 5.1 in Grain Size section, the obtained mode value is -1φ (2mm) while the median is 1.25φ (1.18mm). Mean is 1.44φ (0.4mm) and the standard deviation is 13.04. Therefore the most frequent occurring particle class is size of 2mm which is categorized as very coarse sand. The histogram shows only one (1) higher value (-1φ) and that shows this layer has good grain sorting.

Generally, rocks with good grain sorting will have good porosity. This is proven by porosity measurement which gives high porosity (22.77%).

The permeability is only 19.51mD. This value is quite low for a sandstone reservoir. This can be caused by those thin shale and mud layers that act as permeability barrier.

5.2.3. Layer C

Facies C consists of yellowish sandstone. There are thick shale layers interbedding the whole layer. The differences between both types of layers are quite clear due to erosion of sandstone by weathering. From the facies identification, Layer C is continuous along the 30m of the studied area. The thickness ranges between 1.20 to 2.00m.

From Table 5.1 in Grain Size section, the obtained mode value is 4φ (0.063mm) while the median is 2.25φ (0.212mm). Mean is 1.44φ (0.4mm) and the standard deviation is 14.02. Therefore the most frequent occurring particle class is size of 0.063mm which is categorized as very fine sand. The histogram for this model is bimodal with secondary mode of -1φ (2mm). A bimodal histogram shows a very poor grain sorting.

There is no porosity and permeability measurement for Layer C. However from the observation of the layer that contains thick shale layers interbedded, it should have low permeability.

5.2.4. Layer D

Facies D consists of whitish sandstone. Thin shale layers are common throughout Layer D. Layer D is continuous along the 30m of the studied area. The thickness ranges between 1.60 to 2.40m.

The obtained mode value is 4φ (0.063mm) while the median is 1.25φ (1.18mm). Mean is 1.44φ (0.4mm) and the standard deviation is 13.04. Therefore the most frequent occurring particle class is size of 0.063mm which is categorized as very fine sand. The histogram shows a well distributed model with three (3) dominant sizes. It shows that this layer have medium to poor grain sorting.

The porosity measurement gives quite high porosity (21.53%) while the permeability is very low (1.63mD). This value is very low for a sandstone reservoir. Having high porosity but low permeability might have been caused by the presence of the thin shale layers.

5.2.5. Layer E

Facies E consists of a group of very thin silty sandstone layers. Layer E is continuous along the 30m of the studied area. The thickness ranges between 0.16 to 0.40m.

From Table 5.1, the obtained mode value is -1φ (2mm) while the median is 2φ (0.25mm). Mean is 1.44φ (0.4mm) and the standard deviation is 11.57. Therefore the most frequent occurring particle class is size of 2mm which is categorized as very coarse sand. The histogram shows a highly distributed model with four (4) sizes having higher values. It shows this layer have medium to poor grain sorting.

There is no porosity and permeability measurement for this layer. However from the grain sorting (medium to poor sorting), the structure of the layer (many thin shale layers), and the non-uniform thickness, it should have poor porosity and permeability.

5.2.6. Layer F

Facies F consists of whitish sandstone with rust-colored spots. The layer is formed by many sandstone layers that are stacked onto each other. From the facies identification, Layer F is continuous along the 30m of the studied area. The thickness ranges between 1.84 to 2.40m.

The obtained mode value is -1φ (2mm) while the median is -0.63φ (1.18mm). Mean is 1.44φ (0.4mm) and the standard deviation is high (16.09). Therefore the most frequent occurring particle class is size of 2mm which is categorized as very coarse sand. High value of standard deviation shows it has good grain sorting. Furthermore the histogram shows only one (1) higher value (-1φ) and that also shows this layer has good grain sorting. There is no porosity and permeability measurement done for this layer.

5.3. Heterogeneities in Different Scales

5.3.1. Microscopic & Macroscopic Heterogeneities (10 µm – 100 mm's)

Grain size distribution analyses have been done in range of size of 63µm to 2mm. As can be seen from the analyses, the grain size are distributed and sorted differently. High distribution and poorly sorted grain will increase the heterogeneity, which will then directly affect the porosity and permeability.

Layer A, B, and F shows well sorting grain therefore the microscopic heterogeneities in grains of those layers are low. Meanwhile Layer C, D, and E shows high distribution of grain size and also poorly sorted which contributing higher heterogeneities. It is proven for Layer D that in permeability measurement it yields low value (1.63mD).

5.3.2. Mesoscopic Heterogeneities (1 – 100 cm)

In mesoscopic scale, the heterogeneities will be the differences of facies and structure in a layer. There are shale or mud drapes and laminations, bioturbation, and crossbedding. Laminations and crossbedding can affect vertical permeability while drapes and bioturbation can decrease both porosity and permeability.

In Layer A there are bioturbations without any other barriers. Those bioturbations exist along the whole layer. However in another five (5) layers (Layer B, C, D, E, and F) there are thin shale and mud laminations.

5.3.3. Megascopic Heterogeneities (1 – 10m)

In megascopic scale, the characteristic of the formation as a whole outcrop is considered. Across the outcrop, all the seven (7) layers show different facies. From laboratory analyses, the obtained porosity and permeability show different values. The grain size distributions are also varied with facies.

Thickness variations are clear. There is one (1) to two (2) layer having the smaller thickness while the others have quite similar thickness. Other than that, net to gross value of the outcrop are differed along the outcrop. The values range from 90 to 96%.

5.4. Error and Uncertainties

Throughout the laboratory works done, there are several errors and uncertainties occur that have affected the results.

First is the equipment error. During sieving work done, different types and brands of sieves were used which was then resulted different initial mass of sieve. Therefore the percentage of mass of sample retained in the sieve for every layer was not consistent. Besides before using the sieve, the sieve might not be cleaned enough and there are still portions of remainder from previous experiment. Furthermore, not all samples are sieved with same initial mass. This type of error was tried to be reduced by repeating the experiment.

Secondly, during porosity measurement there might be errors occurred. Prior to start the measurement, initial values of volume and density are needed to be keyed in the system. Those values are manually calculated and since the shape of the samples is not geometric, the values might not accurate. Therefore, volume of mercury injected based on the initial values might not filled whole pores.

Thirdly, due to time constraint and limited equipment, not all samples can be used for porosity measurement. Hence, porosity varieties for the formation cannot be observed for every layer.

5.5. Recommendation

There are several points that can be recommended to improve the experiments:

- Use wider range of sieve diameter for grain size distribution experiment to increase the accuracy of the distribution.
- Since there are two methods can be used to measure porosity in UTP which is either use rock fragment or core plugs, both methods should be used. Therefore comparison can be made in scale aspect and the accuracy of upscaling can be evaluated.
- Additional laboratory works of thin section analysis and SEM photographs can be done to evaluate microscopic heterogeneities of a rock.

6. CONCLUSION

- From the studies, there are seven (7) facies that have been identified. From the seven layers, five (5) of them are sandstone layers. All the sandstone layers consist of different type of sandstone (whitish sandstone, yellowish sandstone) with different permeability barrier content (shale and mud laminations, mud drapes, bioturbations). Every layer has different types of grain sorting and size that dominated the rock.

- The best reservoir layer is Layer F (whitish sandstone layer). The reason of the selection is because it has the largest thickness (1.84 – 2.40) and the grain is well sorted. In this layer there is not much shale content compared to other layers.

- The second best reservoir is Layer D. The reason of the selection is because it has relatively high thickness (1.60 – 2.40m) compared to other layer. Even though there are several shale and mud laminations in the layer, the grain has medium to poor sorting. It is better compared to Layer C that has a very poor grain sorting. The porosity is proven to be high (21.53%).

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8. APPENDIX

8.1. Sample of Result Sheet

Sample	Sieve No.	Diameter	Mass of empty Sieve (g)	Mass of Sieve + Soil Retained	Mass of Soil Retained (g)	Percentage of Mass Retained	Percentage of Mass Passing

8.2. Raw data of sample sieving

Sample	Sieve Diameter (micron)	First Experiment					Second Experiment					Average	
		Mass of empty sieve (g)	Mass of Sieve + Soil Retained (g)	Soil Retained (g)	Percent Retained	Percent Passing	Mass of empty sieve (g)	Mass of Sieve + Soil Retained (g)	Soil Retained (g)	Percent Retained	Percent Passing	Percent Retained	Percent Passing
A	63	261.94	373.93	111.99	39.78	60.22	261.91	358.30	96.39	43.06	56.94	41.42	58.58
	150	276.52	318.49	41.97	14.91	85.09	276.66	311.90	35.24	15.74	84.26	15.33	84.67
	212	275.88	292.15	16.27	5.78	94.22	275.87	290.34	14.47	6.46	93.54	6.12	93.88
	300	355.39	367.17	11.78	4.18	95.82	355.30	362.69	7.39	3.30	96.70	3.74	96.26
	425	386.20	399.67	13.47	4.78	95.22	386.21	393.71	7.50	3.35	96.65	4.07	95.93
	600	339.51	368.82	29.31	10.41	89.59	339.47	364.18	24.71	11.04	88.96	10.72	89.28
	1180	354.02	369.48	15.46	5.49	94.51	353.84	366.87	13.03	5.82	94.18	5.66	94.34
	2000	380.00	391.75	11.75	4.17	95.83	379.91	382.37	2.46	1.10	98.90	2.64	97.36

	Pan	388.76	418.28	29.52	10.49	89.51	388.72	411.38	22.66	10.12	89.88	10.30	89.70
B	63	261.94	411.77	149.83	34.09	65.91	261.94	411.77	149.83	34.09	65.91	34.09	65.91
	150	276.48	311.53	35.05	7.97	92.03	276.48	311.53	35.05	7.97	92.03	7.97	92.03
	212	275.89	297.19	21.30	4.85	95.15	275.89	297.19	21.30	4.85	95.15	4.85	95.15
	300	355.35	373.32	17.97	4.09	95.91	355.35	373.32	17.97	4.09	95.91	4.09	95.91
	425	386.22	405.64	19.42	4.42	95.58	386.22	405.64	19.42	4.42	95.58	4.42	95.58
	600	339.59	386.40	46.81	10.65	89.35	339.59	386.40	46.81	10.65	89.35	10.65	89.35
	1180	353.82	403.14	49.32	11.22	88.78	353.82	403.14	49.32	11.22	88.78	11.22	88.78
	2000	379.95	442.77	62.82	14.29	85.71	379.95	442.77	62.82	14.29	85.71	14.29	85.71
	Pan	388.76	425.80	37.04	8.43	91.57	388.76	425.80	37.04	8.43	91.57	8.43	91.57
C	63	261.68	386.31	124.63	26.98	73.02	261.91	380.95	119.04	29.48	70.52	28.23	71.77
	150	276.47	297.55	21.08	4.56	95.44	276.48	293.18	16.70	4.14	95.86	4.35	95.65
	212	275.89	291.43	15.54	3.36	96.64	275.87	288.82	12.95	3.21	96.79	3.29	96.71
	300	280.00	295.01	15.01	3.25	96.75	355.36	367.97	12.61	3.12	96.88	3.19	96.81
	425	386.27	405.18	18.91	4.09	95.91	386.23	403.48	17.25	4.27	95.73	4.18	95.82
	600	330.15	368.19	38.04	8.24	91.76	339.57	368.60	29.03	7.19	92.81	7.71	92.29
	1180	379.43	431.52	52.09	11.28	88.72	378.99	418.73	39.74	9.84	90.16	10.56	89.44
	2000	414.31	566.80	152.49	33.01	66.99	414.26	530.60	116.34	28.82	71.18	30.91	69.09
	Pan	388.92	413.04	24.12	5.22	94.78	388.77	428.85	40.08	9.93	90.07	7.57	92.43
D	63	261.96	319.93	57.97	20.05	79.95	261.86	303.89	42.03	21.28	78.72	20.66	79.34
	150	276.41	292.06	15.65	5.41	94.59	276.46	281.08	4.62	2.34	97.66	3.88	96.12
	212	275.83	286.00	10.17	3.52	96.48	275.85	280.23	4.38	2.22	97.78	2.87	97.13
	300	355.31	365.65	10.34	3.58	96.42	355.28	360.09	4.81	2.44	97.56	3.01	96.99
	425	386.20	399.79	13.59	4.70	95.30	386.17	392.62	6.45	3.27	96.73	3.98	96.02
	600	339.65	379.37	39.72	13.74	86.26	339.48	370.50	31.02	15.70	84.30	14.72	85.28
	1180	353.87	403.82	49.95	17.28	82.72	350.26	399.74	49.48	25.05	74.95	21.16	78.84
	2000	379.99	435.93	55.94	19.35	80.65	379.98	428.15	48.17	24.39	75.61	21.87	78.13
	Pan	388.75	424.54	35.79	12.38	87.62	388.71	395.27	6.56	3.32	96.68	7.85	92.15
E	63	261.92	329.61	67.69	28.03	71.97	261.70	292.07	30.37	17.30	82.70	22.66	77.34
	150	276.53	298.99	22.46	9.30	90.70	276.47	287.98	11.51	6.56	93.44	7.93	92.07
	212	275.89	287.32	11.43	4.73	95.27	275.90	282.31	6.41	3.65	96.35	4.19	95.81
	300	355.30	365.27	9.97	4.13	95.87	280.01	286.22	6.21	3.54	96.46	3.83	96.17
	425	386.18	399.20	13.02	5.39	94.61	386.29	395.22	8.93	5.09	94.91	5.24	94.76
	600	339.51	378.82	39.31	16.28	83.72	330.16	369.47	39.31	22.40	77.60	19.34	80.66
	1180	353.92	383.88	29.96	12.40	87.60	353.92	383.88	29.96	17.07	82.93	14.74	85.26

	2000	380.00	405.40	25.40	10.52	89.48	380.00	405.40	25.40	14.47	85.53	12.49	87.51
	Pan	388.76	411.04	22.28	9.22	90.78	388.95	406.37	17.42	9.92	90.08	9.57	90.43
F	63	261.64	334.80	73.16	45.07	54.93	261.64	334.8	73.16	45.07	53.74	45.07	54.93
	150	276.44	305.83	29.39	18.11	81.89	276.44	305.83	29.39	18.11	81.42	18.11	81.89
	212	275.85	286.77	10.92	6.73	93.27	275.85	286.77	10.92	6.73	93.10	6.73	93.27
	300	279.99	286.35	6.36	3.92	96.08	279.99	286.35	6.36	3.92	95.98	3.92	96.08
	425	386.25	392.70	6.45	3.97	96.03	386.25	392.7	6.45	3.97	95.92	3.97	96.03
	600	330.12	339.33	9.21	5.67	94.33	330.12	339.33	9.21	5.67	94.33	5.67	94.33
	1180	353.85	360.67	6.82	4.20	95.80	353.85	360.67	6.82	4.20	95.80	4.20	95.80
	2000	379.93	382.75	2.82	1.74	98.26	379.93	382.75	2.82	1.74	98.26	1.74	98.26
	Pan	388.93	406.12	17.19	10.59	89.41	388.93	406.12	17.19	10.59	89.13	10.59	89.41