Scales and Characteristics of Heterogeneity in Sandstone Reservoirs Miri Field, Miri, Sarawak (Miri-Pujut Road Outcrop)

By

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10254

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

JAN 2011

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CERTIFICATION OF APPROVAL

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A project dissertation submitted due to the

Petroleum Engineering Programme

Universiti Teknologi PETRONAS

In partial fulfillment of the requirement for the

BACHELOR OF (HONS) PETROLEUM ENGINEERING

Approved by,

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JAN 2011

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 accept as the specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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(MOHD KHAIRULLAH BIN MOHD HADZIR)

ABSTRACT

This document discusses on the study of sandstone reservoir heterogeneity characteristics of Miri field within different scale levels. The objective of this study is to identify the characteristics of the reservoir units in terms of sedimentology properties and petrophysical properties. The purpose of this study is also to identify the degree of heterogeneity in different scale (megascopic scale (10's m), macroscopic scale (10 -100's mm) and microscopic level (10-100's μm)). The outcrop is located at Miri- Pujut Road and belongs to Baram delta basin. It is comprises of 20 layers but in this study, only 10 of the layers, including sand and shale layers are considered. The layers are having four different facies; bioturbated, cross bedded, laminated sandstone and interbedded sandstone and the best sand layer, with highest quality of porosity and permeability is layer VII.

ACKNOWLEDGEMENT

Firstly, I would like to express my gratitude and appreciation to my zealous supervisor, AP. Dr. Abdul Hadi Abdul Rahman for his full commitment in assisting me and giving a valuable advises. His willingness to teach and guide me along the period of this project greatly inspired me to successfully complete the project even though he is in tight and fixed schedule.

These special thanks also dedicated to a placed name Universiti Teknologi Petronas (UTP) for giving me an opportunity to handle a self dependence project which really examines my capabilities. Additionally, UTP also provides good facilities and fully equipped laboratory which make my project easier to be accomplished and achieved and not to forget Mr. Fakhrudin and Mr. Najib for facilitating me throughout this project.

Besides, I would like to take this opportunity to portray my thankfulness all my supportive and helpful classmates that support me since the beginning of the project and thanks God that I have been given such a nice and wonderful classmates.

Furthermore, I would like to dedicate my gratitude to my dearly loved mother and father who always loved me with full of their heart and continuously give priceless supports that cannot be compared by anyone else and you are my number one. Lastly, to all my family members and to who contribute directly and indirectly thank you very much.

LIST OF FIGURES

LIST OF TABLES

TABLE OF CONTENTS

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND STUDIES

Miri field was the first oil field in Malaysia and was discovered by SHELL on 1910. The initial production was 83 barrels per day and reached its peak production at 15 000 barrels per day on 1929[4]. After producing more than 80 million barrels of oil, it was abandoned on 1972 and the first oil well called Grand Old Lady becomes a famous tourist spot in Miri[4]. However, up until today, after about 39 years of abandonment, the hydrocarbon presence still noticeable around Miri area and most of the activities are located in offshore which motivate the study of reservoir heterogeneity characteristics of Miri field.

Heterogeneity is relations between petrophysical and sedimentological studies which include the variation of the rock matrix in terms of shape, orientation and packing[15]. The heterogeneity affects the production of a reservoir due to the inconsistency of the porosity and permeability which controls the volume and flow of the hydrocarbon. This phenomenon occurs and initiates from the deposition of the sediments itself. It starts with the deposition of the sediments at particular deposition environment which then undergone diagenesis process. Diagenesis is the chemical, physical or biological alteration and modification that change the texture or the mineralogy of the rock after the lithification process[3]. Then, due to the weathering or plate tectonic movement, fault, joints or fracture are formed. This physical alteration is called compartmentalization where the rocks are divided into parts. In the concept of heterogeneity, the main focus area will be the internal architecture and characteristic within the rock that leads to variation of porosity and permeability and several factors and elements need to be studied thoroughly to identify the characteristics of the reservoir heterogeneity.

- **Reservoir lithology**

The first step to identify the reservoir characteristics is to know the reservoir itself. The reservoir can be determined to be clastic or non-clastic reservoir rock. Clastic is a sand reservoir while non - clastic is a carbonate reservoir.

- **Deposition environment and geometry of reservoir unit**

From the grain size analysis, the trend and distribution of the sand can be seen. Every deposition environment has different and unique sand distribution trend. By knowing the deposition environment, some of the properties can be predicted according to the previous study and experiments on such deposition environment. Generally, all the properties and behavior should be the same according to the same deposition environment[23].

- **Diagenetic modification of reservoir**

Diagenesis is the process where the sediments turn into sedimentary rocks by alteration and modification of its mineralogy and/or texture physically, chemically or biologically[3]. Diagenesis occurred due to composition, pressure (due to burial), temperature, the composition and nature of the pore fluids, grain size, porosity, permeability and the amount of fluid flow. These elements will change the rock properties by compaction, recrystallization, solution, cementation, authigenesis, replacement and bioturbation[22].

- **Impact of compartmentalization on rock heterogeneity**

Compartmentalization means division of the rock particles to sections. This phenomenon is possible to occur with the existence of fault and joints. Additional to that, fractures also affect the physical properties of the rocks either naturally or artificially.

Reservoir characterization is a complex process of identifying and quantifying reservoir properties by establishing interdisciplinary relationships from pore to basin scale (Schatzinger & Jordan, 1999) which comes to heterogeneity. Due to that, heterogeneity will also vary with scales. However this document will only discuss heterogeneity characteristics in terms of porosity and permeability relations with the sedimentology settings.

1.2 PROBLEM STATEMENT

In practice, a producing well will produce only some amount from the whole calculated hydrocarbon volume. There are a lot of factors due to uncertainties which leads to this situation. One of the major factors is reservoir heterogeneity. All reservoirs show some degree of heterogeneities - orientation of the sand particles, grain size and sorting which can cause variation of porosity and permeability in the pay zone. At the early production, the oil produce are driven by the natural drive for example, water drive and gas cap. The pressure declines with the production so pressure maintenances are used to keep the production rate. By time, at a point where the pressure cannot be maintained anymore, tertiary recovery or enhanced oil recovery (EOR) might be the solution to recover the immobile oil in the pay zone. In this case, detailed studies of reservoir heterogeneity characteristics in smaller scale must be carried out to determine the best EOR method for the highest percent of recovery.

1.3 OBJECTIVES

- To identify the heterogeneities in different scales
- To identify the factors leading to reservoir heterogeneity
- To analyze the effects of heterogeneity on porosity and permeability

1.4 SCOPE OF STUDY

- Sedimentological logging – thickness, lithology and geometry of sandstone layers
- Grain sizes characterization by units
- Porosity and permeabilities of reservoir units
- Different scales of heterogeneity – megascopic (10's m), macroscopic (10 – 100's mm), microscopic (10 – 100's μm)

1.5 SIGNIFICANCE OF THE PROJECT

1.5.1 Identification of heterogeneity in different scale

This study will evaluate clastic reservoir heterogeneity in Miri Field at several different scales: megascopic (10's m), macroscopic (10 – 100's mm) and grain size level (63μm – 2 mm). At megascopic level, the outcrop will be studied for its lithology, thickness and layers exposed on the surface. At macroscopic level sandstone layers are analyzed for its facies and at grain size level (63μm – 2 mm) more detailed properties analyzed – grain size, sorting and skewness.

1.5.2 Identification of heterogeneity effects on porosity and permeability

Inconsistency of porosity and permeability affects the production of the hydrocarbon. The flow of hydrocarbon is affected by the variations of the sediments settings at grain level (63μm – 2 mm) which are the grain size, sorting and skewness. The sediments settings are physically affecting the porosity and permeability value which make them inconsistent. So the micro-scale heterogeneity characteristics are an important factor to be considered as its major effects on porosity and permeability.

1.6 FEASIBILITY OF THE PROJECT WITHIN SCOPE AND TIME FRAME

Due to time constraint, this project needs to be done as soon as possible. It requires a lot effort and understanding on both geological and reservoir knowledge. However it is not impossible to complete this project within the given period. There are three essentials elements to make this project possible:-

i. **Information from previous study**

Information on the reservoir is available from the past studies. The data and the outcomes of the studies and researches can be referred as a guide for more understanding on the subject. With the data, further studies and researches can be carried out and we can compare the changes occur in the reservoir for deeper understanding of the reservoir.

ii. **Application of theories and concepts**

Theories and concepts related to reservoir heterogeneity characterization must be known. It is crucial to have this knowledge for interpretation and analysis works.

iii. **Sample and data availability**

For experiments and laboratory works, rock sample is needed. A field trip was arranged to Miri Field to obtain the rock samples. From the field, the samples then were brought to laboratory to identify the characteristics. In this project, small pieces of the rock samples are tested for porosity and permeability which are closely related to reservoir heterogeneity. Part of the samples will be used for sieving for grain size analysis.

For further explanations regarding the time frame, please refer to Appendix for the Project Milestone.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

Hydrocarbons are contained in the pores of the reservoir rocks. It is a complex organic compound undergone various processes under high temperature and pressure. The main objective of a field is to extract as much hydrocarbon available from the reservoir. However, due to the complexity of reservoir heterogeneity, fewer hydrocarbons are produced and the rest of it stays underground. In the study of reservoir heterogeneity, sedimentological and petrophysical properties are the crucial elements. Understanding the relations of those properties will lead to understanding the character of the reservoir itself; allowing the planning for enhanced oil recovery to be made.

2.2 PETROLEUM SYSTEM

In petroleum system, there are several elements and processes involved. The origin of Petroleum is from the organic compound, either animal or plant based. These organic compounds were buried and deposited by transportation agent like river and wind to a particular deposition area. Due to deep burial with high temperature and pressure around it, the organic compound becomes solid source rock. By time, the continuous pressure and temperature cause the organic compound to be matured and initiate the generation of hydrocarbon. From the source rock, the hydrocarbon generated moves upward through the migration route and settle in the reservoir rock[3]. Reservoir rock holds the hydrocarbon in its pores which is called hydrocarbon accumulation. The hydrocarbon will continue to moves upward until it is trapped by either structural (anticline, fault, salt) or stratigraphy trap (unconformity, lens, pinch-out) or the combination of these traps[3]. In additional to that, the hydrocarbon trapped is retained by impermeable layer called seal rock. Seal rock traps the hydrocarbon and retains it from passing through it. However, if faulting occurs, the hydrocarbon may leak and trapped by the fault[3]. There are a many drive mechanism that controls the movement of the hydrocarbon. In the reservoir, the gas will be on top, followed by oil and aquifer due to its density difference. The petroleum system is illustrated in Figure 1.

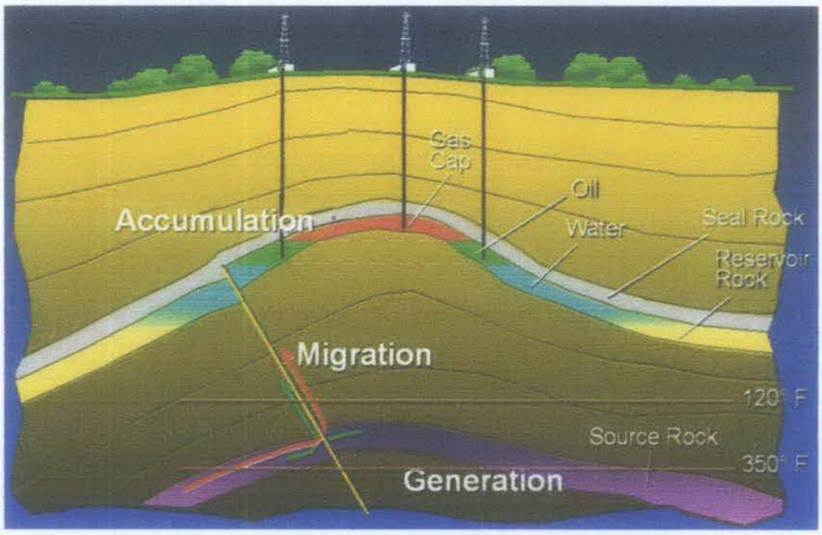


Figure 1 : Petroleum system[28]

2.3 RESERVOIR ROCK

Reservoir rock is the porous rock that has the ability to contain fluid in it. There are two most common reservoir rock type; clastic (sandstone) reservoir and non-clastic (carbonate) reservoir. However, besides these types of reservoir, sometimes when fracturing occurs, other type of rock could be the reservoir rock. Reservoir rock plays important role in accumulating the hydrocarbon. Here, porosity and permeability indicates whether it is a good reservoir or not. The porosity and permeability took crucial part in determining the performance of the hydrocarbon production. They are also the uncertainties, resulted by the sedimentology setting in the rock itself, causing heterogeneity. Miri field is a clastic reservoir, which this document will only be focusing on this type of reservoir.

- **Sandstone Reservoir**

Sandstone reservoir is a common type of reservoir. It consisted of clastic sedimentary rock with the size ranging from 2.0 mm to 0.0063 mm. It is formed due to deposition of rock particles by transporting agent such as wind and water to the depositional site. The parent rocks could be either igneous or metamorphic or sedimentary rock itself. The burial of the sediments then undergone mechanical and weathering process and after the deposition, physical alteration and chemical process changes the properties of the reservoir rock[9]. The heterogeneity already exists since the deposition as there are a lot of different minerals contained in the rock. Common minerals that can be found in sandstone such as quartz and feldspar both have different properties that lead to heterogeneity in microscopic level. Besides, the weathering process before deposition and the location of the deposition site cause different sizes of rock fragments to be deposited together. The classification of sandstone is made by the percentage of quartz, feldspar, rock fragments and matrix in the rock[3]. It is also commonly named after its lithology, origin or geological age of the rock[3].

2.4 FACIES CHARACTERIZATION

Facies characterization describes the sedimentology settings of the rock. It is very unique for each rock and also the source of uncertainties. The facies includes the geometry, sedimentary structure, organic content, as well the lithology and texture.

2.4.1 Geometry

The shape geometry of different deposition environment differs to each other. The shape geometry also differs in within different scales. The shape geometry of the rock shows the pre-depositional topography, geomorphology of the deposition environment and its post-depositional history. The geometry of the rock also reflects different environment, for example deltaic, fluvial and etc. The determination of the geometry at particular deposition environment is quite easy is it is visible at the surface[3]. Some common rock or bed shape geometries are tabular, wedged-shape sheet, fan and belt[3].

Figure 2 : Example of shape geometry; Alluvial fan[26]

2.4.2 Sedimentary structure

The structure of the sediments in the rock is crucial in heterogeneity. It can be caused by either physical process or chemical reaction process. The Primary structure occurs during the deposition physically while secondary structure occurred due to chemical reaction after being deposited[6][29]. The physical alteration of the rock and the chemical process within the rock change the rock properties and make it heterogeneous. By studying the sedimentary structure, the depositional environment of the rock can be explained besides the palaeocurrent pattern and palaeography determination.

2.4.3 Organic content (Fossil)

Fossil is related to the remaining of animal or plant in the sediment[29]. For example, shell, fish scales, and leaves. The existence of the fossil will affect the porosity and permeability of the reservoir. The existence of the fossil also proves the deposition environment of the rock. Besides animals and plant fossil, the track, trails, burrows and borings which is called trace fossil that is visible on the rock also gives information on its deposition environment[6]. The fossil also is an important element for hydrocarbon generation.

Figure 3 : Rock Fossil

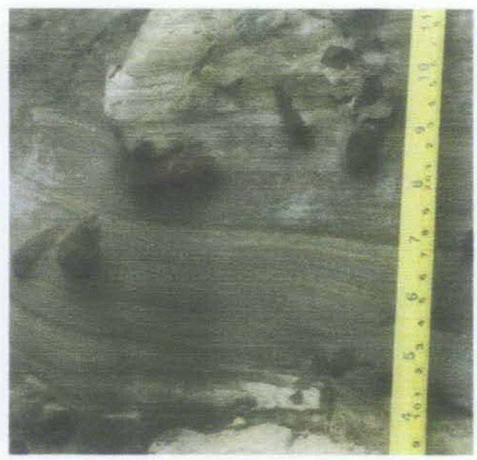


Figure 4 : Trace Fossil

2.4.4 Lithology and Texture

Both lithology and texture of the rock reflects the deposition environment and pre-existing parent rocks. Lithology and texture affect heterogeneity by grain size, sorting and shape, orientation and packing. These properties relate to each other and define the reservoir heterogeneity with their unique characteristics. These properties also determine the origin of the sediments and its deposition environment[3][6].

2.4.4.1 Grain Size

Most widely used grain size scale was established by Wentworth (1922) to classify the sedimentary rocks. The grain size classification is based on the grain diameter and sorting of the grain sizes usually done in sieving analysis. The grain size distribution determines the percentage of the finer and coarse grains. With that information, assumption can be made where finer sediments are transported by slower flowing current while coarser sediments to be transported by faster flowing currents. Figure 5 shows the scales and categories of the sediments by Wentworth.

Median diameter in mm	Phi Scale	Sediment name
		Boulder gravel
256	-8	Course cobble gravel
128	-7	Fine cobble gravel
64	-6	Very course pebble gravel
32	-5	Course pebble gravel
16	-4	Medium pebble gravel
8	-3	Fine pebble gravel
4	-2	Very fine pebble gravel
2	-1	Very course sand
1	0	Coarse sand
0.5	1	Medium sand
0.25	2	Fine sand
0.125	3	Very fine sand
0.06	4	Coarse silt
0.03	5	Medium silt
0.015	6	Fine silt
0.008	7	Very fine silt
0.004	8	Clay

Figure 5 : Grain Size Table[5]

2.4.4.2 Sorting

As to relation with the grain size distribution, sorting is the arrangement of the sediments in the rock. A well sorted rock will have same sizes particles and shapes but if it is poorly sorted, the particles will be different in sizes and shapes[3][15]. The sorting of the particles will cause variation in porosity and permeability.

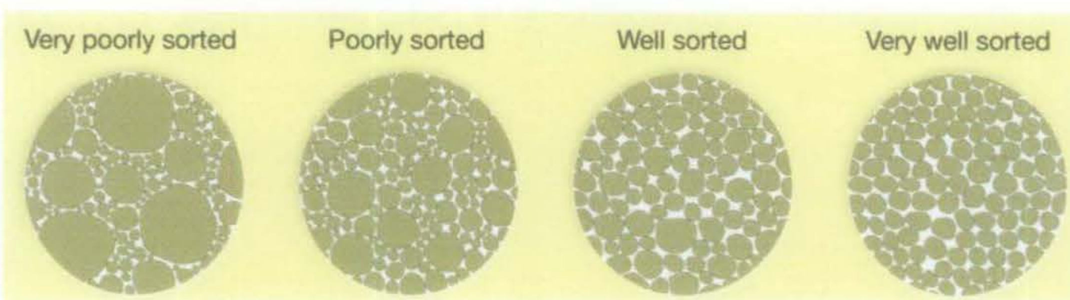


Figure 6 : Sediment sorting[27]

2.4.4.3 Grain morphology

Grain morphology is the description of the grains in terms of shape, sphericity and roundness. The grain morphology is closely related with sorting and packing of the rock. Sphericity is a measure of how spherical an object is. It is defined by Wadell in 1935, that sphericity of a particle is the ratio surface area of a sphere to the surface area of the particle with the same volume. Figure 7 shows the sphericity of a grain as angular and rounded. The shape, roundness and sphericity of the grains are controlled by several factors such as mineralogy and the abrasion during transportation of the sediments.

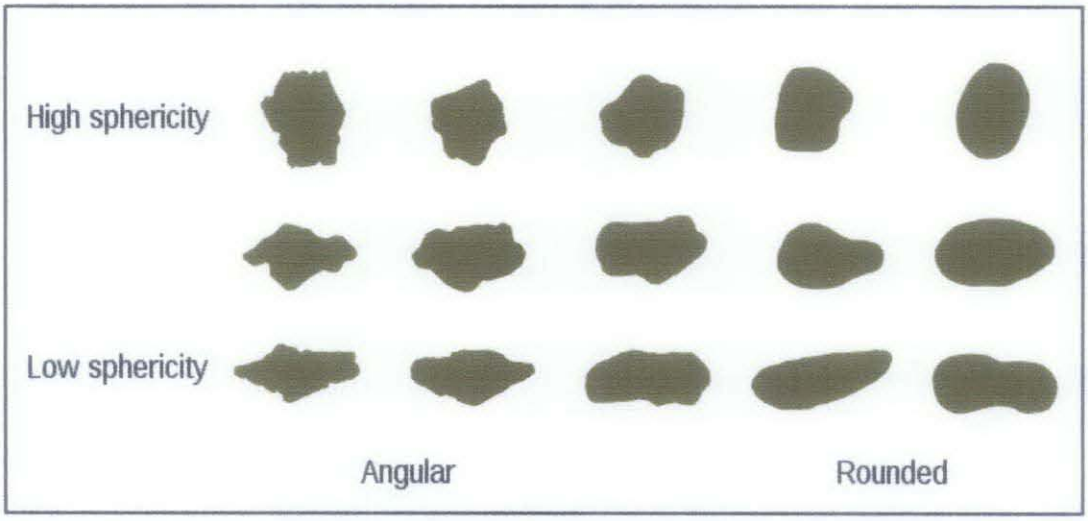


Figure 7 : Grain Sphericity[27]

2.4.4.4 Packing

The packing and orientation of the grains also affect the porosity and permeability of the rock. It depends on the shape, size and sorting of the grains itself. The packing of the sediments is the configuration of the sediments in the rock body. Poorly sorted sediments with various sizes of grains will have tighter packing which reduces the porosity compared to well sorted sediments[3][6][8]. There are several types of packing and each of them gives different value of porosity. For example, cubic packing, rhombohedral packing and grain-supported fabric.

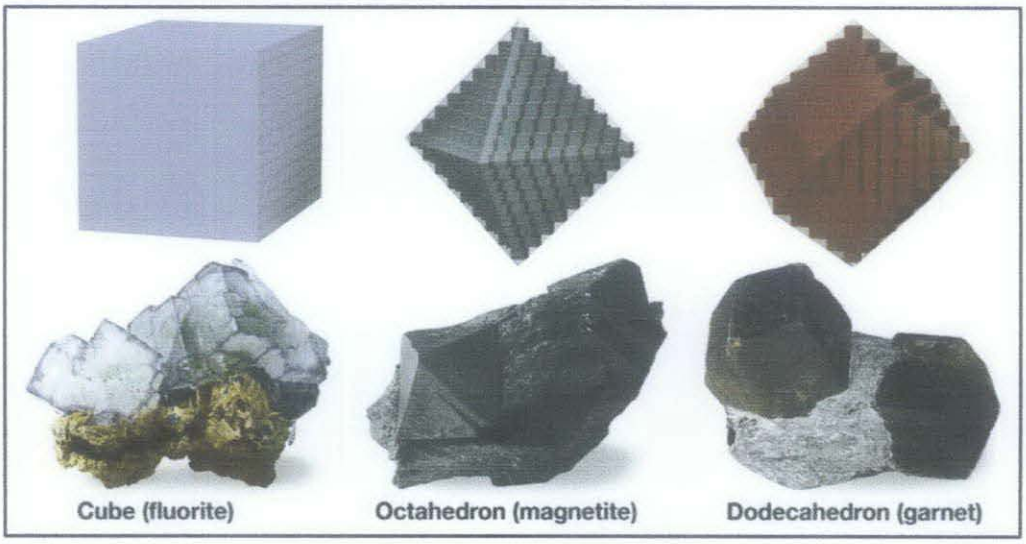


Figure 8 : Rock packing[27]

2.5 PETROPHYSICAL PROPERTIES

Petrophysical characteristics are the results of the sedimentology setting. The properties to be affected are porosity, permeability, density, and velocity.

2.5.1 Porosity

Porosity is the pore spaces in the rocks which act as the storage for the fluids. Porosity is the ratio of the pore spaces volume with the bulk volume. Porosity can be reduced and increased by either physical or chemical alteration towards the rock. It is also can be altered naturally or artificially[2][6][24]. In terms of heterogeneity, the porosity is inconsistent within a reservoir rock. It is due to the sediments fabric and sorting which gives different sizes of pores within the rock. There are two types of porosity which are effective porosity and closed pores. The producible fluid comes from effective porosity but not from closed pores except fracturing or fissure through the closed pores occur[2][6][24].

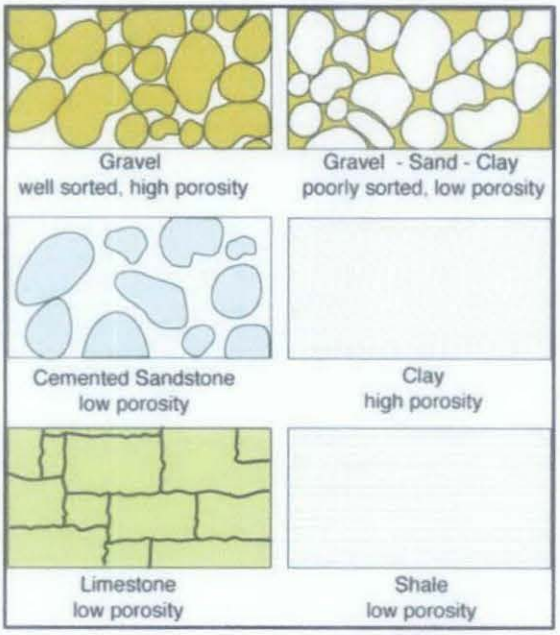


Figure 9 : Porosity[27]

2.5.2 Permeability

Permeability is very much related with porosity. It is related with the flow of the fluid through it and defined by Darcy's Law as

$$Q = \frac{-kA}{\mu}\frac{(P_b - P_a)}{L}$$

Where Q is the flowrate, k is the permeability, A is the area, μ is the viscosity. L is the length and (Pb-Pa) is the pressure difference between point a and b. Permeability is measured in Darcy or mili Darcy (mD).The connected pores in the rock creates links which allows fluid to travel out of the rocks. It is also called effective permeability[6][8][11]. Similar with porosity, it can be altered naturally of artificially. Permeability is not applicable if the pore spaces is isolated excepted there are fracture or fissure. When there are more than one fluid exist within the rock, the flowing fluid is said to be having relative permeability. It is a complex relation with the fluid types and their properties such as wettability and viscosity.

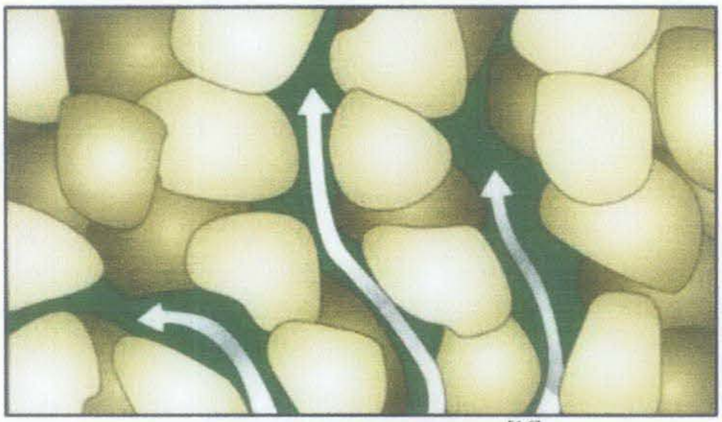


Figure 10 : Permeability[16]

2.6 APPLICATION OF HETEROGENEITY

Heterogeneity brings great effect on reservoir properties and performance. It creates uncertainty which leads to misinterpretation that will give false information about the reservoir. However, sometimes the heterogeneity of the reservoir need to be simplified or otherwise the operation will take a long time to be completed. Below are the normal task involving reservoir heterogeneity:

2.6.1 Upscaling

Upscaling is the process used in reservoir modeling. It simplifies the reservoir to make it easier for calculation and also save time. In reservoir modeling the model is upscaled using several methods. In terms of reservoir heterogeneity, the upscaled reservoir model is simplifying the heterogeneity, from the microscopic level to the macroscopic level[2]. The relevancy of simplifying the reservoir is due to complex calculations and long time required to solve the equations, even with the computers. Even though, the upscaling of the reservoir increases more uncertainty of that reservoir. So, in case of enhanced oil recovery (EOR) consideration, heterogeneity characteristic must be identified to determine the most effective method to recover the hydrocarbon, economically.

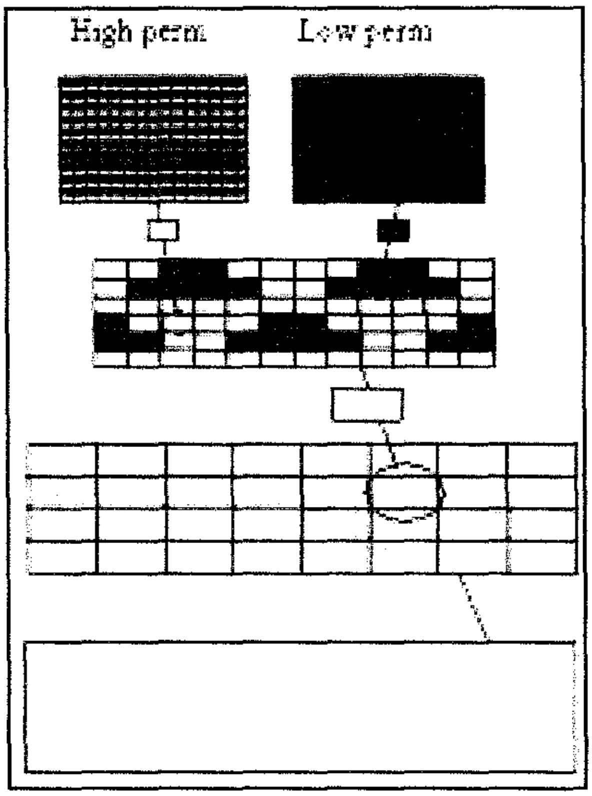


Figure 11 : Upscaled reservoir model[32]

CHAPTER 3

RESEARCH METHODOLOGY

To make sure this project runs smoothly, proper methods will be used. There are several stages needed to be done till the end of the project completion.

3.1 Planning phase

The planning for the project is the most crucial part. Tasks are divided into sections within the period of time. The tasks should comprise all the essential works needed to achieve the project objectives. In planning phase, Gant Chart and milestones are constructed at this stage as a guide for the rest of the project.

3.2 Data collection

For data collection, several methods will be used:

- **Books**

  Reading books relating to reservoir characteristics and geology processes which closely related with heterogeneity. From the books, theories and concepts of the sedimentology and petrophysics are extracted and interpreted to obtain sufficient knowledge about the topics. By understanding the theories, any misinterpretation can be prevented during the analysis in the later part.

- **Field works**

  Observation and interpretation from field trip to Miri Field will helps to understand more about what had been read earlier. The application of theories can be seen from the field trip. Since Miri Field is a clastic reservoir, then theories on sandstone reservoir including the deposition processes and its features will be the priority.

- **Paper and journals**

  There are a lot of studies and researches in form of journals relating heterogeneity characteristics. The journals are usually describing case studies or researches on particular topics. From the journals, relations between the reservoir properties and well performance are explained to aid futher studies on reservoir heterogeneity. There are old and new journals available and by studying both of them, the development of reservoir characterization studies will be visible.

- **Websites**

A lot of informative websites containing information on clastic reservoir characteristics are available on the internet. Although, some of the websites are not reliable as there is no valid sources stated. Plus, the websites belongs to different parties which have different interpretation on the interested subject. With that, comparing the informations between the websites will be good as the additional to the books and journals read as the references.

3.3 Data interpretation

With the data available, interpretation can be done to identify the reservoir characteristics. In this phase, seismic lines and well logs can be interpreted to generate the reservoir maps. With reservoir mapping, the distribution of the sand will be identified which lead to types of deposition environment. With the reservoir mapping also the gross bulk volume of the hydrocarbon can be calculated.

3.4 Sample acquisition

For further study the reservoir heterogeneity characteristics, rock samples of the Miri Field are required. The rock samples will be used for experiments which determine the reservoir properties. A field trip to Miri field was conducted and a suitable outcrop was picked. For this project, the outcrop is the Miri-Pujut Road outcrop, located at the heart of the Miri Town. The rock samples were taken for each layers, labeled and packed properly before being posted back to the lab. Besides rock sampling, the pictures of the outcrop and its layers were taken as part of data acquisition.

3.5 Experiments and laboratory works

The rock samples are divided for different experiments. They must be divided carefully to avoid any insufficient sample for the particular experiment. There are two experiments conducted which are the grain size analysis experiment and porosity and permeability experiment.

3.5.1 Grain size analysis

For grain size analysis, samples from each sand layers were taken and crushed to small particles. For this experiment, the equipments needed are sieve shaker and sets of mesh with particular sizes. Since the rock sample is sand, according to scale by Wentworth (1922), the mesh sizes that will be used are 2.00 mm, 1.00 mm, 0.5 mm, 0.25 mm, 0.125 mm and 0.063 mm.

Figure 12 : Seive Shaker

Below are the procedures for this experiment:

1. The dry-weight of the meshes are measured
2. The weight of a rock sample is measured
3. The meshes are arranged with the ascending order of sizes to the top and pan at the bottom of the mesh.
4. The crushed rock sample is put into the top mesh.
5. The mesh set are fixed into the sieve shaker.

6. The shaker is on for 5 minutes.

7. The weight of the grain and mesh are measured for each mesh sizes.

8. All the weights measured recorded and the dry weight of rock at particular sizes can be calculated by subtracting the dry weight of the mesh of the same size.

9. The frequency curve is plotted to see the grain size distribution of the sand layer.

10. The procedures are repeated for other rock samples.

Besides grain sizes distribution, other sedimentology properties can be determined, such as sorting, kurtosis and skewness. The grain size distribution can be shown graphically in form of histogram or bar charts. However, for sorting, kurtosis and skewness, statistic method is used.

3.5.2 Poro-Perm (Porosimeter) experiment

The rock samples from Miri-Pujut Road are brittle, thus tends to break during coring process. So, porosimeter using core sample cannot be used. Due to that, porosity and permeability of the rock samples are determined by Mercury Porosimeter (Pascal 140) which requires only small part of the rock sample. Although, full precautions are needed when handling this experiment as it involved pure mercury which is known hazardous. The samples undergone this experiment **MUST NOT** be re-used for same or different experiment and **MUST** be disposed safely according to the safety protocol. This experiment is operated by the machine itself which integrates with the computer for data recording. At the end of experiment, a file containing results including porosity and permeability will be stored in the computer.

Figure 13 : Porosimeter PASCAL 140

Below is the procedure for Porosimeter Pascal 140:

1. Cut the rock sample to a small piece, with maximum size 1 cm x 1cm x 0.5 cm.
2. The volume of the sample is calculated
3. The weight of the sample is measured
4. The density of the sample calculated
5. The sample is put into the dilatometer
6. Dilatometer is setup at the designed place on the Pascal 140.
7. On the computer, the rock density is keyed in
8. Type all the relevant information about the sample and experiment (Captions, titles)
9. Press Run and wait until the experiment is complete
10. Open the results and save it for future use
11. The dilatometer is removed from the porosimeter
12. The rock sample is disposed as in safety protocol
13. The procedures are repeated for other rock samples

3.6 Project Activities

- Study and researches on reservoir characteristics
- Seiving for grain size analysis
- Execute porosity and permeability experiments using porosimeter
- Calculations and plotting to determine sedimentology properties

3.7 Tools and equipments

- Hammer and chisel – rock sample acquisition during field trip
- Sieving lab equipment – for grain size analysis purpose

- Porosimeter – determining porosity and permeability

3.8 Software Specification

- Windows operating system
- Microsoft Excel – data recording and graphs
- Statcato – plotting purpose

CHAPTER 4

RESULTS

4.1 INTRODUCTION

This project is divided into two parts; fieldwork and laboratory analyses. During the fieldwork, data such as rock types, layers, facies, thickness and lateral continuity will be collected. The laboratory analyses carried out are the grain size analysis and poro-perm analysis. The laboratory analyses will include the grain sizes, sorting and skewness as well the porosity and the permeability of each sand unit.

4.1.1 Field Overview

Miri field is located in West Baram Delta. Its formation consists of an alternation of coastal sandstones and marine shales of middle Miocene age (9-14 million years) where the sandstones vary from very fine grained, laminated, cm-thick tidal deposits to medium grained, massive cross bedded or bioturbated shoreface and bar deposits[26]. The poorest reservoirs consist of muddy, fine-grained storm sand deposits with poor lateral continuity[26]. Figure 15 shows the Miri field location with its cross section.

Figure 14 : Miri location on Malaysia map[24]

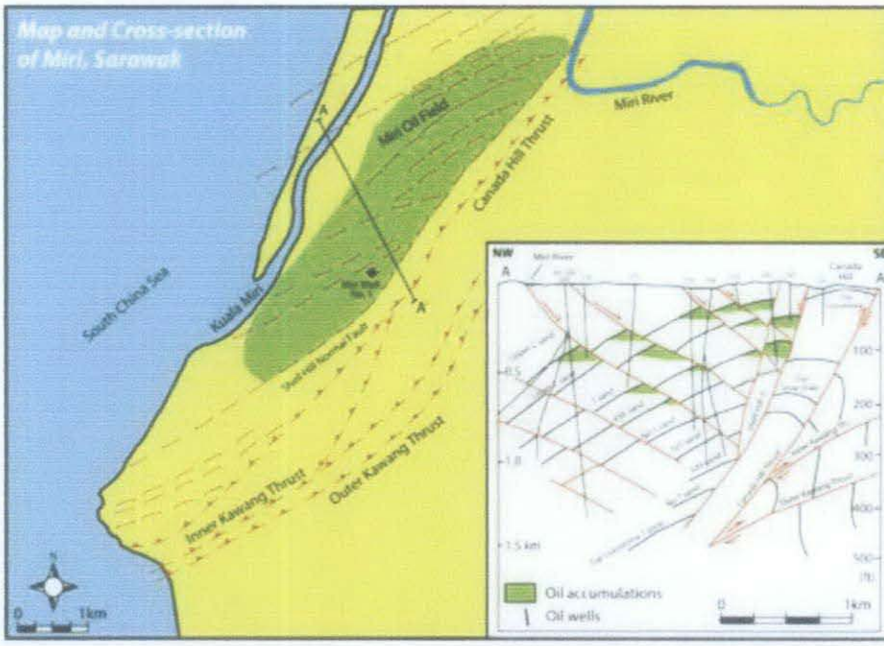


Figure 15 : The map shows the location of Miri Oil Field and the smaller picture to the right shows the cross section of the Miri Field from NW to SE[5]

Miri – Pujut Outcrop is located opposite to the Boulevard Commercial Center and next to the PETRONAS oil station. Currently, the site is undergoing a construction of religious building for Miri community. Figure 14 shows location of Miri in Malaysia map and Figure 16, the satellite image of the outcrop obtained from Google.

Figure 16 : Red circle shows the location of the outcrop at Miri-Pujut Road area which is located opposite to a shopping complex (Google Map, 2011).

4.2 SEDIMENTARY STRUCTURE ANALYSIS

4.2.1 Outcrop analysis

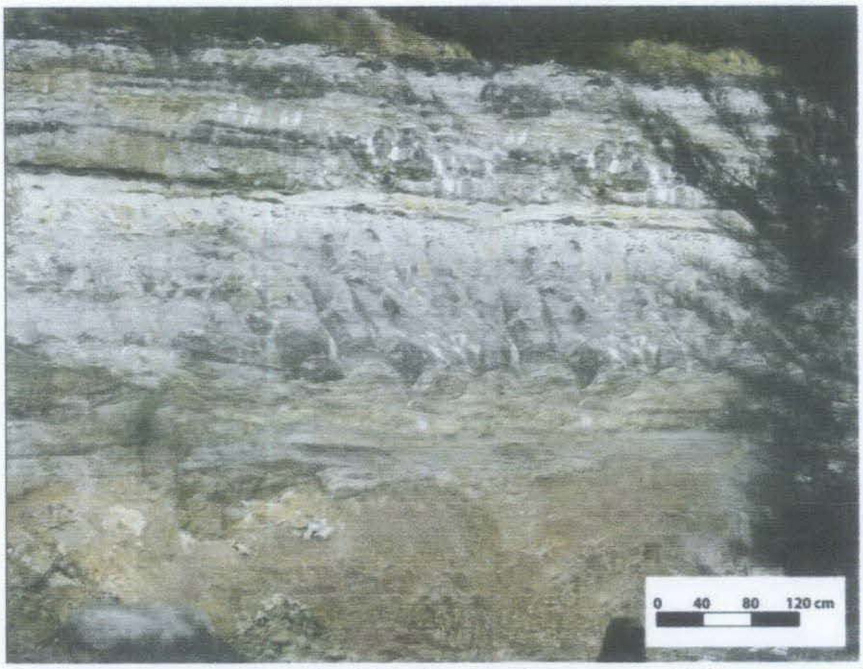


Figure 17 : Lower part of Miri-Pujut Road Outcrop within megascopic level (10's m)

The outcrop at Pujut-Miri Road exposed about 20 layers and roughly consisted of clean whitish sand layers, with thin shale layers between them. Due to construction works, the outcrop had been divided to the upper and lower part. There are layers having trace fossils of marine organisms visible on the layer surface. For this study, only 10 layers are considered including sand and shale layers. Figure 17 shows the lower part of Miri-Pujut Road outcrop.

The outcrop sketch was drawn for clearer view of the outcrop layers and facies. Figure 18 shows the outcrop sketch with the sedimentology logging of the outcrop. The layers are drawn to differentiate between sand and shale layers. The lower part of Miri - Pujut Road outcrop has 11 layers. Generally, the sand layers are thicker than the shale layers and some of shale layers are very thin that they are not significantly visible from a distance.

The width of the outcrop is about 100 m and there are normal faults visible at the outcrop. However, this study will cover only 30 m of the whole outcrop's width and is not located at the fault range to neglect the effect of reservoir compartmentalization.

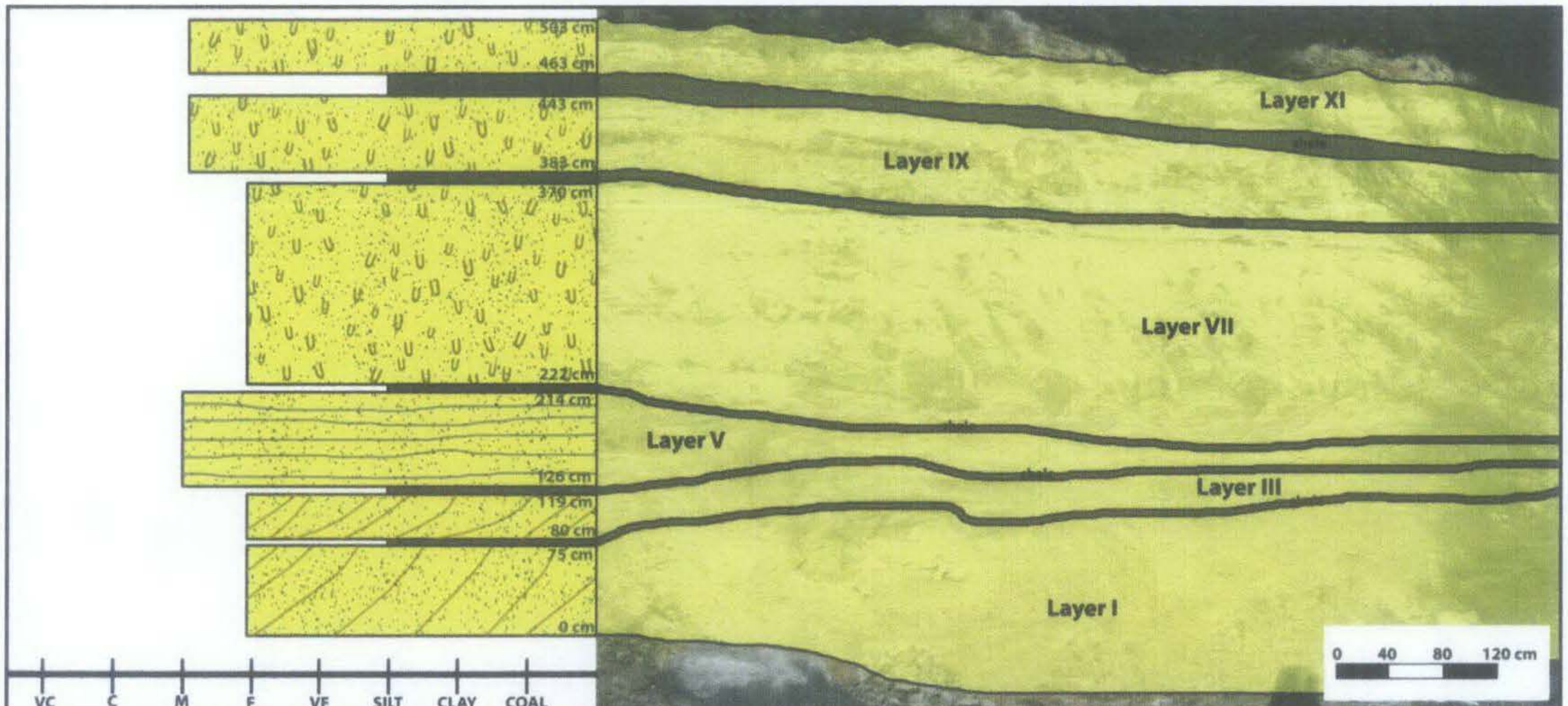


Figure 18: The sketch of lower part of Miri-Pujut Road Outcrop within megascopic level (10's m) and the sedimentary log at the side of the outcrop sketch.

4.2.1.1 Heterogeneity characteristics at megascopic level (10's m)

The sketch of the outcrop is shown in Figure 18. In megascopic level (10's m) the heterogeneity characteristics identified are the lithology, layers and thickness:

- **Lithology**

The outcrop is roughly consisted of whitish sandstone. However from the analysis, major rock types of the outcrop are identified to be the sandstone and shale. With more than one type of rock types, the reservoir cannot be homogeneous. So sandstone and shale layers in the outcrop will contribute to reservoir heterogeneity.

- **Layers**

Layers of sand and shale are identified from the outcrop within the study area of about 5 meters height and 30 meters width. There are 6 sand layers with 5 shale layers as the boundary that separates between the sand units. The alternate layering of sand and shale will results in different permeability values of the reservoir from the bottom to the top reservoir units which cause the heterogeneity.

- **Thickness**

Every different sand layers have different thickness. From the analysis, the net to gross of the outcrop ranges from 81% to 89%. The variation of the sand thickness will cause the pay zone area of the outcrop vary, according to the net to gross calculation.

4.2.2 Outcrop layers and thickness

In this study, 10 layers are observed including shale and sand layers which consisted of five sand layers and five shale layers. Below are the facies for each layer and the layer thickness. However, only the characteristics of the sand layers will be focused in this study. Table 1 shows the facies of each outcrop layers from bottom to the top layers.

Unit	Facies (layer)	Thickness (cm)	Description
I		75 - 163	Layer I is the bottom layer of the outcrop. The base of the layer is not visible so the actual thickness should be more than had been measured. It is clean sand with cross bedding. Its measured thickness ranged from 75 – 163 cm within the 30 m width. The layer is continuous within 30 m of the width.
II		5 - 17	Layer II is a sand interbedded shale layer. Its thickness ranged from 5 – 17 cm and continuous within the study area.
III		78 - 89	Layer III is a continuous cross-bedded sand layer. Its thickness ranged from 78 – 89 cm and laterally thinning and thickening within the study area. There's no sign of bioturbation and the sand grains seems to be fine and whitish in color.
IV		3 - 9	This is the thinnest shale layer in the outcrop. It is not significantly visible at a distance since its thickness is ranged from 3 – 4 cm. There is no sign of interbedded sand in the layer and it is continuous and laterally uniform along the 30 m of the study area.
V		64 - 88	Layer V is a parallel bedded laminated sand. It has streaks of clay layers within the sand. This layer is the thinnest sand layer and predicted to have low porosity due to clay contents in the layer. It is continuous and the thickness ranged from 64 – 88 cm.
VI		5 - 9	Layer VI is a sand interbedded shale layer. It is a thin layer of shale ranged from 5 – 9 cm and continuous within the 30 m width of the study area.
VII		146 - 191	Layer VII is the cleanest sand of the outcrop. It has whitish sand layer with bioturbation of trace fossils visible on its surface. It is also the thickest sand layer of the outcrop and ranged from 186 – 191 cm. like all other layers, it is continuous throughout 30 m of the outcrop.
VIII		12 - 29	Layer VIII is a shale layer with thin sand interbedded within the layer. The interbedded sand layer is very thin that it is not visibly significant. Its thickness ranged from 12 -29 cm and continous within the study area.
IX		90 - 164	Layer IX is a whitish bioturbated sand layer. It contains trace fossils of shallow marine livings. Its thickness ranged from 90 to 164 cm. It is continuous through out the 30 m of the interested area.
X		19 - 48	Layer X is the thickest shale layer (19-48cm) in the outcrop. It has thin interbedded sand within the layer. It is continuous throughout the 30 m of the interested area.

Table 1: This table shows the facies, thickness and description of layers of Miri - Pujut outcrop from the bottom layer (Layer I) to Layer X.

4.2.2.1 Heterogeneity of reservoir layers at macroscopic level (10 – 100's mm)

At the layer level, the heterogeneity characteristic is identified to be the facies of the layers. There are three types of facies recognized from five different sand layers – cross-bedding, laminated sand, and bioturbation. Table 2 shows the sketch of facies for each reservoir unit.

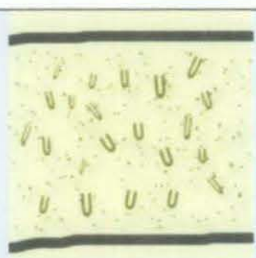
Unit	Facies - sketch	Description
I		Layer I consisted of cross-bedded sand. It shows how the sediments were deposited during the deposition time and the sediments properties will varies according to its deposition environment at the deposition time. Due to that, the porosity and permeability varies within the layer.
III		Layer III is also cross-bedded sand. Same as Layer, the variation of the grain size according to its deposition environment at the deposition time controls the sediment properties affecting the porosity and permeability of the sand unit.
V		Layer V is a parallel bedded laminated sand layer. There are thin layers of clay within the layers. The existence of the clay contents will cause the sand to be semi-permeable as the clay will block the fluid flow, thus affecting the porosity and permeability values.
VII		Layer VII is a bioturbated sand layer. There are trace fossils visible on the layer surface. The existence of fossils will caused variations of permeability and porosity.
IX		Layer IX is also a bioturbated sand layer. The trace fossils are visible on the layer surfaces which results different value of porosity and permeability in the layer.

Table 2: The facies characteristics for sandstone layer of Pujut-Miri outcrop

4.3 LABORATORY ANALYSIS

There are two experiments carried out to identify the sedimentology characteristics as well the porosity and permeability of the reservoir units. For the experiments, only sand layers are tested, neglecting the shale layers as to suit the objective of this study which is identification of sandstone reservoir characteristics. The shale layers also are thin and have no significant interbedded sand layers within them. For porosity and permeability, the rock samples are tested using porosimeter. For each experiment, 3 different samples within same layer are tested and the best value will be recorded.

4.3.1 Grain size distribution

Grain size analysis is carried out by sieving the crushed rock samples through set of sieving mesh sets. Since it is clastic reservoir, the mesh sizes used are 2.00mm, 1.00mm, 0.5mm, 0.25mm and 0.00625mm which ranges from very coarse sand to very fine sand. The pan is installed at the bottom to accumulate grains with smaller size than the finest sand which indicates the presence of silt in the rock sample. The sieving process takes about 10 minutes per sample and three samples are tested for each sand layer. Table 3 shows the grain size distribution of the sand layer III from the sieving analysis. Grain size distribution table for other sand layers can be seen in Appendix. The grain sizes distribution for each sand unit is plot in histogram and frequency curve as shown in Figure 19. For the plotting, the grain sizes are converted from millimeters (mm) to phi scale. Phi scale is commonly used in to indicate the grain sizes instead of microns, millimeters or inches. One phi unit is equal to one Udden-Wentworth grade[25]. It can be calculated to convert mm to phi using this equation:

$$\varphi = -log_2 D/D_o$$

Where Φ is the phi scale, D equals to diameter of particle and D_o as the reference diameter, equals to 1 mm to make the equation dimensionally consistent.

Layer III						
Sizes (mm)	**Mash (g)**	**Gross (g)**	**Clean (g)**	**%**	**%(cum.)**	**phi**
2	381.18	393.64	12.46	4.45	4.45	-1.00
1	351.2	369.99	18.79	6.71	11.17	0.00
0.5	296.61	336.6	39.99	14.29	25.46	1.00
0.25	275.88	303.04	27.16	9.71	35.16	2.00
0.125	337.07	351.8	14.73	5.26	40.43	3.00
0.0625	261.63	406.96	145.33	51.94	92.36	4.00
Pan	389.05	410.42	21.37	7.64	100.00	5.00
Total:	2292.62	2572.45	**279.83**	100		

Table 3 : An example of grain size distribution table of layer III from the sand sieve analysis.

From Figure 19, all of the sand layers are having bimodal distribution except layer V which is having normal distribution. Bimodal distribution means there are two peaks of the frequency curve indicating two major grain sizes within the rock samples. All of the sand units also contains small amount of silts which means that all the sand layers are not purely sand. Table 4 shows the mod and median for each sand unit.

Other sedimentary characteristics can be determined from the grain size analysis such as average size, sorting, skewness. From the grain size frequency curve, cumulative frequency curve is plotted for each sand unit. The cumulative frequency curve shows the cumulative frequency of the grain size from the coarsest grain size to the finest grain size. Figure 20 shows the cumulative frequency for every sand layers.

Layer	Mod (phi)	Median (phi)
I	1 and 4	3.4
III	1 and 4	3.2
V	1 and 4	0.6
VII	1 and 4	3.4
IX	2	1.3

Table 4 : Mod and median of each sand units from the frequency curves

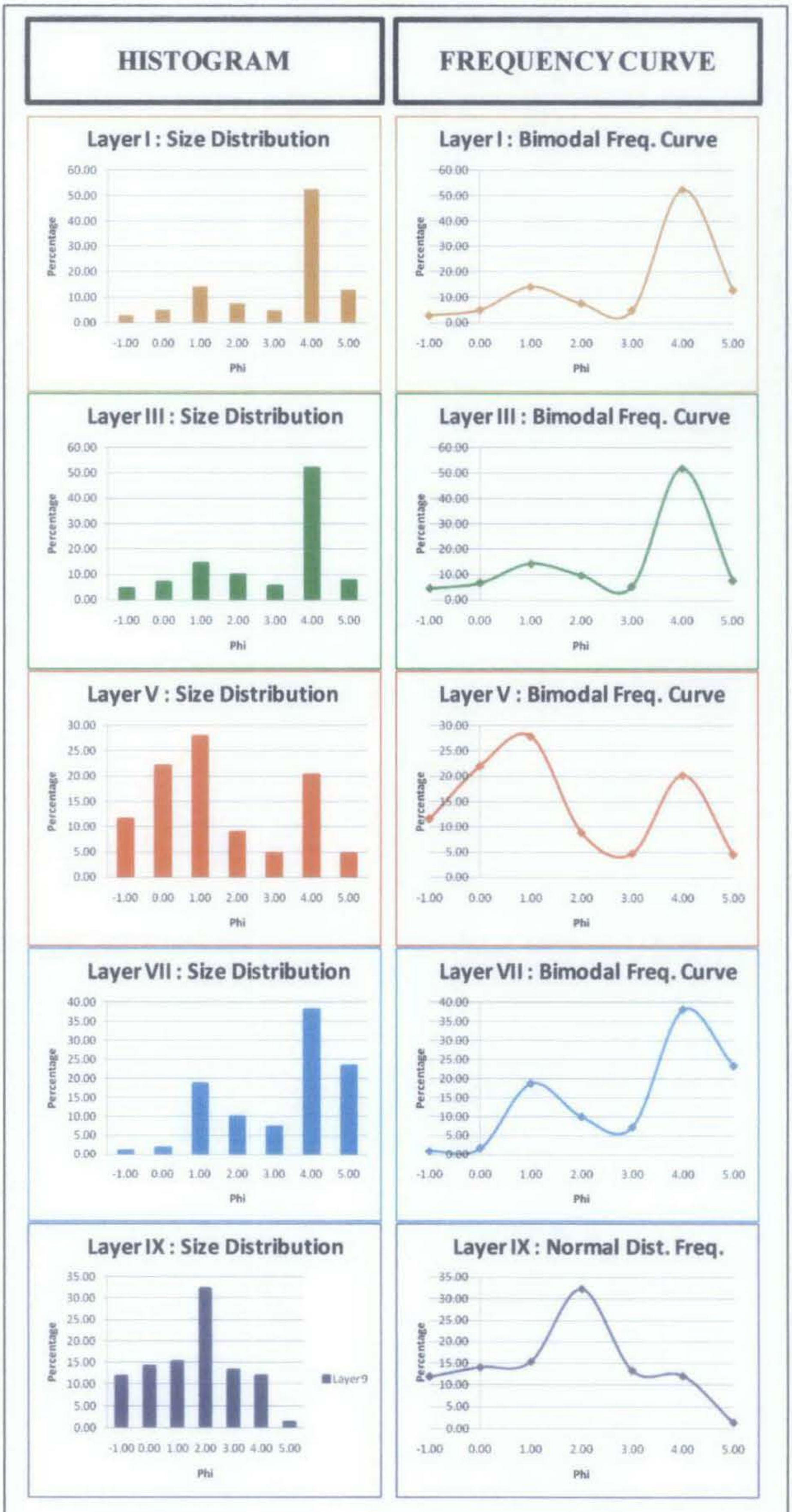


Figure 19 : Grain size distribution frequency for each sand unit in histogram and frequency curve

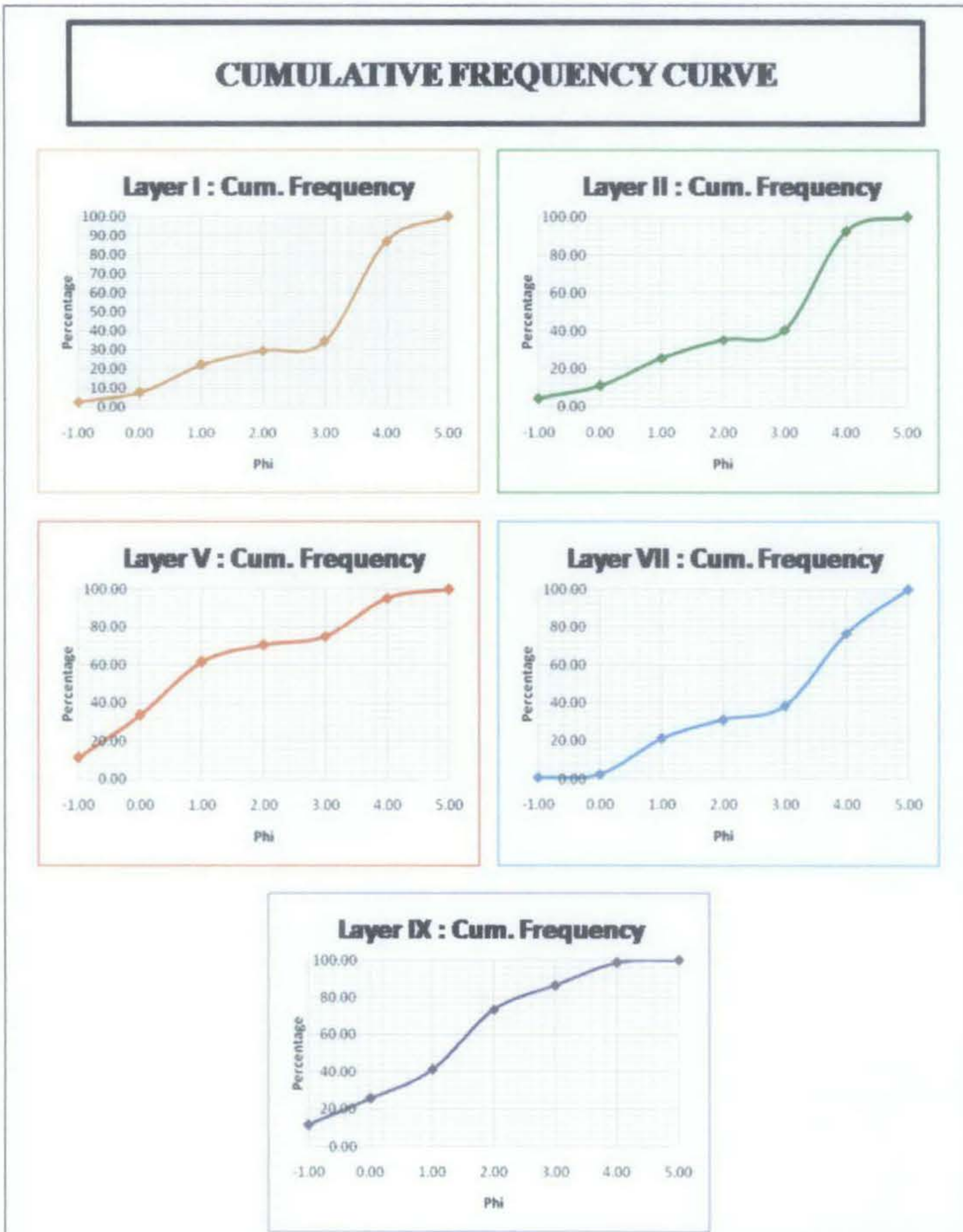


Figure 20 : Cumulative frequency curve for each sand layer.

With the cumulative frequency curve, statistic calculation can be done to determine the rock sorting and skewness. First of all, the phi value at $\phi 5$, $\phi 16$, $\phi 25$, $\phi 50$, $\phi 75$, $\phi 84$, $\phi 95$ from the cumulative frequency curve are recorded in Table 5.

Cum. %	Phi				
	Layer I	Layer III	Layer V	Layer VII	Layer IX
95	4.4	4.1	4.0	7.8	3.6
84	3.9	3.8	3.5	4.2	2.7
75	3.8	3.6	3.0	4.0	2.05
50	3.4	3.2	0.6	3.4	1.3
25	1.3	1.0	0.6	1.3	-0.1
16	0.5	0.23	-0.8	0.6	-0.8
5	-0.6	0.0	-1.4	0.2	-1.5

Table 5 : Cumulative frequency data

To determine the sedimentology characteristics of the rock samples, calculations are made using the statistic equations.

4.3.2 Heterogeneity characteristics at grain level (2 mm – 63μm)

Micro-scale characteristics of the reservoir rock are very important factor of reservoir heterogeneities. From the analyses, the sediments properties including grain size, sorting and skewness are identified to be contributing to heterogeneities. The porosity and permeability values are different for each layer due to the degree of sediments properties at grain size level.

4.3.2.1 Average grain size

The average size for each sand unit is calculated using graphic mean equation:

$$M = \frac{\phi 16 + \phi 50 + \phi 84}{3}$$

Where M is the average grain size while ϕ 16, ϕ 50 and ϕ 84 are the phi values at respective percent. The calculated average size values are recorded in Table 6.

Layer	Average size (phi)
I	2.60 (0.16 mm)
III	2.41 (0.19 mm)
V	1.10 (0.47 mm)
VII	2.73 (0.15 mm)
IX	1.07 (0.48 mm)

Table 6 : Average size of each sand units from the cumulative frequency curves

4.3.2.2 Grain sorting

Sorting is the degree of the grains arrangements in the rock sample. Poor sorting will results poor porosity value while good sorting reflects good porosity value. The sorting for each reservoir unit can be done using the inclusive graphic standard deviation equation below:

$$D = \frac{\phi 84 - \phi 16}{4}$$

Where D is the sorting degree and $\phi 84$ and $\phi 16$ are the phi values at respective percent. Table 7 shows the degree of the sorting in each sand layers.

Layer	Sorting
I	0.85
III	0.89
V	1.08
VII	0.90
IX	0.88

Table 7 : Degree of sorting for each reservoir unit

4.3.2.3 Skewness

Skewness is the degree of the sorting or standard deviation, a measure of the range, scatter, or variation in grain size[27]. It can be calculated using the inclusive graphic skewness equation below:

$$S = \frac{\phi 84 + \phi 16 - 2(\phi 50)}{2(\phi 84 - \phi 16)} + \frac{\phi 95 + \phi 5 - 2(\phi 5}{2(\phi 95 - \phi 5)}$$

Where S is the degree of skewness and $\phi84$, $\phi16$, $\phi50$, $\phi95$ and $\phi5$ are the phi values at the respective percent. The results of the skewness degree are shown in Table 8.

Layer	Skewness
I	-0.65
III	-0.61
V	0.30
VII	-0.20
IX	-0.15

Table 8 : Degree of skewness for each reservoir units

4.3.3 Sediments characteristics summary

In summary, the degrees of the sedimentology characteristics, according to its traits are as shown below in Table 9.

Properties	Layer I	Layer III	Layer V	Layer VII	Layer IX
Average size (phi)	**2.60 (0.16mm)**	**2.41 (0.19mm)**	**1.10 (0.47mm)**	**2.73 (0.15mm)**	**1.07 (0.48mm)**
Sorting	**0.85**	**0.89**	**1.08**	**0.90**	**0.88**
Skewness	**-0.65**	**-0.61**	**0.30**	**-0.20**	**-0.15**

Table 9 : Summary of the degree of the sedimentology characteristics of Miri - Pujut outcrop

4.3.4 Poro-perm analysis

To determine the poro-perm of the reservoir units, mercury porosimeter is used. There are two outcomes of the porosimeter experiment; porosity and permeability.

4.3.4.1 Porosity

The porosity of each sand layer was tested using porosimeter. Three samples were tested for each layer and the average of the porosity is recorded. Table 10 shows the porosity for each sand layer. Even the porosity for each layer is quite good it does not mean it has good permeability. From the experiment, the bottom layers have lower porosity than the upper layers.

Layer	Porosity (%)
I	20
II	20
V	17
VII	22
IX	23

Table 10 : Porosity for each sand unit

4.3.4.2 Permeability

Beside porosity, the porosimeter also test for the rock samples' permeability. The outcome permeability is based on tortuosity of the grains in the rock. Below, Table 11 shows the averaged permeability for each sand unit.

Layer	Permeability (μm^2)	Permeability (mD)
I	557.25E-5	5.65
III	575.38E-5	5.83
V	295.12E-5	2.99
VII	465.13E-4	47.13
IX	446.09E-4	45.20

Table 11 : Permeability of each sand unit

PASCAL 140 porosimeter gives the permeability value in μm^2. To convert to Darcy unit, the permeability values are divided by 0.9869233×10^{-3}. From Table 11, it shows that the lower layers of the outcrop have low permeability but the layers at the upper layers have significant value of permeability.

CHAPTER 5

DISCUSSION

5.1 INTRODUCTION

From the results obtained from the structure sedimentary analysis and laboratory analysis, the degree and values of the sedimentology characteristics, according to its traits; average grain size, sorting and skewness were calculated and had been summarized in Table 9 while for the porosity and permeability values obtained from the porosimeter were recorded in Table 10 and Table 11 respectively. This section will discuss on the sedimentology characteristics from the calculated values and the relations with porosity and permeability.

5.2 CLASSIFICATION OF SEDIMENTOLOGY CHARACTERISTICS

Referring to Figure 22, it shows sets of sedimentary characteristic tables within specific range of values. So by comparing the results from Table 9 with its respective characteristics table, the sand units are categorized and the characteristics classifications are identified. For permeability, the results are compared with Figure 21 to classify the reservoir units according to the permeability values. Table 12 shows the summary of the Miri – Pujut Road outcrop sand layers according to their characteristics.

<table>
<tr><th>Permeability</th><th colspan="4">Pervious</th><th colspan="4">Semi-Pervious</th><th colspan="5">Impervious</th></tr>
<tr><td>Unconsolidated Sand & Gravel</td><td colspan="2">Well Sorted Gravel</td><td colspan="3">Well Sorted Sand or Sand & Gravel</td><td colspan="4">Very Fine Sand, Silt,Loess, Loam</td><td colspan="4"></td></tr>
<tr><td>Unconsolidated Clay & Organic</td><td colspan="4"></td><td colspan="2">Peat</td><td colspan="3">Layered Clay</td><td colspan="4">Unweathered Clay</td></tr>
<tr><td>Consolidated Rocks</td><td colspan="4">Highly Fractured Rocks</td><td colspan="3">Oil Reservoir Rocks</td><td colspan="2">Fresh Sandstone</td><td colspan="2">Fresh Limestone, Dolomite</td><td colspan="2">Fresh Granite</td></tr>
<tr><td>κ (cm²)</td><td>0.001</td><td>1E-04</td><td>10^{-5}</td><td>10^{-6}</td><td>10^{-7}</td><td>10^{-8}</td><td>10^{-9}</td><td>10^{-10}</td><td>10^{-11}</td><td>10^{-12}</td><td>10^{-13}</td><td>10^{-14}</td><td>10^{-15}</td></tr>
<tr><td>κ (millidarcy)</td><td>10^{+8}</td><td>10^{+7}</td><td>10^{+6}</td><td>10^{+5}</td><td>10,000</td><td>1,000</td><td>100</td><td>10</td><td>1</td><td>0.1</td><td>0.01</td><td>0.001</td><td>1E-04</td></tr>
</table>

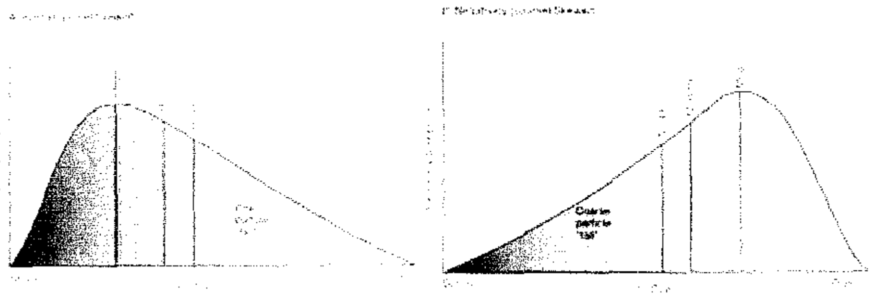
Figure 21 : The permeability and hydraulic conductivity table classifying the rock type and grain sizes (Modified from Bear, 1972)

Grain Size: (from graphic mean)

boulder	-12 to -8 phi
cobble	-8 to -6 phi
pebble	-6 to -2 phi
granular	-2 to -1 phi
very coarse grained	-1 to 0.0 phi
coarse grained	0.0 to 1.0 phi
medium grained	1.0 to 2.0 phi
fine grained	2.0 to 3.0 phi
very fine grained	3.0 to 4.0 phi
coarse silt	4.0 to 5.0 phi
medium silt	5.0 to 6.0 phi
fine silt	6.0 to 7.0 phi
very fine silt	7.0 to 8.0 phi
clay	8.0 phi and smaller

Sorting: (from inclusive graphic standard deviation)

very well sorted	under 0.35 phi
well sorted	0.35 to 0.50 phi
moderately well sorted	0.50 to 0.71 phi
moderately sorted	0.71 to 1.0 phi
poorly sorted	1.0 to 2.0 phi
very poorly sorted	2.0 to 4.0 phi
extremely poorly sorted	over 4.0 phi



Sorting skewness: (from inclusive graphic skewness)

strongly fine- skewed	+1.00 to +0.30
fine- skewed	+0.30 to +0.10
near symmetrical	+0.10 to 0.10
coarse-skewed	0.10 to 0.30
strongly coarse-skewed	0.30 to 1.00

Figure 22 : This figure shows the classification table for grain size, sorting and skewness to be compared with the calculated value from the respective equations[25]

Unit	Layer	Facies	Thickness (cm)	Lateral continuity	Grain size	Sorting	Skewness	Porosity (%)	Pemeability (mD)
I		Cross-bedded sand	75 – 163	Continous (30 m)	Fine grained (0.16 mm)	Moderately sorted	Strongly coarse-skewed	20	5.65
III		Cross-bedded sand	78 – 89	Continous (30 m)	Fine grained (0.19 mm)	Moderately sorted	Strongly coarse-skewed	20	5.83
V		Parallel bedded laminated sand	64 – 88	Continous (30 m)	Medium grained (0.47 mm)	Poorly sorted	Strongly fine-skewed	17	2.99
VII		Bioturbated sand	146 – 191	Continous (30 m)	Fine grained (0.15 mm)	Moderately sorted	Coarse skewed	22	47.13
IX		Bioturbated sand	90 – 164	Continous (30 m)	Medium grained (0.48 mm)	Moderately sorted	Coarse skewed	23	45.20

Table 12 : Summary of Miri-Pujut outcrop sand layers characteristics

5.3 RESERVOIR HETEROGENEITY CHARACTERISTICS

The main objective of this project is to identify the characteristics of heterogeneity in Miri Field within different scale. There are three scale levels involved: megascopic (10's m), macroscopic (10-100's mm) and grain size level (2mm – 63 μm).

At megascopic level, the outcrop had been identified to be heterogeneous with the existence of sand and shale layers. The thickness of the sand and shale layers also varies along the minimum of 30 meters of the study area. The net to gross calculated also ranges from 81% - 89%.

At macroscopic level, the facies is identified to be contributing to heterogeneities. There are five sand layers and three different facies are identified – cross bedding, laminated sand and bioturbation. The facies are formed during the time of the deposition according to its deposition environment and transportation agent.

At micro-scale or grain size level, sediments characteristics are the most important factor leading to heterogeneities. The setting of the sediments physically change the petrophysical properties of the reservoir. Below discusses the relations between the sediments characteristics and the porosity and permeability:

5.3.1 Layer I

From bottom to the top, Layer I is whitish clean-look sandstone and cross bedded. It is thickening and thinning continuously throughout the layer. The thickness ranges from 150 – 163 cm but the layer might be thicker since the base is not visible. From the sand analysis the average size of the sediment is fine grained (0.16 mm). There is silt content within the layer showing the impurity of the sand layer. Porosity of the layer is approximately 20% which is good but the permeability is very low (5.65 mD).

Pryor (1973) analyzed nearly 1000 modern sands and showed that the porosity decreases as the grain size increases. The finer sands tend to be angular and be able to support looser packing fabrics, which cause higher porosity value than coarser sands[6]. In terms of sorting, the better the sorting the higher the sorting will be (Fraser, 1935; Rogers and Head, 1961; Pryor, 1973; Beard and Weyl,1973). However, permeability increases as the grain size increases (Fraser 1935; Krunbein and Monk, 1942; Pryor, 1973). Same like porosity, permeability increases with better grain sorting (Krunbein and Monk, 1942; Beard and Weyl, 1973). In relations with the facies, cross-bedding has a complex relations with permeability[6]. The beddings cause variations in grain sizes from the top to the bottom of the layer. So, Layer I is averagely fine-grained and cross-bedded. It is moderately sorted and strongly-coarse skewed so it has high porosity and low permeability. Compared to the permeability classification table (Figure 21), Layer 1 is semi-pervious and is a poor hydrocarbon reservoir.

5.3.2 Layer III

Layer III has the same characteristics with Layer I. It is also having whitish clean-look sandstone and cross bedded. The sand analysis shows that Layer III is fine grained (0.19 mm), moderately sorted and strongly coarse-skewed. The porosity value is 20% which is good. However, the permeability of Layer III is very low (5.83 mD).

Identical to Layer I, the porosity is good due to the fine grains which are moderately-sorted even it is strongly coarse-skewed. The permeability also is very low due to the fine-grained sediments which reduce the throat passage size and the cross-bedded facies cause the uncertainty of permeabilities in the layer due to the beddings. From Figure 21, Layer III is identified to be semi-pervious and is not a good reservoir.

5.3.3 Layer V

Layer V is the thinnest sand layer of Miri – Pujut outcrop. It ranges from 64 – 70 cm and continuously thicken and thinning throughout the layer. Layer V is parallel bedded laminated sandstone where streaks of clay layers are visible on the surface. The sediments are identified to be medium grained and poorly sorted. Layer V has the poorest value of porosity which is 17% and also poorest value of permeability which is 2.99 mD.

The lamination of the clay layers caused the layers to be impermeable at some level, causing the vertical permeability to be low. The clay also caused the porosity of the sand is low since clay has closed pores which is not good for reservoir. The grains size is averagely medium sized and is poorly sorted leading to low porosity and permeability. The grains are strongly fine-skewed due to the silt contains which is much finer than sand particles.

5.3.4 Layer VII

Layer VII is whitish clean-look sand bioturbated with shallow marine trace fossils. Layer VII has the thickest thickness ranges from 186 – 191 cm and continuous throughout the layer. The sediments are found to be medium grained and moderately sorted. It has good porosity value of 22% and the highest value of permeability of 47.13 mD which indicates a good potential oil reservoir rock.

Layer VII is having shallow marine depositional environment by the existence of bioturbation. In beach and dune sands, the permeability increases as the sorting decreases (Pryor, 1973). Layer VII is fine grained and moderately sorted. It is also coarse-skewed which results good porosity and permeability. The orientation of the trace fossil in the layer can cause variations in porosity and permeability[6]. Permeability ranging from 10-100 mD are good and above that is considered to be exceptionally high[6]. In this case, layer VII is a good reservoir layer with good porosity and permeability.

5.3.5 Layer IX

Layer IX is also whitish clean-look sand and bioturbated with shallow marine trace fossils. It is located at the top layer and continuously thicken and thinning throughout the layer. Layer IX is thinner than Layer VII which ranges from 150 – 164 cm. From the sand analysis, Layer IX is medium grained and moderately sorted. It is also coarse skewed. Layer IX has the highest porosity of 23% and high permeability of 45.20 mD.

Layer IX is having the same characteristics as Layer VII, except that it is medium grained. Since the average grains size is larger than Layer VII, it has higher porosity. Even though, its permeability is slightly lower than Layer VII. This could be caused by different type of packing the layers having or the orientation of the trace fossils within the layer.

5.3.6 Overall reservoir characteristics

Overall, there are three type of facies identified from Miri – Pujut outcrop; cross bedded sandstone (Layer I and III), parallel bedded laminated sandstone (Layer V), and bioturbated sandstone (Layer VII and IX). The grain sizes ranges from fine to medium grained, with moderate sorting except Layer V. The porosity also ranged from 17% to 23% but the permeability of the lower layers (Layer V – Layer I) is too low (2.99 -5.83 mD) while Layer VII and IX indicates good permeability (47.13 – 45.20 mD).

5.3 ERRORS AND UNCERTAINTY

The analysis shows that all the sand layers, regardless of its thickness and facies, have about the same porosity which is between 0.20 and 0.23 except layer 5 which has lower porosity of 0.17. However, still it is uncertain that the layers are having the same porosity as the layers expand. This is because the rock samples taken represent only the properties of that particular area, instead of the layer. However, in this case, same application of upscaling is used, where the porosity of three different places within same layer are tested and averaged to have a porosity value. The porosity value of the layer also might deviates from its supposed value, referring to the sedimentology properties as the tests of the sediments only cover small partial of the particular layers.

Other than that, the presence of silt grains in the rock sample shows the impurity of the sand layers. However, it is uncertain that the rock samples taken are located within the real sand layer instead of at the shale-sand layer boundary as the sample is taken at the surface.

Furthermore, since the samples is obtain from the surfaces of the layer, weathering process could have changed the sand properties and new sediments might had been deposited on the sand layer surface.

For this study, to reduce the error and uncertainty, for each experiment the three samples from different spot within same layer were analyzed so the best and averaged value will be chosen as the analysis outcomes.

CHAPTER 6

CONCLUSION

1. Heterogeneities occur within different scales – megascopic (10's m), macroscopic (10-100 mm) and grain size level (2 mm – 63µm). At megascopic level, the lithology, layers and their thickness are different within the outcrop. At macroscopic level, the facies type is the main contributor to heterogeneity. At micro-scale level or grain size level, the grains size, sorting and skewness are the critical characteristics which caused the heterogeneity.

2. The sediments characteristics are directly related to the porosity and permeability of the reservoir. Generally, the porosity and permeability increases with better sorting and the skewness show the tendency of the reservoir towards coarse or fine grains. The porosity is increasing with decreasing grain sizes while permeability is vice versa. However, the relations can be varied due to its complexity of its facies and post-depositional environment.

3. For Miri-Pujut outcrop, the studies indicate that it comprises of sand and shale layers of different thickness. There are three type of reservoir facies identified – cross bedded sand, laminated sand, and bioturbated sand. In summary, Miri – Pujut outcrop has grain size ranges from medium to fine grained. Most of the reservoir is moderately sorted and the skewness generally to be strongly coarse-skewed. The porosity of Miri–Pujut Road outcrop mostly ranged from 0.20 – 0.23 (except layer V) indicates good porosity. However only upper sand layers have good permeability values (45.2 – 47.13 mD).

4. Layer VII has the best quality of a good reservoir. It has good porosity and permeability and the thickest layer of the outcrop.

5. The second best layer will be layer IX which has about the same value of porosity and permeability as Layer VII but relatively thinner than Layer VII.

6. The worst reservoir layer in Miri-Pujut Outcrop is layer V. It is laminated with clay and has low porosity of 17%. Layer V also has the lowest permeability of 2.99 mD which is not favorable for fluid flow.

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FINAL YEAR PROJECT 2 PROJECT SCHEDULE

Activities	Week															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Sample acquisition	■															
Sample preparation		■														
FYP 2 briefing			■													
Lab preparation			■	■												
Lab experiment				■	■	■	■	■								
Progress report							■	■								
Final report preparation									■	■						
Poster										■						
Pre-EDX											■					
FYP 2 final report submission											■					
Oral presentation												■	■			
Finalizing final report														■		
Hardbound service															■	
Submission of hardbound final report																■

Grain Size Analysis Data

Layer I						
Sizes (mm)	**Mash (g)**	**Gross (g)**	**Clean (g)**	**%**	**%(cum.)**	**phi**
2	381.17	388.98	7.81	2.87	2.87	-1.00
1	351.37	365.13	13.76	5.05	7.92	0.00
0.5	296.67	335.33	38.66	14.20	22.12	1.00
0.25	276.02	296.59	20.57	7.55	29.67	2.00
0.125	337.32	350.71	13.39	4.92	34.59	3.00
0.0625	261.76	404.73	142.97	52.50	87.09	4.00
Pan	389.13	424.29	35.16	12.91	100.00	5.00
Total :	2293.44	2565.76	**272.32**	100		

Layer III						
Sizes (mm)	**Mash (g)**	**Gross (g)**	**Clean (g)**	**%**	**%(cum.)**	**phi**
2	381.18	393.64	12.46	4.45	4.45	-1.00
1	351.2	369.99	18.79	6.71	11.17	0.00
0.5	296.61	336.6	39.99	14.29	25.46	1.00
0.25	275.88	303.04	27.16	9.71	35.16	2.00
0.125	337.07	351.8	14.73	5.26	40.43	3.00
0.0625	261.63	406.96	145.33	51.94	92.36	4.00
Pan	389.05	410.42	21.37	7.64	100.00	5.00
Total :	2292.62	2572.45	**279.83**	100		

Layer V						
Sizes (mm)	**Mash (g)**	**Gross (g)**	**Clean (g)**	**%**	**%(cum.)**	**phi**
2	380.98	400.43	19.45	11.59	11.59	-1.00
1	351.24	388.29	37.05	22.08	33.67	0.00
0.5	296.55	343.37	46.82	27.90	61.58	1.00
0.25	275.86	290.73	14.87	8.86	70.44	2.00
0.125	337.19	345.11	7.92	4.72	75.16	3.00
0.0625	261.66	295.69	34.03	20.28	95.44	4.00
Pan	389.07	396.72	7.65	4.56	100.00	5.00
Total :	2292.55	2460.34	**167.79**	100		

Layer VII						
Sizes (mm)	**Mash (g)**	**Gross (g)**	**Clean (g)**	**%**	**%(cum.)**	**phi**
2	380.84	384.43	1.03	0.96	0.96	-1.00
1	351.28	353.1	1.82	1.70	2.67	0.00
0.5	296.63	316.58	19.95	18.69	21.36	1.00
0.25	275.91	286.48	10.57	9.90	31.26	2.00
0.125	337.22	345	7.78	7.29	38.55	3.00
0.0625	261.75	302.39	40.64	38.07	76.62	4.00
Pan	389.06	414.02	24.96	23.38	100.00	5.00
Total :	2292.69	2402	**106.75**	100		

Layer IX						
Sizes (mm)	**Mash (g)**	**Gross (g)**	**Clean (g)**	**%**	**%(cum.)**	**phi**
2	381.12	408.35	27.23	11.85	11.85	-1.00
1	351.35	383.63	32.28	14.05	25.90	0.00
0.5	296.56	331.72	35.16	15.30	41.20	1.00
0.25	275.91	349.9	73.99	32.20	73.40	2.00
0.125	337.21	367.6	30.39	13.23	86.63	3.00
0.0625	261.73	289.36	27.63	12.02	98.65	4.00
Pan	389.14	392.24	3.1	1.35	100.00	5.00
Total :	2293.02	2522.8	**229.78**	100		