

**CHARACTERISTICS OF SEDIMENTARY FACIES AND RESERVOIR
PROPERTIES OF SOME TERTIARY SANDSTONES IN
SABAH AND SARAWAK, EAST MALAYSIA**

by

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SYMBOLS AND ABBREVIATIONS

SYMBOL:

Φ : Porosity

k: Permeability

d: Density

v: Velocity

>: greater than

<: less than

UNIT:

%: Percentage

md: milidarcy

g: gram

cm: centimeter

m: meter

s: second

ABBREVIATION:

HCS: Hummocky cross-stratified

SCS: Swaley cross-stratified

TCB: Trough cross-bedded

Biot: Bioturbated

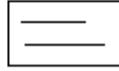
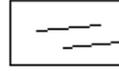
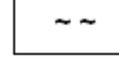
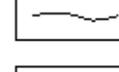
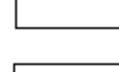
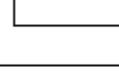
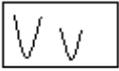
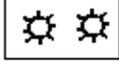
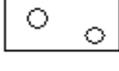
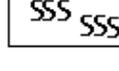
Sst: Sandstone

x-b: cross-bedded

lam: laminated

poro-perm: Porosity and permeability

SEDIMENTOLOGICAL LEGEND

Sedimentary structures:			
	Sandstone		Fining upward
	Siltstone		Coarsening upward
	Mudstone	E	Erosive base
	Coal		
	Low-angle to parallel stratification		
	Swaley to hummocky cross-bedding		
	Trough cross-bedding		
	Herringbone cross-bedding		
	Flaser-bedding		
	Mud laminas		
	Mud clasts		
	Mud drapes		
		Trace fossils:	
			Vertical <i>Ophiomorpha</i> burrows
			Horizontal <i>Ophiomorpha</i> burrows
			<i>Skolithos</i>
			Bioturbated sandstones

CIRI-CIRI FASIES SEDIMENTARI DAN SIFAT-SIFAT TAKUNGAN BAGI SEBAHAGIAN BATU PASIR TERTIARI DI SABAH DAN SARAWAK, MALAYSIA TIMUR

ABSTRAK

Batu pasir adalah sangat penting sebagai takungan bagi minyak dan gas; lebih dari 50% simpanan petroleum berlaku pada batu pasir. Keadaan pengendapan dan ciri-ciri fasies menentukan kesemuanya sifat takungan. Tujuan untuk menjalankan penyelidikan ini adalah menentukan perkaitan antara ciri-ciri sedimentologi, sifat fasies dan ciri-ciri takungan bagi batu pasir yang lain jenis. Untuk mencapai tujuan penyelidikan ini, kaedah-kaedah berikut digunakan: (i) analisa sedimentologi lapangan, termasuk penjelasan fasies; (ii) pengutipan sampel batuan pada outcrop terpilih; (iii) pengukuran dan ujian petrofizik di dalam makmal. Pengukuran petrofizik termasuklah analisis saiz butiran, analisis keliangan, analisis ketelapan, pengukuran halaju dan ketumpatan.

Batu pasir dari Formasi Sandakan (Sandakan, Sabah), Formasi Miri (Miri, Sarawak), Formasi Nyalau (Bintulu, Sarawak) and Formasi West Crocker (Kota Kinabalu, Sabah) dikaji dalam penyelidikan ini. Seksyen sedimentari yang dikaji mewakili pelbagai jenis batuan dari aspek fasies pengendapan dan umur geologi.

Batu pasir dari Sandakan, Miri dan Nyalau mempamerkan kawalan yang kuat antara fasies pengendapan ke atas keliangan-ketelapan bagi batu pasir. Batu pasir berbentuk kekanta dari Sandakan merekodkan nilai keliangan-ketelapan yang paling tinggi ($\Phi > 20\%$; $k > 10\text{md}$), tetapi kesinambungan lateral dan tegaknya sangat terhad. Batu pasir lapisan silang hummocky dan lapisan silang swaley dari Sandakan menunjukkan keliangan-ketelapan yang sederhana ($\Phi: \sim 20\%$; $k: 1-10\text{md}$) dengan kesinambungan lateral yang baik. Batu pasir lapisan silang hummocky dan lapisan silang swaley dari Miri merekodkan nilai keliangan-ketelapan yang lebih baik berbanding dengan batu pasir lapisan silang palung. Ini adalah kerana mereka

mempunyai pemilihan butir yang lebih baik, saiz butir yang halus dan lumpur berlamina yang kurang. Batu pasir biokacau dari Miri merekodkan nilai keliangan yang rendah disebabkan oleh pemilihan buruk berkaitan dengan kemasukan lumpur ke dalam ruang antara butir. Nilai ketumpatan yang tinggi ($d: \sim 2.3\text{g/cm}^3$) bagi batu pasir Nyalau menggambarkan pepadatan dan penyimenan berlaku pada tahap yang lebih tinggi berbanding dengan batu pasir dari Sandakan dan Miri. Nilai keliangan yang rendah bagi batu pasir Nyalau ($\Phi: \sim 15\%$) mencerminkan sejarah pengkebumian / pepadatannya.

Batu pasir Formasi West Crocker menunjukkan perkaitan yang kuat antara diagenesis dan nilai-nilai keliangan-ketelapan kerana batu pasir tersebut mengalami tahap pepadatan dan penyimenan yang amat tinggi (umur geologi batuan lebih tua dari batu pasir formasi-formasi Sandakan, Miri dan Nyalau). Batu pasir ini merekodkan nilai ketumpatan yang tinggi ($d: 2.3-2.8\text{g/cm}^3$), nilai kelajuan yang tinggi ($v: 4500-7500\text{m/s}$) dan nilai keliangan-ketelapan yang rendah ($\Phi: < 10\%$; $k: < 1\text{md}$).

Batu pasir lapisan silang hummocky dari Formasi Miri menunjukkan kualiti takungan yang tinggi ($\Phi: > 20\%$; $k: > 10\text{md}$) dengan kesinambungan lateral yang baik dan ketebalan yang seragam. Batu pasir lapisan silang hummocky dan lapisan silang swaley dari Sandakan menunjukkan kualiti takungan yang sederhana, saiz butirannya halus, pemilihan butiran yang sederhana dan laminasi lumpur wujud dengan sekali-sekala. Penyusunan butiran yang sederhana dan pewujudan laminasi lumpur mengakibatkan pengurangan kualiti takungan. Batu pasir Crocker mempunyai nilai keliangan-ketelapan yang rendah, ketumpatan yang tinggi dan kelajuan yang tinggi. Ini merupakan batuan yang tiada kualiti sebagai takungan kerana pepadatan dan penyimenan yang dialami oleh batuan tersebut.

CHARACTERISTICS OF SEDIMENTARY FACIES AND RESERVOIR PROPERTIES OF SOME TERTIARY SANDSTONES IN SABAH AND SARAWAK, EAST MALAYSIA

ABSTRACT

Sandstones are very important as reservoirs for oil and gas; more than 50% of the world's petroleum reserve is estimated to occur in sandstones. Depositional environments, and thus facies characteristics, determine the overall reservoir properties of sandstones. The purpose of studying the reservoir sedimentological characteristics and petrophysical properties of Tertiary reservoir quality sandstones from Sabah and Sarawak is to investigate and determine the relationships between sedimentological and facies characteristics, and reservoir properties of the different types of sandstones. To achieve the objectives of the study, the following methods of investigations have been employed. These are: (i) field sedimentological analysis, which include facies description; (ii) collection of sandstone samples at selected outcrops; (iii) laboratory petrophysical testing and measurements. The laboratory petrophysical measurements include grain size analysis, porosity analysis, permeability analysis, velocity and density measurements.

Sandstones from Sandakan Formation (Sandakan, Sabah), Miri Formation (Miri, Sarawak), Nyalau Formation (Bintulu, Sarawak) and West Crocker Formation (Kota Kinabalu, Sabah) were investigated and analysed in this study. The sedimentary sections represent a variety of rock types in terms of depositional facies and ages.

The Sandakan, Miri and Nyalau sandstones exhibit strong depositional facies control on their poro-perm properties. The sandstone lenses (gutter casts) from Sandakan recorded the highest poro-perm (Φ :> 20%; k :> 10md), but with very limited lateral and vertical continuity. The hummocky cross-stratified and swaley cross-stratified sandstones from Sandakan show moderate poro-perm (Φ : ~20%; k: 1-10md) and good lateral continuity. Hummocky cross-stratified and swaley cross-stratified sandstones from Miri recorded better poro-perm values than trough cross-bedded

sandstones because they are generally better sorted, fine average grain size and lack muddy laminations or drapes. Bioturbated sandstones from Miri are with low porosities due to the poor sorting caused by infiltration of silty or muddy particles. The high density values ($d: \sim 2.3\text{g/cm}^3$) for Nyalau sandstones reflect a higher degree of compaction and cementation than Sandakan and Miri sandstones. The lower porosities of Nyalau sandstones ($\Phi: \sim 15\%$) reflects their burial history/ compaction.

The sandstones of West Crocker Formation show close relationships between diagenesis and poro-perm values, because these sandstones have undergone higher degree of compaction and cementation (geologically much older than Sandakan, Miri and Nyalau Formations). These sandstones recorded high densities ($d: 2.3\text{-}2.8\text{g/cm}^3$), high velocities ($v: 4500\text{-}7500\text{m/s}$) and low poro-perm values ($\Phi: < 10\%$; $k: < 1\text{md}$).

Hummocky cross-stratified sandstones of Miri Formation show high reservoir qualities ($\Phi :> 20\%$; $k :> 10\text{md}$) with good lateral extent and uniform thickness. The hummocky cross-stratified and swaley cross-stratified sandstones of Sandakan show moderate reservoir qualities. They are fine grained, moderately sorted and with occasional mud lamination. The reduced sorting and the presence of mud laminations must have contributed to the slight reduction in reservoir quality. Low poro-perm values, high densities and high velocities Crocker sandstones are tight, non-reservoir quality sandstones because they have been cemented and compacted.

CHAPTER 1

INTRODUCTION

1.1 Introduction

Sandstones are very important as reservoirs for oil and gas; about 50% of the world's petroleum reserve is estimated to occur in sandstones (Berg, 1986). The purpose of studying the reservoir sedimentological characteristics, petrophysical and rock physics properties of sandstones from Sabah and Sarawak, East Malaysia is to investigate and determine the rock and reservoir properties of different types (facies, diagenesis and age) of sandstones.

Understanding the properties of sandstones is essential in the exploration and production of hydrocarbon from the subsurface sedimentary strata as these properties strongly influence their reservoir qualities. Sandstones are deposited within sedimentary environments ranging from continental alluvial settings, to marginal coastal areas which are affected by riverine, waves and tidal processes, to deep submarine region. The primary properties of sandstones (texture, composition, sedimentary structures, morphology and stratigraphic heterogeneity) are largely determined by the source materials and by the environment of deposition (Berg, 1986; Morse, 1994).

This study on the sedimentological (facies, grain size) and reservoir petrophysical properties (grain size, porosity, permeability, density, sonic velocity) of sandstones were conducted on the sedimentary rocks belonging to the Sandakan Formation (Late Miocene) from Sandakan and West Crocker Formation (Oligocene-Early Miocene) from Kota Kinabalu in Sabah, Miri Formation (Middle Miocene) from Miri and Nyalau Formation (Oligocene- Middle Miocene) from Bintulu in Sarawak.

1.1.1 Reservoir Characteristic

Oil- and gas-bearing rocks are generally referred to as reservoir rocks. Reservoir rocks must be porous, because hydrocarbons can occur only in pores. These rocks must also be permeable which means that the pores are connected. If hydrocarbons are in the pores of a rock, they must be able to move through them. A suitable reservoir rock must therefore be porous, permeable, and contain enough hydrocarbons to make it economically feasible for the operating company to drill for and produce them.

In sandstone reservoirs, important characteristics such as porosity, permeability, and capillary properties are determined by a combination of depositional and diagenetic effects. It is critical to know the distribution of these properties within a reservoir rock in order to achieve the maximum efficiency in reservoir management for hydrocarbon production.

Reservoir characterization is a complex process to identify reservoir properties by establishing interdisciplinary relationships from pore to basin scale (Schatzinger & Jordan, 1999). For oilfields in Sabah and Sarawak, a quantitative work in characterizing and evaluating the reservoirs is needed to understand the complex reservoir characteristics.

1.1.2 Petrophysics and Rock Physics

Petrophysics involve the investigation and study of the physical behavior and properties of rocks (Yale, 1985). It is a highly interdisciplinary field incorporating geology, well logging, core analysis, geophysics, geochemistry and sedimentology.

This subject involves the study of the physical properties of rock which are related to the pore and fluid distribution (Archie, 1950). This generally refers to three properties of rocks: porosity, specific internal surface and permeability. These pore-space properties are very complex for rocks; simple mathematical or experimental

models only approximate the pore-space properties of natural rocks (Jordan and Campbell, 1984).

The connection between physical properties of rocks and geophysical observables is known as Rock Physics. Rock Physics describes a reservoir rock by physical properties such as porosity, rigidity, compressibility. These properties are dependent on the composition of rock materials (texture, rock fabric, minerals, pore space, depositional and post-depositional features) and affected by pressure and temperature (Schön, 1996). It also affects how seismic waves physically travel through the rocks. Rock Physics discusses about velocities and elastic parameters, because these are properties that link physical rock properties to seismic expressions. Rock physics may use information provided by the petrophysicist, such as shale volume, saturation levels, and porosity in establishing relations between rock properties or in performing fluid substitution analysis.

1.2 Objectives

The objectives of this research project are as follow:

- i. To investigate the reservoir sedimentological characteristics (facies, grain size, thickness) of sandstone samples from Sabah and Sarawak in East Malaysia;
- ii. To investigate some of the petrophysical and rock physics properties (such as density, porosity, permeability and seismic velocity of the sandstone samples;
- iii. To establish relationships between the sandstones sedimentological, petrophysical and rock physics properties;

To achieve the objectives of the study, two main methods of investigations have been employed. These are:

- i. Field and laboratory reservoir sedimentological analysis;
- ii. Laboratory petrophysical and rock physic testing and measurements. These include porosity and permeability analysis, density measurements, and grain size analysis. Seismic velocities of the

different sandstone samples were also measured. This helps to establish the relationships between sedimentological expression and petrophysical rock properties.

1.3 Study Area

This study was conducted on onshore sedimentary rocks exposed in Sandakan and Kota Kinabalu (Sabah), and Miri and Bintulu (Sarawak) in East Malaysia (Figure 1.1).

1.3.1 The Sandakan Formation, Sandakan (Sabah)

The Sandakan Formation comprises more than 2500 m of mudstone, sandstone and siltstone of late Miocene (Tf stage) or younger age (Lee, 1970). Stauffer and Lee (1972) stated that the formation forms faulted synclinal structures in the central and southern Sandakan Peninsula. Yin (1985) defined the Sandakan Formation as the fill of the (onshore) portion of the Sandakan basin. Lee (1970) and Wilson (1961) reported that the Sandakan Formation is considered to correlate closely with the Bongaya Formation of Tf age and is overlain unconformably by Quaternary deposits dominated by quartz pebble conglomerates.

Sandakan Formation rock shows plenty of primary sedimentary structures, which include fine lamination, small to medium scale cross-bedding, current and wave ripples, channeling and ball and pillow structures (Lee, 1970; Stauffer and Lee, 1972). Fitch (1958) stated that early work on the Sandakan Formation found that much of the mudstones are barren of microfossils. Lee (1970) stated that the macrofossils have been recorded from the Sandakan Formation, and have been dated as Late Miocene in age.

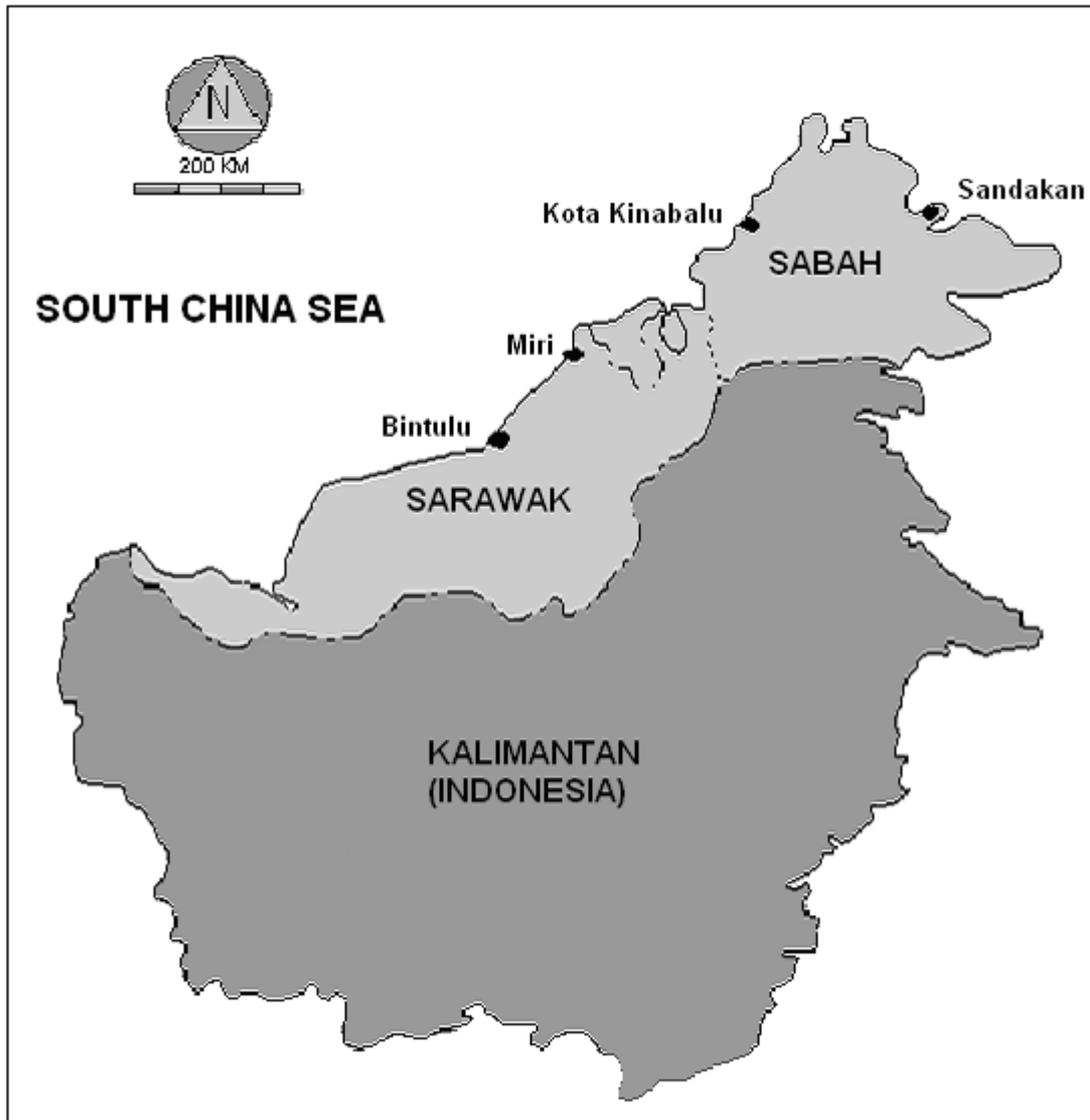


Figure 1.1: Map of Borneo Island showing the study area of Sandakan and Kota Kinabalu in Sabah, and Miri and Bintulu in Sarawak, East Malaysia.

These structures and fossil content have been interpreted to suggest that Sandakan Formation was deposited mainly in a shallow marine and deltaic environment, probably with a fluvial source in the west (Lee, 1970; Stauffer and Lee, 1972).

1.3.2 The Miri Formation, Miri (Sarawak)

The rocks exposed around the Miri town, Sarawak, which belongs to the Middle Miocene Miri Formation, are the uplifted part of the subsurface, oil-bearing sedimentary strata of the Miri oilfield and possibly also for the offshore fields. The subsurface successions have been explored for hydrocarbon for since the 19th century; however, modern western oil technology was only employed in 1899 and the first, modern production well, the Miri-1, came into production in 1910 (Tan *et al.*, 1999).

Liechti *et al.* (1960) described the formation as a predominantly marine arenaceous succession, based on observations of outcrops of the Miri Anticline and examination of subsurface material from the Miri and the Seria oil field. The basal contact with the underlying Setap Shale Formation is a gradual transition from an arenaceous succession downward into a predominantly argillaceous succession. Based on lithological differences and small benthonic Foraminifera assemblage, Liechti *et al.* (1960) and Wilford (1961) divided the formation into a Lower and Upper unit.

The maximum total thickness of Miri Formation estimated in the Seria Field in Brunei is over 6,000 feet. The difference between the Lower and the Upper Miri is not clear enough to map the boundary on lithology alone. The Lower Miri consists of well-defined beds of sandstones and shales, with the shales slightly prevailing. These lower unit shales out downwards to merge gradually into the underlying Setap Shale Formation. The Upper Miri Formation is more arenaceous. It consists of rapidly recurrent and irregular sandstone-shale alternations, with the sandstone beds merging gradually into clayey sandstone and sandy or silty shale. From the identification of marine microfauna and lithological characteristics, Liechti *et al.* (1960) concluded that these sediments were

deposited in a littoral to inner neritic shallow marine environment. The beds of Miri Formation are gently to moderately folded. The average dips in the Jerudong area are 45°, but in the Belait syncline the dips are less than 20°. The Miri anticline has a northeasterly trend. Its north-west flank consists of overthrust blocks, while the structure is cut by normal faults (Wilford, 1961).

1.3.3 The Nyalau Formation, Bintulu (Sarawak)

The Nyalau Formation (Middle Miocene) of Bintulu area, Sarawak occurred as (i) offshore- subtidal estuarine sandstones, sandy shales, and shales with dispersed lignite bands and marls, (ii) silty sandstone interval partly calcareous and grading into sandy-limestone, (iii) Biban sandstone Member with Oligocene-Miocene age which consists of fine- to medium-grained sandstones and siltstones with calcareous nodules and (iv) Kakus Member of this formation with Lower-Middle Miocene age which consists of massive sandstone intervals, laminated clays, and brackish-shales and lignites (Liechti & Haile, 1960).

1.3.4 The West Crocker Formation, Kota Kinabalu (Sabah)

The West Crocker Formation of Sabah occupies part of western Sabah (Collenette, 1957; Stauffer, 1967). It outcrops along the narrow coastal plain and foothills of the Crocker Range fringing the South China Sea (Hutchison et al., 2000). The formation comprises predominantly metamorphosed turbidites and other deep-marine sediments of Oligocene-Early Miocene age (Wilson, 1964). They are generally well-deformed, imbricated and thrust (Leong, 1999; Lee, 1980; Tongkul, 1989).

This essentially siliciclastic succession has been interpreted as flysh, turbidites, submarine fans, and/or “mass-flow” deposits (e.g. Stauffer, 1967; Tongkul, 1989; Crevello, 1998; Hutchison, 2005) of a foreland basin that developed along the Oligocene-Miocene subduction zone along the NW Sabah margin.

An extensive hill-cut in Taman Maju, Sepanggar exposes a huge, steeply dipping to vertical beds of the West Crocker Formation. The succession here is characterized by regular or “rhythmic” interbedding of sandstone and mudstone, within a larger cycle of thinning-upward, fining-upward facies associations. The samples used in this study were collected from this single outcrop.

1.4 Outline of the Thesis

Chapter 1 presents the outline and objectives of this study. In chapter 2, the geological background of the study area is review. Chapter 2 contains the literature review on reservoir facies characterization and petrophysical properties. Chapter 3 discusses the methodology and equipments used in this study. The results of analysis are presented in Chapter 4, while Chapter 5 presents the discussion on the sedimentological, petrophysical, and reservoir characteristics of the samples studied. Chapter 6 summarizes the conclusion and the recommendation for further study.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The aim of this study is to describe, characterize and quantify the reservoir properties of Tertiary sandstones of Sabah and Sarawak by integrating the sedimentary facies characteristics and petrophysical properties. Sedimentary rocks are the result of weathering and sedimentation processes, originating from older igneous, metamorphic and previously deposited sediments that have been broken down physically and chemically. The weathered material is transported as debris and accumulates at the locus of deposition.

One of the most important groups of sedimentary rocks is the sandstones. Sandstones frequently form major aquifers and petroleum reservoirs, with predictable geometry and reservoir performance compared to carbonates. This is because sandstones are more uniform in their facies characteristics and petrophysical properties.

The reservoir is an essential element of the petroleum system and it must be able to accommodate a significant volume of fluids to obtain its hydrocarbon charge and be produced (North, 1985). Some reservoirs are sedimentologically homogeneous and petrophysically isotropic; however most are heterogenous and petrophysically anisotropic. Geophysics, geology, well logging, sedimentology and petrophysics methods are integrated to understand these reservoir characteristics from pore to tectonic and basin scales.

Petroleum in Sarawak and Sabah are produced mostly from the Neogene rocks which occur mostly in the offshore areas of the Sarawak Basin and Sabah Basin. There has been more exploration and production in the north-eastern part of the Sarawak basin. Sabah, which is situated in the northern part of the Borneo Island, has a

complex geological history. The Tertiary continental margin basin of northeastern Borneo comprises both of the Sarawak and Sabah basins.

To understand how the reservoir properties are related to the stratigraphic sequences and depositional processes, their sedimentological and petrophysical characteristics must be known. Integrated sedimentological and petrophysical methods in characterizing sandstone reservoirs had been carried out by many authors (Abdul Hadi, 1995; Castle & Byrnes, 2005; Lima & De Ros, 2003; Reifenstuhel, 2002; Shirley *et al.*, 2003; Walton *et al.*, 1986; Westphal *et al.*, 2004).

2.2 Sedimentology and Facies Characteristics of Sandstones

The term facies refers to all of the characteristics of a particular rock unit. The characteristics of the rock unit come from the depositional environment. Every depositional environment puts its own distinctive imprint on the sediment, resulting in an almost unique facies. Thus, a facies is a distinct kind of rock for that area or environment. Each depositional environment grades laterally into other environments. We call this *facies change* when dealing with the sedimentary rock record.

Sedimentary facies is defined as a unit of rock that is distinguished by its individual sedimentological character. Its individuality is a combination of all or some of the following characteristics such as sedimentary structures, fossil content, lithology, geometry and paleocurrent pattern (Reineck & Singh, 1980; Tucker, 1981; Selley, 2000). Sedimentary facies reflects the physical, chemical and biological conditions and processes of the depositional environment.

2.2.1 Sedimentary structures

Sedimentary structures reflect the hydrodynamic processes during deposition and they are simply divided into primary and secondary classes. Primary structures are those generated in sediment during or shortly after deposition and result mainly from

the physical processes (e.g. current and waves). Examples of sedimentary structures are ripples, cross-bedding and slumps. Secondary sedimentary structures are formed sometime after sedimentation and result from essentially chemical processes, such as those which lead to the diagenetic formation of concretions.

Primary sedimentary structures are divisible into inorganic structures and organic structures (Table 2.1) and the division between the various groups provides a useful framework on which to build the analysis of sedimentary structures (Selley, 1988).

Sedimentary structures can be studied at the outcrop and in cores taken from wells. There are two basic approaches to observe sedimentary structures. The first approach is to pretend the outcrop is a bore hole and to measure a detailed sedimentological log while the second approach is a two-dimensional survey of all, or a major part, of the outcrop.

Table 2.1: A classification of sedimentary structures (Selley, 1988)

I.	Primary (physical)	Inorganic	Fabric Cross-bedding, ripples, etc.	} Microscopic
		Organic	Burrows and trails	
II.	Secondary (chemical)	Diagenetic	Concretions, etc.	

2.2.2 Fossils

Fossil content reflects the ecological processes at the time of deposition. Fossils are usually preserved when they are buried under the layers of sand and mud. The sand and mud become sedimentary rock under great pressure. Minerals seep into the fossil replacing the organic matter and creating a replica in stone. This is how fossils formed. Discovered and undiscovered fossils and fossil-containing in rock formations and sedimentary layers is known as the *fossil record*.

A fossil can be a trace fossil or a body fossil. A body fossil is actually organic material from an animal (bone) or plant. A body fossil is usually composed of the bones

of an animal. Preservation of the "soft" tissue of a body is rare especially over long periods of time. Most body fossils are made when an animal dies and falls, or is washed into a stream, and is covered with mud.

Fossils come in all sizes. The largest are dinosaur bones (which may be ten or more feet in length for a single bone) and the smallest are plant spores only a few hundredths of an inch across. The study of fossils is called *Paleontology*. The study of fossil plants is *Paleobotany*.

Trace fossil

Trace fossils are traces and tracks related to the work of organisms. They include plant rootlets, vertebrate footprints (tracks), trails (due to invertebrates), soft sediment burrows and hard rock borings. If body fossils are not preserved, trace fossils may be the evidence of life in sediment.

The most useful aspect of trace fossils is relationships between its characteristics and the depositional environments. Trace fossils have been grouped based on their environments (ichnofacies) and figure 2.1 shows this grouping.

The landward ichnofacies consist largely of vertebrate tracks, such as footprints of birds and terrestrial animals. However, the preservation potential of such tracks is low. Moving seaward, a well-defined ichnofacies occurs in the tidal zone and it is characterized by simple vertical tubes (*Scolithos*), vertical U-tubes (*Diplocraterion yoyo*) and complex networks of passageways (*Ophiomorpha*). This ichnofacies named *Scolithos* ichnofacies and in this environment the sediment substrate is commonly subjected to scouring current action which often erodes and reworks sediment.

In subtidal and shallow marine environments, *Cruziana* and *Zoophycus* ichnofacies have been defined. *Cruziana* ichnofacies is characterized by the bilobate trails, which have been recorded from fluvial formation (Selley, 1970; Bromley and Asgaard, 1972) and *Zoophycus* is a trace fossil with a characteristic helical spiral generally present at sand/shale interface (Crimes and Harper, 1970).

For deep water environments, the ichnofacies is named *Nereites* and invertebrates live on. The sediment substrate and burrows largely absent in this ichnofacies. Meandriform traces (*Nereites*, *Helminthoidea* and *Cosmorhaphe*) and polygonal reticulate trails (*Paleodictyon*) are characteristic of this facies.

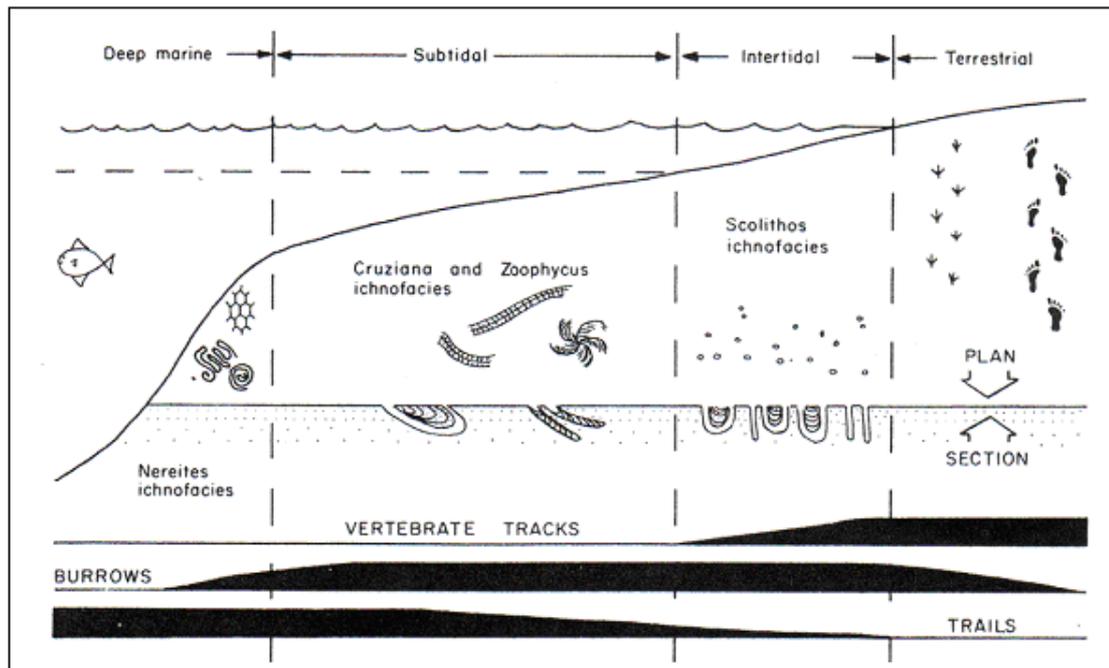


Figure 2.1: Relationship between ichnofacies and environments (Seilacher, 1964; Heckel, 1972; Selley, 1988)

2.2.3 Lithology and texture

Lithology is a function of transportation processes and the macroscopic nature of the mineral content, grain size, texture and color of rocks. The characters of reservoir rocks vary based on their sedimentary textures that are produced by depositional and diagenetic processes. The term texture has a broad meaning and refers to the interrelationships among the population (Krynine, 1948). Texture is also considered as a main factor controlling some petrophysical properties, such as porosity and permeability. The principal elements of texture are grain size and sorting and these elements are the commonly measured elements.

2.2.3.1 Grain size

Grain size is the most fundamental physical property of sediment because grains are the particles which support the framework of a sediment. Sedimentary particles come in all sizes; it is convenient to be able to describe sediments as gravels, sands (of several grades), silt and clay. For many years, the size and distribution of the sand and gravel fractions were determined solely by sieve analyses. After the sieve analyses, the sample is separated into classes or groups. The classes are designated by logarithmic units or phi classes for statistical purposes (Table 2.2).

In general, the grain size of sediments is a sign of the hydraulic energy of the environment. During the transport, movement and sedimentation, grains change their shape which is described by parameters of sphericity and roundness.

Table 2.2: The Wentworth grade scale for sediments (Wentworth, 1922)

ϕ values	Particle diameter (mm diam.)	Wentworth grades	Rock name
-6	64	Cobbles	Conglomerate
-2	4	Pebbles	
-1	2	Granules	Granulestone
0	1	Very coarse	Sandstone
1	0.5	Coarse	
2	0.25	Medium	
3	0.125	Fine	
4	0.0625	Very fine	
8	0.0039	Silt	Siltstone
		Clay	Claystone

2.2.3.2 Sorting

The degree of dispersion of the grain population about the median or mean size is a very important textural parameter. Dispersion is referred to qualitatively as sorting but is expressed quantitatively as standard deviation, i.e. spread of the grain-size distribution. Sorting gives an indication of the depositional mechanism. Sediments deposited with high energy (strong current or waves) are generally poorly sorted; sediments which have been worked and reworked are much better sorted (Tucker, 1981).

Many sedimentology studies have shown that porosity increases with increasing sorting (Fraser, 1935; Rogers and Head, 1961; Pryor, 1973; Beard and Weyl, 1973). Increasing sorting also correlates with increasing permeabilities (Krumbein and Monk, 1942; Beard and Weyl, 1973). A well-sorted grain is about the same size and shape while poorly sorted sand contains grains with different sizes and shapes (Figure 2.2). Figure 2.2 shows the finer grains of the matrix block up both the pores and throat passages within the framework for poorly sorted sediment but well-sorted sediment will have better porosity and permeability.

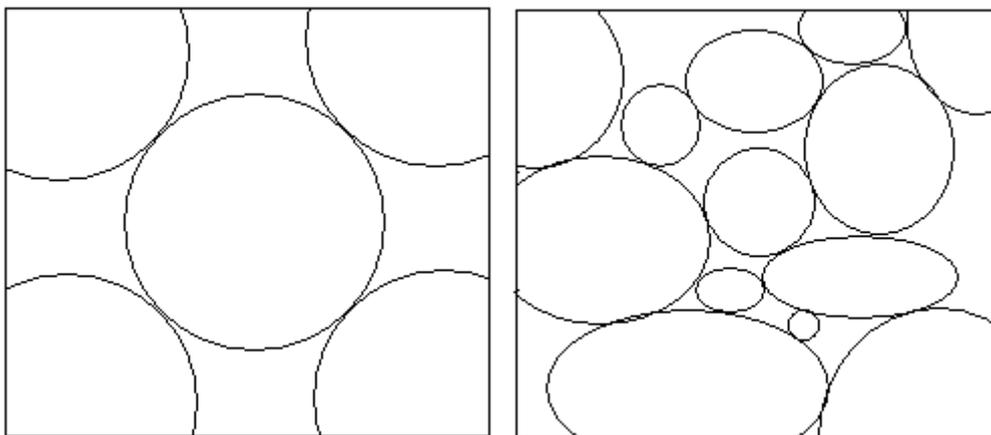


Figure 2.2: A well-sorted sediment (left) and poorly sorted sediment (right)

2.3 Reservoir and petrophysical Properties of Sandstones

Sandstones are common reservoirs for oil and gas, and thus they are a class of sedimentary rocks of great economic importance. Knowledge of their properties is essential in the exploration for, and the production of subsurface fluids. Besides that, it is also essential to understand the reservoir and its capacity for oil and gas production.

Many reservoir studies require that geologic variables be handled in a quantitative manner. For the purpose of analysis it is important to categorize reservoir rock properties so that interrelationships among the variables may be recognized.

Rocks are homogeneous or inhomogeneous in a considered volume; this pair of terms indicates whether the property is a function of local coordinates within the volume or not. The property is the same at every point in the case of homogeneity and it differs for inhomogeneity (Schön, 1996).

Rocks are also isotropic or anisotropic in a considered volume; this pair of terms indicates whether the property is a function of direction or not. The property is equal in all directions and can be used as a scalar in the case of isotropy. The property depends on direction and must be used as tensor with its significant symmetry in the case of anisotropy.

Sandstone reservoirs are deposited in fluvial, eolian and lacustrine environments in non-marine settings, whereas in marine settings, these rocks may be deposited in deltaic, shallow marine and deep marine settings (Morse, 1994).

Petrophysical properties of sedimentary rocks are influenced by porosity, permeability, velocity and density; these properties are partly controlled by facies characteristics which in turn are related to depositional processes. To predict the movement of hydrocarbon in a reservoir, the transport of contaminants in an underground aquifer or weathering processes and stone decay in numerous architectural structures, these petrophysical properties are very important and needed.

The geometry of pore space is described by pore-size distribution, connection and orientation to control reservoir characteristics (Figure 2.3). There are three properties

related to the pore space: porosity, specific internal surface and permeability. These pore-space properties are very complex for rocks. Simple mathematical or experimental models are needed to approximate the pore-space properties of natural rocks (Jordan and Campbell, 1984).

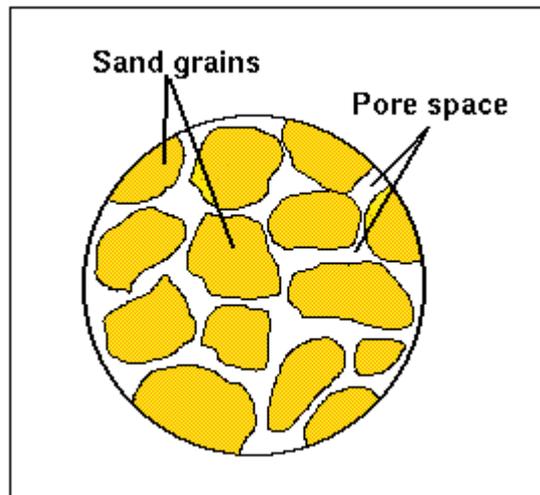


Figure 2.3: The distribution of sand grains showing the pore space

2.3.1 Porosity

Porosity (symbol, Φ) is the ratio of pore space volume, which is not occupied by the solid constituents, to the total volume (Schön, 1996; Selley, 2000). Porosity (Φ) is a dimensionless quantity and expressed either as a decimal fraction or as a percentage.

$$\begin{aligned}\text{Porosity, } \Phi &= (\text{pore volume}) / (\text{total volume}) \\ &= (\text{total volume} - \text{solid volume}) / (\text{total volume})\end{aligned}$$

Serra (1984) gives the following short definition:” Porosity is the fraction of the total volume of a rock that is not occupied by the solid constituents.” Porosity describes the volume of the voids (pores, cracks, fissures, fractures etc.) in relation to the considered rock volume. Sedimentary rocks consist of grains of solid matter with

varying shapes which are more or less cemented, and which there are empty spaces. In this case the rock is called porous (Figure 2.4).

Effective porosity is the amount of mutually interconnected pore spaces present in a rock which is available for free fluids and excludes all non-connected porosity including the space occupied by the clay-bound water. An important distinction must be made between the total porosity of a rock and its effective porosity. Since that the effective porosity is generally economically important, it is determined by most of the porosity measurements.

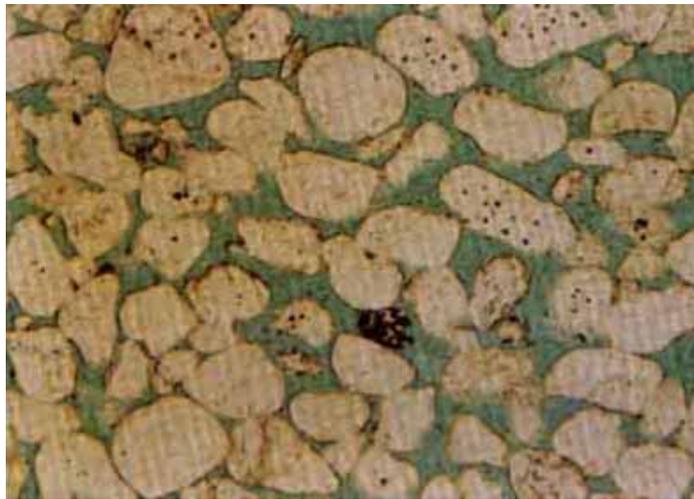


Figure 2.4: A well-rounded and clean sandstone with porosity showing by green colour part

2.3.2 Permeability

Sedimentary rocks consist of grains of solid matter with varying shapes which are more or less cemented, and may be surrounded by voids. The voids are able to contain fluids such as water or liquid or gaseous hydrocarbons and allow them to circulate. This ability of the rock to allow fluids to circulate is called permeability, in the other words; permeability is the ability of the sediment to transmit fluid (Selley, 1998).

Pore throats are the smaller connecting spaces linking pores and providing the more significant restrictions to fluid flow. Permeability describes the property of a porous rock regarding fluid flow through the pore space. In 1856, the French engineer

Henry Darcy found the main relationship to define the laminar flow of a viscous fluid through a porous rock.

$$u = - (k/\eta) \cdot \nabla p \quad \rightarrow \quad k = - \eta \cdot (u/\nabla p)$$

Where u is the volume flow density or flow rate per cross section area; p is the fluid pressure; η is the dynamic viscosity of the fluid and k is the rock permeability.

Permeability is related in a variable and complex way to porosity, pore size, arrangement of pores and pore throats, and grain size. Fine sediments such as clay exhibit low permeability compared to sand and gravel, due to the lack of connection between the pore space and the small size of the pore throat. Grain packing also influences permeability. Open packing shows high porosity and therefore high permeability than closed packing.

2.3.3 Velocity

One of the key factors needed for the successful use of seismic wave velocities in reservoir development, characterization, and recovery is a fuller understanding of what seismic waves can tell about the state of reservoir rocks and the fluids contained in their pore space (Amos and Wang, 1988).

The porous sedimentary rocks generally show lower velocities and a broader range for an individual rock type compared to igneous and metamorphic rocks. Both features are mainly due to the influence of the pore contents with their low elastic parameters. Petrophysical analysis shows a general decrease in rock velocity with increasing porosity (Gregory, 1976).

A study which used ultra sound tool to investigate the relationships between sound wave velocity, grain size, cementing material concentration and rock properties such as porosity, permeability and cementing condition at different confining pressure shows that seismic wave velocity decreases with porosity and mean pore size

increases while velocity increases with cementation and compaction pressure (Al-Homadh & Hamada, 2001).

2.3.4 Density of rocks

Density is defined as the quotient of the mass per unit volume of a material and it is regarded as a fundamental physical property of rock.

$$\text{Density (gm/cm}^3\text{)} = (\text{mass weight}) / (\text{volume})$$

Density is a physical property that changes significantly among various rock types owing to differences in mineralogy and porosity. If the distributions of underground rock densities are known, potentially much information can be learned about subsurface geology (Olhoeft and Johnson, 1989). Laboratory or borehole measurements of density can thus aid in the interpretation of field studies and, especially, gravity surveys.

In common usage, density is defined as the weight in air of a unit volume of an object at a specific temperature; however, in strict usage, the density of an object is defined as mass per unit volume. Weight is defined as the force that gravitation exerts on a body and thus varies with location, whereas mass is a fundamental property, a measure of the matter in a body; and mass is constant irrespective of geographic location, altitude, or barometric pressure. In many instances, such as routine density measurements of rocks, the sample weights are considered to be equivalent to their masses because the discrepancy between weight and mass will result in less error in the computed density than will experimental errors encountered in the measurement of volume. Therefore, density is often determined using weight rather than mass.

With regard to density controlling, the two main groups of sedimentary rocks are pore-free (chemogenic) sediments and porous sediments (the most abundant group, the typical sedimentary rock). Pore-free sediments are formed by chemical processes. In their original state, they are practically pore-free. But it is possible that later processes (mechanical or chemical) can cause "secondary" porosity.

2.4 Geological Background

Sabah and Sarawak states are located on the Borneo Island, East Malaysia. The continental margin of Sarawak forms part of the Sunda Shelf, which structurally connects Borneo with Peninsula Malaysia and the rest of continental Southeast Asia (Mazlan, 1999). Since the early Tertiary, the manifestation of several regional tectonics events happened in Sabah (Leong, 1999). The distinctive tectonic elements in offshore NW Sabah are the Sabah Trough while the NW Sabah Platform covering the Dangerous Ground area in the South China Sea.

Late Cretaceous and Tertiary represent a time of evolution for much of Sarawak, Sabah, and the adjacent continental margins. This evolution was brought about by accretion and amalgamation of linked continental fragments, island-arcs, subduction complexes and associated sedimentation.

Sabah basin is a predominantly offshore Middle Miocene sedimentary basin that situated on the northwestern continental margin of Sabah and overlies the deformed deep-water sediments, which now form the Crocker Formation and Rajang Group rocks in the western part of Sabah. It is subdivided into provinces that characterized by discrete structural and sedimentation histories.

Sarawak basin was defined as the Upper Eocene-Recent sedimentary succession unconformable and overlying the Rajang Group, which consists of highly deformed low-grade metamorphosed deep marine shales, turbidites and etc. (Mazlan, 1999). It is subdivided into several tectono-stratigraphic provinces based on structural styles and sedimentation histories.

2.4.1 Geology of Sandakan Area (Northeast Sabah Basin)

The Northeast Sabah Basin overlies the Labang and older with the age of Miocene-Pliocene (Figure 2.5). Hydrocarbon discoveries have been made in the overlapping areas of Central Sabah and Sandakan sub-basins (Northeast Sabah Basin) mainly in thin sands of Middle and Early Miocene age. Northeast Sabah Basin are formed by NS

to NNE-SSW-trending anticlinal structures and developed with marked vertical relief (Leong, 1999).

The oldest rocks in Sandakan Peninsula are slump breccia and interbedded sequences of mudstone, tuff, tuffite and the sandstones of the Garinono Formation. P. Collenette (1965a, 1966) introduced the term, Garinono Formation to describe a slump breccia deposit exposed west of Mile 16½, Labuk Road. So the oldest rocks in Sandakan Peninsula were deposited in a marine trough in Upper Miocene time. During Pliocene time, uplift, gentle folding and faulting took place in the Sandakan Peninsula and quartz pebbles, silt and carbonaceous clay were deposited during late Pliocene and Quaternary.

Refer to Lee (1970), during the late Miocene; the area now occupied by the Sandakan Peninsula and its adjacent areas was a deep sea basin. Conditions there were unstable and marked by intermittent volcanic activity and earth movements. Similar unstable conditions in the late Miocene are evident in the Dent Peninsula (Haile & Wong, 1965) and may have been widespread in eastern Sabah. It is filled up to 8km of sediments, including the pre-Dent Group (CCOP, 1991).

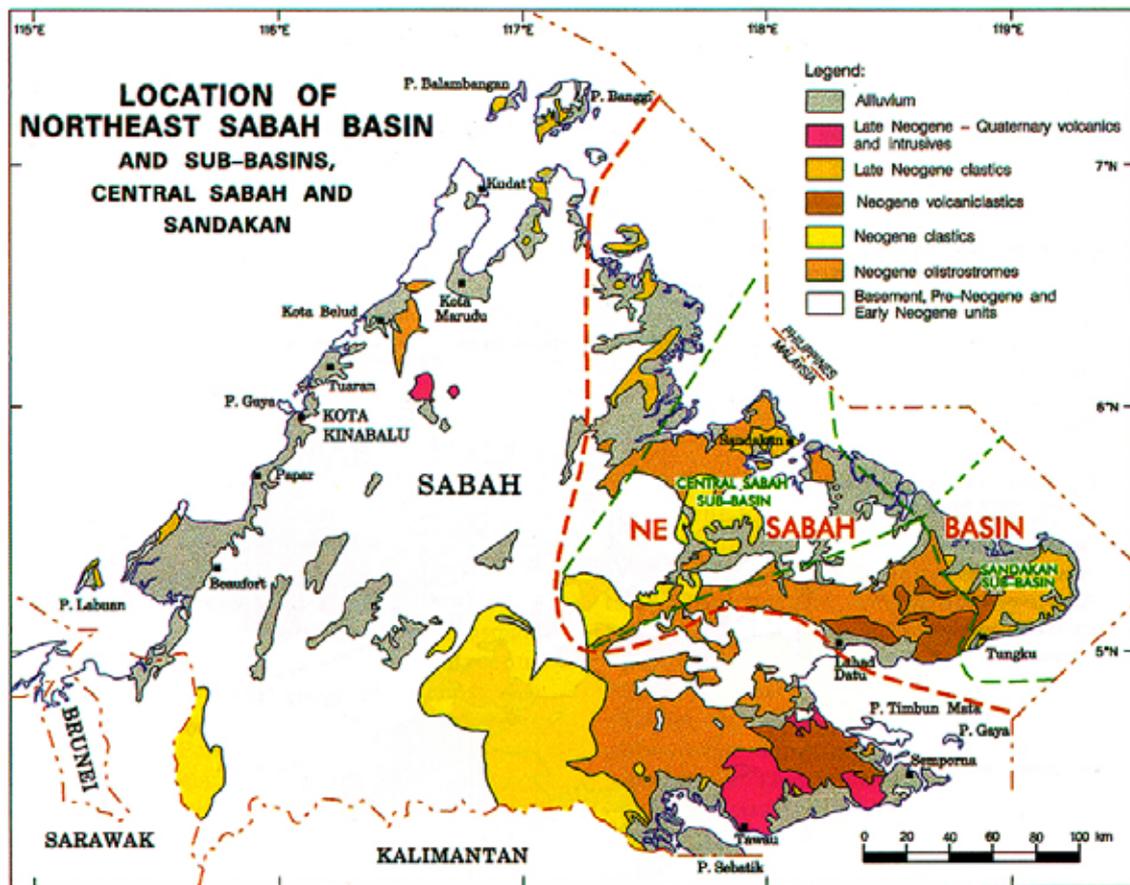


Figure 2.5: Location of Northeast Sabah Basin (Petronas, 1999)

2.4.2 Geology of Kota Kinabalu Area (Sabah Basin)

The Sabah Basin also known as Northwest Sabah Basin and it is a predominantly offshore Middle Miocene sedimentary basin that underlies the continental margin off western Sabah. The complex structural history of the Sabah Basin is the result of multiple phases of structural development that may be local or regional in nature. It was formed on the southern margin of a foreland basin that resulted from the collision between the NW Sabah Platform and western Sabah during the early Middle Miocene (Mazlan *et al.*, 1999).

Hydrocarbons in the Sabah Basin are essentially very similar in composition and have originated from source rocks rich in mainly terrigenous organic matter (Scherer, 1980; Awang Sapawi Awang Jamil *et al.*, 1991; Abdul Jalil Muhamad *et al.*, 1992;

Azlina Anuar, 1994; Azlina Anuar *et al.*, 1997). The majority of rock samples in Sabah Basin regardless of formation contains essentially terrigenous organic matter and has poor to fair hydrocarbon-generating potentials. Furthermore, samples of the Eocene and Oligocene Crocker Formation are generally mature to late mature (Mazlan *et al.*, 1999).

Mainly, the hydrocarbons accumulations have been found and produced from siliciclastic reservoirs. The reservoirs range from coastal/shallow-marine sediments to deep-marine turbidites and are found in structural/stratigraphic traps including extensional growth fault structures and wrench-related compressive anticlines (Mazlan *et al.*, 1999). In general, lower coastal plain facies have better reservoir quality (higher permeability) and tend to form thicker reservoir than the fluvio-marine facies while reservoirs of fluvio-marine facies tend to have better lateral continuity (Scherer, 1980).

2.4.3 Geology of Miri Area (West Baram Delta)

The geology of Miri is considered as a part of the Tertiary continental margin of Northwest Borneo Basins. The Baram Delta Province is roughly in triangular shape, extends offshore and onshore in northeast-southwest direction lying on both sides of northeastern Sarawak and western Sabah including Brunei water. Towards southwest, the province extends into the northeastern coastal area of Sarawak, which is named as West Baram Delta (Tan *et al.*, 1999).

West Baram Line is marked as western margin of the Baram Delta. It separates the delta from the old Balingian and Central Luconia Provinces to the west. Morris Fault – Jerudong Line is the eastern margin of the Baram Delta and it separates the delta from the older, intensely tectonised Inboard Belt of offshore NW Sabah (Figure 2.6).

The West Baram Delta is characterized by the deposition of a northwestward prograding delta since Middle Miocene times. Growing in sedimentary section thickness was accompanied by growth faulting trending in NE-SW direction towards the west of Baram Delta (Mazlan, 1999; Tan *et al.*, 1999) (Fig 2.7).