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PROPERTIES OF RESERVOIR QUALITY ROCKS OF THE BELAIT AND LAMBIR FORMATIONS, NORTH EAST SARAWAK

by

MOHD SYAMIM RAMLI

The undersigned certify that they have read, and recommend to the Postgraduate Studies Programme for acceptance this thesis for the fulfilment of the requirements for the degree stated.

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PROPERTIES OF RESERVOIR QUALITY ROCKS OF THE BELAIT AND LAMBIR FORMATIONS, NORTH EAST SARAWAK

By

MOHD SYAMIM RAMLI

A Thesis

Submitted to the Postgraduate Studies Programme
as a Requirement for the Degree of

MASTERS OF SCIENCE

GEOSCIENCE AND PETROLEUM ENGINEERING DEPARTMENT

UNIVERSITI TEKNOLOGI PETRONAS
BANDAR SRI ISKANDAR

PERAK

MARCH 2012

DECLARATION OF THESIS

Title of thesis	PROPERTIES OF RESERVOIR QUALITY ROCKS OF THE BELAIT AND LAMBIR FORMATIONS, NORTH EAST SARAWAK.

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ACKNOWLEDGEMENT

My deepest appreciation goes to Ministry of Higher Education (MOHE) Malaysia through Fundamental Research Grant Scheme for the funding provided during this entire study. Assoc. Prof. Dr. Eswaran Padmanabhan for the supervision and constant encouragement throughout the course of this study. Without his guidance and persistent help this dissertation would not have been possible. Thank you so much Sir, for pushing me beyond my limitations, for being a true friend, a mentor and a father. I would also like to thank Assoc. Prof. Wan Ismail Wan Yusoff, my co-supervisor for the support and brilliant advices given during our discussion sessions.

Thanks to all the lecturers at the Petroleum Geoscience Department for the advices and supports during my entire two years stay at the university. Special thanks goes to Assoc. Prof Dr. Hadi Abd. Rahman, Assoc. Prof. Dr. Abdelaziz Lotfy, Assoc. Prof Askury Abd. Kadir, Assoc. Prof. Dr. Chow Weng Sum, Assoc. Prof. Dr. Swappan Bhattacharya, Assoc. Prof. Dr. Zuhar Zahir Tuan Harith, Mr. Jasmi Ab. Talib , Dr. Aaron Hunter and Dr. Hilfan for their positive criticism and advices either during symposium sessions or in one of our casual meetings. Thanks to various technologists, especially at Geoscience and Petroleum Engineering Department (you guys are the best, period) for the limitless help and ideas, and all other departments for lending me a hand whenever I am in need. Assoc. Prof. Dr. Zauyah and Mrs. Zarina at Department of Soil Science, Universiti Putra Malaysia are thanked for their hospitalities during my stay at their labs.

Last but not least I would like to convey my deepest gratitude to my parents for their endless supports and prayers everyday and every time.

Syamim Ramli.

DEDICATION

"For a friend and a father that I'll never have the
chance to speak with, again – May you all forever be at peace, Jannah.
Al-fatihah."

ABSTRACT

This study was conducted to evaluate the field characteristics, mineralogical, physical and geochemical properties of the Early to Late Miocene Belait Formation in Marudi and the Early to Middle Miocene Lambir Formation in Miri, Sarawak at various scales of observations and to provide a key differentiation between these two formations. Representative samples were collected at Marudi, Northern Sarawak (Belait Formation) and nearby Miri, Sarawak (Lambir Formation). Field observations suggested that there are at least four differentiating characteristics between these Formations. The four major differentiating characteristics are; microfabric analysis revealed that the Belait Formation consists of angular to sub-angular grains whereas the Lambir Formation has sub-rounded grains. Presence of mudclasts in the Belait Formation suggests deposition in a low energy, muddy environment with short transportation. Extensive fracturing of the quartz grains in the Belait Formation suggests variations in the degree of compaction resulting from differences in thickness or rates of diagenesis. This suggests the presence of geopressure anomalies in the Belait Formation; a feature that is probably absent in the Lambir Formation. Tremendous spatial and temporal variability of hydrocarbons was detected in both formations. Mineralo-chemical observation indicates a dominance of aliphatic components in the Lambir Formation whereas Belait Formation is dominated by aromatic components. Both intra- and inter-formation variations in hydrocarbon components exist in the formations evaluated. Aryl-olefins (C=C) aromatic compounds were present in all samples with peaks occurring at around the 400-600cm^{-1} region. This compound was frequently detected and with transmittance as low as 30% in the Belait Formation samples. Aliphatic compounds such as CH, CH_2 and CH_3 were found more frequent in the Lambir Formation samples with varying transmittance values. Heterogeneity in the distributions of hydrocarbon between both formations suggests that different rates of migration might occur within the reservoir quality rocks of both formations. This indicates differences in show type between both formations. The qualities of the hydrocarbon shown in the Lambir Formation samples are comparable to a Type-I or Type-II class reservoir rocks while the hydrocarbon in the Belait Formation samples are comparable to a Type-III. A differentiation key that could distinguish the Belait and Lambir Formation is proposed at the end of the study to aid future researchs.

ABSTRAK

Formasi Belait yang berusia awal sehingga lewat Miosen di Marudi, Sarawak terdiri daripada selang lapis heterolitik di antara lapisan pasir dan lumpur manakala Formasi Lambir (awal ke pertengahan Miosen) di Miri, Sarawak terdiri daripada selang lapis di antara batu pasir masif yang berbutir halus hingga sangat halus dengan syal kelabu. Persamaan jelas kedua-dua Formasi dapat dilihat bukan sahaja pada rentasan seismik malah di lapangan. Walaupun perbezaan sekitaran pengenapan telah dinyatakan dalam terbitan-terbitan utama namun, kedua-dua Formasi tetap sukar untuk dibezakan. Eksplorasi semasa untuk pencarian minyak dan atau gas di blok SK333 yang melibatkan kedua-dua Formasi telah mengembalikan perhatian untuk mengkaji semula geologi formasi-formasi ini. Sehubungan dengan itu, kajian ini telah di laksanakan bagi menilai ciri-ciri lapangan, mineralogi, fizikal dan sifat-sifat geokimia kedua-dua Formasi pada pelbagai skala dan pemerhatian bertujuan untuk menyenaraikan sifat-sifat utama bagi membezakan formasi-formasi ini. Persampelan untuk Formasi Belait telah dilakukan di Marudi yang terletak di Sarawak utara. Manakala sampel Formasi Lambir telah dikutip di sekitar bandar Miri, Sarawak. Pemerhatian di lapangan menunjukkan bahawa terdapt sekurang-kurangnya empat perbezaan utama di antara kedua-dua Formasi. Analisis mikrofabrik menunjukkan Formasi Belait mempunyai tekstur butiran bersegi ke separa-bersegi manakala Formasi Lambir mempunyai butiran berbentuk separa-bundar. Kehadiran klas-klas lumpur di dalam Formasi Belait mencadangkan kemungkinan pengendapan formasi ini di pengaruhi oleh sekitaran yang berlumpur dengan tenaga rendah serta mengalami proses pengangkutan singkat. Rekahan butiran quarza secara ekstensif pada batu pasir Formasi Belait mencadangkan kemungkinan terdapatnya variasi semasa proses pemampatan disebabkan oleh perbezaan di antara jumlah ketebalan batuan atau perbezaan kadar diagenesis yang di alami kedua-dua Formasi. Sifat-sifat ini mencadangkan kehadiran anomali *geopressure* yang mungkin hanya dialami oleh batuan Formasi Belait. Variasi ruang dan masa yang luas di dalam kandungan hidrokarbon juga dapat di lihat pada sampel kedua-dua Formasi. Walaupun Formasi Belait pernah dianggap sebagai formasi yang tandus namun kajian yang dilakukan

menunjukkan bahawa hidrokarbon dilihat dapat hadir dalam pelbagai keadaan. Pemerhatian terhadap sifat-sifat mineral-kimia menunjukkan bahawa Formasi Lambir didominasi oleh hidrokarbon jenis alifatik bertentangan dengan Formasi Belait yang didominasi oleh hidrokarbon jenis aromatik. Perbezaan kandungan hidrokarbon ini bukan sahaja dapat dilihat di antara kedua-dua Formasi, malah dalam setiap formasi yang dikaji. Kehadiran sebatian aromatik olefin (C=C) dapat dilihat pada kebanyakkan sampel pada puncak di sekitar rantau FTIR 400-600cm^{-1}. Sebatian ini kerap dikesan pada sampel Formasi Belait dan dilihat mempunyai transmitans serendah 30%. Sebatian alifatik seperti CH, CH_2 dan CH_3 pula lebih kerap dijumpai di dalam sampel Formasi Lambir dengan kadar transmitans yang berbeza-beza. Kepelbagaian dalam kualiti hidrokarbon antara kedua-dua Formasi ini mencadangkan bahawa masa dan kadar penghijrahan hidrokarbon di dalam batuan kualiti reservoir kedua-dua Formasi adalah berlainan. Kualiti hidrokarbon dalam sampel Formasi Lambir adalah setanding dengan batuan reservoir jenis-I atau jenis-II manakala hidrokarbon dalam sampel Formasi Belait boleh dibandingkan dengan batuan reservoir jenis-III. Senarai perbezaan utama bagi membezakan antara Formasi Belait dan Lambir telah dicadangkan di akhir kajian ini bagi membantu pengkaji-pengkaji yang berminat untuk meneruskan kajian terhadap Formasi-Formasi ini dimasa hadapan.

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CHAPTER 1

INTRODUCTION

1.1 Chapter Overview

This chapter will provide the general overview for the entire work. It includes the study background, problem statement and the objectives to generally give clarifications regarding this research.

1.2 Background of Study

Rock characterization study has been performed widely for different purposes in the oil and gas industry. Much of the rock characterization studies rely heavily on the rock properties itself in order to distinguish one rock from other rocks. Properties such as carbon contents, porosity, permeability, thermal properties, and mineralogical properties of a rock are of particular interest in the industry especially during the exploration and production level. Rock typings, reservoir properties, reservoir predictions, source rock characterization are some of the areas which benefited from the rock characterization studies [1, 2].

The region of Borneo has been producing oil and gas since 1903, the first exploration well in Malaysia, Miri 1 was drilled around Miri Hills area in 1910 [3, 4]. Complexity in the geology of Sarawak has been highlighted by Liechti et. al. [4] in detailed. The authors stated that the investigation of the area stratigraphy presents special problems. These problems arise due to either rapid lateral changes of lithofacies and observations of lithological uniformity over great distances and thickness between the rocks. Other stratigraphic complexities are due to structural control of deposition, the almost complete absence of macro-fossils, the comparative scarcity of paleontological and lithological markers, and extensive reworking of microfossils. On regional scale, Murphy [5] in Hutchison [3] has concluded that the evolution of Southeast Asia has not been satisfactorily handled.

Petroleum system is a natural system which consists all of the geologic elements and processes (source rocks, migration, reservoir rocks, trap and seal) that are essential for a hydrocarbon accumulation to exist [6]. The reservoir rocks are defined as a body of rock having sufficient porosity and permeability to store and transmit fluids [7]. Sandstones are the most common being a reservoir as they have more porosity than other types of rocks and form at temperature conditions at which hydrocarbon is preserved [7].

It has been estimated that about half of the world's available reservoir for oil and gas occurred in clastic sediments. Understanding the properties of these rocks will yield great knowledge in contributing to as how their properties strongly influence the reservoir qualities [8]. The sandstone reservoir primary properties (texture, composition, sedimentary structures, morphology and stratigraphy heterogeneity) are mainly controlled by the source materials, weathering, transporting agents, and its depositional environments. These primary properties can be directly linked to the production performance of a reservoir [8, 9].

In a petroleum system, the source rock provides the oil and gas. The source rock has substantial amounts of fossilized organic matter incorporated into the sediment during deposition [2, 10, 11]. The organic matter is mainly derived from algal, bacterial and higher plant tissues. A rock can be termed as a source rock, provided that its organic matter content is least 1-2% by weight of the rock.

1.3 Problem Statement

Lambir Formation (Early to Mid Miocene) and the Early to Late Miocene Belait Formation are time-equivalent geological formations in northern Sarawak. Although the depositional environments of these two Formations are known to be different [3, 4], distinguishing both formations is challenging. Current exploration in the SK333 block for oil and / or gas [12] that represents both formations has revived the interests on the geology of the formations.

Therefore this research aims to distinguish both formations at various scales of observation. As a consequence of this characterization work, an enhanced understanding of the nature, properties and behaviour of the reservoir rocks would be obtained.

1.4 Research Objectives

The purpose of studying the characteristics of sedimentary rocks from North-eastern Sarawak, East Malaysia is to investigate the properties of these rocks as part of the area petroleum system. Therefore, the objectives of this study are as follows:

i. To observe the sedimentary features of both formations in the field.
ii. To further evaluate both formations based on their physical, mineralogical and geochemical properties in order to characterise the properties of these reservoir rocks.
iii. To develop a differentiation key that will assist in distinguishing the two formations from each other.

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

i. Field observation / study of selected outcrops in these two formations.
ii. Laboratory petrophysical analysis, mineralogy and geochemical analysis.

1.5 Research area

The study was conducted on onshore sedimentary rock outcrops in Marudi and Miri, Sarawak (Fig. 1.1). The study areas in Marudi include the town itself and the area near Sarawak-Brunei border. The study was also conducted in Miri at Tusan Beach (in between Bakam and Bekenu), Kampung Kuala Masjid beach and on outcrops along Jalan Miri – Bintulu.

1.6 Scope of Work

This study aims to differentiate both formations at various scales and attempts to characterize the Formations based on their nature, behaviour and properties as reservoir rocks. The scope of the study is as follows:

1.6.1 Fieldwork and Sample Collection

Fieldwork was conducted for the Belait Formation in Marudi and the Lambir Formation in Miri. Both Formations were identified at the field based on the geological maps and literatures from previous researchers [3, 4, 13-15]. The field characteristics of these outcrops will be the first basis of characterisation work for these two formations. Fresh, indurated samples were collected in order to further characterize the formations.

1.6.2 Characterization Works

Laboratory analysis was performed to study the properties of rocks from both formations, including petrophysical, mineralogical and petrographical as well as geochemical characterization.

1.6.3 Records and Documentation

The results from this comprehensive study will be analyzed and documented and as to satisfy the objectives, a characterisation key to differentiate these formations would be developed and their characteristics as reservoir qualities will be examined.

1.7 Organization of Thesis

This dissertation is subdivided into five chapters. The introduction chapter describes the research background related to the two Formations and highlights the differences between these two formations and the need to distinguish them. Problem statement of this research, the objectives of the work and scope of study were also clarified in this introductory chapter.

Chapter two contains the literature review for this this dissertation. Brief explanations and theoretical concept related to this study is discussed here. Critical issues and important related research works done in the past is also evaluated here.

Chapter three presents the general methodology and the list of samples used for the study. The features of each outcrop and characterisation techniques performed on each category are also discussed throughout the chapter.

Chapter four discusses the findings of this study. It is divided according to the various types of characterization starting with the field description to the geochemical characterization of the formations. The last section of this chapter evaluates the properties of the two formations as a reservoir quality rocks.

Each section from this chapter was either presented in local or international conferences, including the International Petroleum Technology Conference (IPTC) 2011 or journal. The final section of this chapter (section 4.7) has been submitted to a journal. The detail of this is as follows:

- **Section 4.2** – Some Field Differentiating Characteristics between the Belait and Lambir Formations, North Sarawak – *Presented at Petroleum Geology Conference and Exhibition (PGCE) 2011.*

- **Section 4.3** – Differentiation of the Microfabrics of Sediments in a Fluviatile Grading to Shallow Marine Setting in North-eastern Sarawak – *In preparation for submission in a journal.*

- **Section 4.4** – Spatial and Temporal Variability of the Hydrocarbon Distributions in the Belait Formation, North Sarawak – *Presented at National Geoscience Conference (NGC) 2010.*

- **Section 4.5** – Spatial and Temporal Variability of the Hydrocarbon Distributions in the Lambir Formation, North Sarawak. –*.Submitted to International Conference on Integrated Petroleum Engineering and Geosciences (ICIPEG) 2012*

- **Section 4.6** – Heterogeneity of Hydrocarbon Distribution in Tertiary Sediments of North-eastern Sarawak – *Presented at International Petroleum Technology Conference (IPTC) 2011.*

- **Section 4.7** – Differentiating between a Fluviatile–Shallow Marine Settings in the Tertiary Sediments from North-eastern Sarawak – *Submitted to Journal of Petroleum Geology (JPG), UK.*

The final chapter provides conclusions gained from this research works. The major outcomes, which answer the objectives are summarized to create a differentiation key in order to distinguish between the Lambir and Belait Formation in the field. Recommendations for future works are also proposed.

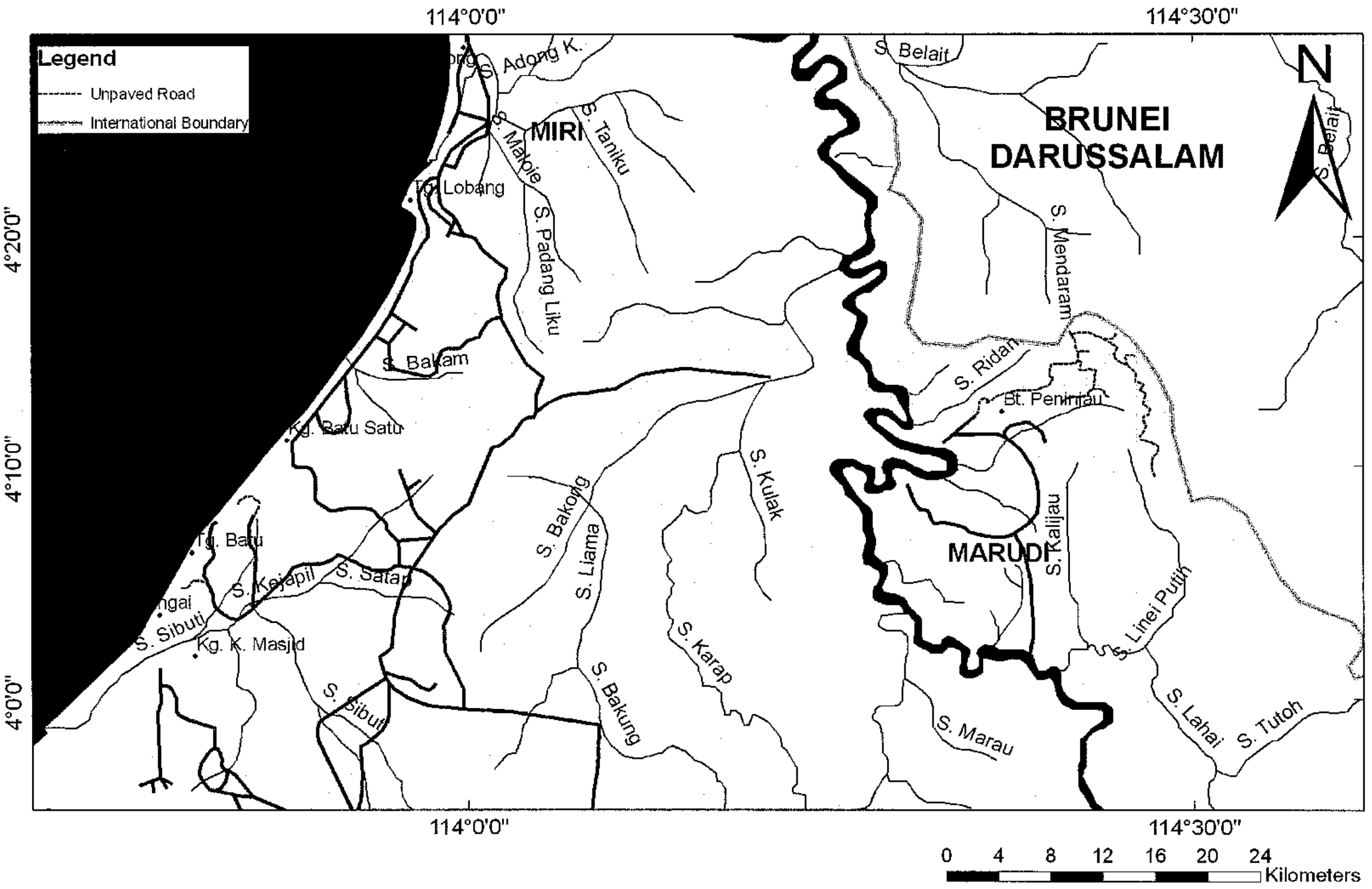


Fig. 1.1 – Location map of the study area.

CHAPTER 2

LITERATURE REVIEW

2.1 Chapter Overview

This chapter will review the literature materials pertinent to this study. It is divided into four sections mainly; geological background of the area, physical characterization, mineralogical characterization and geochemical characterization.

2.2 Geological Background

Sarawak is located on the Borneo Island, East Malaysia. The continental margin of Sarawak forms part of the Sunda Shelf which structurally connects Borneo with the western part of Malaysia and the rest of continental South East Asia [3]. Earlier knowledge regarding the Sarawak geological background was mainly interpreted in terms of the geosynclinal theory [4, 16] before currently being replaced by recent concept relating to the understanding of the plate tectonic. Tectonic association of Borneo Island began with the compilation of Hamilton [17] from his analysis and access to unpublished data from oil companies and has been further studied by various authors [18-28].

The Sundaland foreland buried beneath the South China Sea [3, 26, 29], which is a requirement for a geosynclinal theory to work, does provide us the organizational pattern of the Sarawak geological concept. Hutchison [3] also stated that the four-fold division as proposed by Haile [16, 30] remained valid.

Haile [16, 30] divided Sarawak into four different zones. Namely The Miri Zone, The Sibu Zone, Kuching Zone and West Borneo Basement (WBB). The last zone (WBB) was later renamed in Hutchison [29] as the Pontianak Zone based on the area it occupies. The last subdivision, Pontianak Zone is the southernmost part of the division. It is dominated by Cretaceous volcanic and plutonic rocks that constitute the Schwarner Mountains [31] as well as outcrops from Carboniferous – Permian basement rocks [3, 30]. A more recent map of the geological pattern of Sarawak (Fig. 2.1) has been produced by Hutchison [3].

The most northerly Miri Zone was described by Haile [30] as miogeosynclinal (shelfal part) and molasse (late- or post orogenic) strata deposited upon older continental crusts. The second division which is seperated by the Tatau-Mersing line (Hutchison, 1989) from the first division is known as the Sibu Zone. It is dominated by eugeosynclinal flysch, or thick monotonous sequence of shale/sandstone turbidites which has been deposited upon oceanic crusts [30]. The turbidites flysch was uplifted during Late Eocene [3] which also resulted in several other uplifts `1(Sarawak Orogeny) during the collision between the Luconia Block with the Sarawak margin.

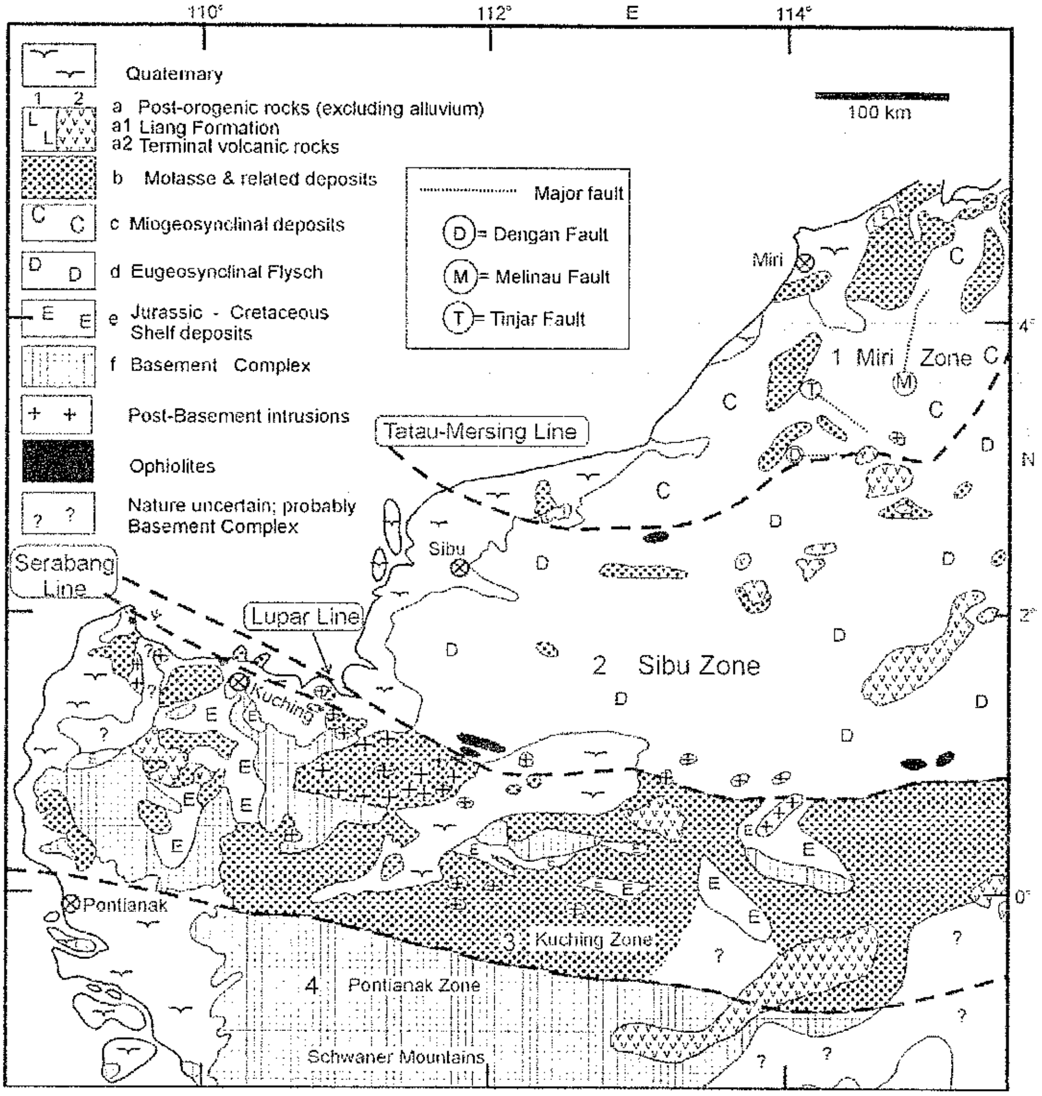
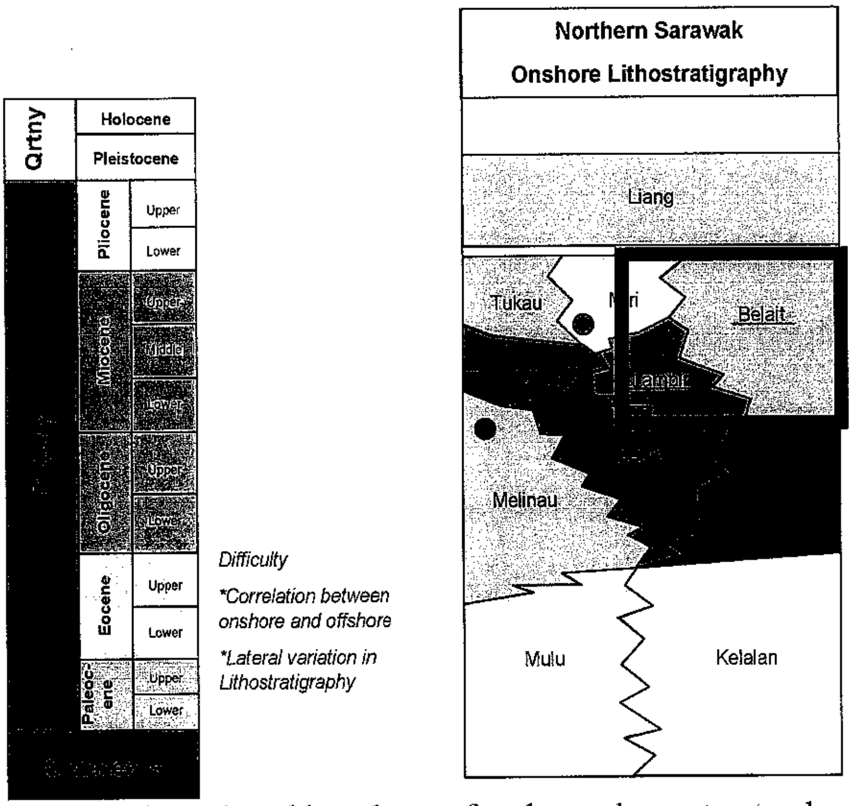


Fig. 2.1 - The structural zones of Borneo (from Hutchison [3]).

2.3 General Stratigraphy

The Miri Zone (Fig. 2.2) is divided into the central part and northern part of Sarawak. It is separated from the Sibu Zone by the Tatau – Mersing line which is a structurally complex zone consisting of Paleocene and Eocene ophiolitic rocks, including spilite, basalt, tuff and radiolarian chert [23].



Difficulty

**Correlation between onshore and offshore*

**Lateral variation in Lithostratigraphy*

Fig. 2.2 – Generalized stratigraphic columns for the onshore structural provinces of Sarawak [32]. The red box indicates the time-stratigraphic position of interested Formations (Belait and Lambir Formations).

2.3.1 The Belait Formation

The Belait Formation which is found in North Sarawak represents the Lower–Upper Miocene age in the northern sector of the Miri Zone. Thickness of the formation is estimated to be around 20,000 feet (6096 meters) thick [33]. In most area, the Belait Formation overlies the Setap Shale Formation conformably, or with slight unconformity [4, 33]. The relationship between the Belait Formation and Setap Shale Formation is somehow highly diachronous as the junctions between both formations rise towards the north by means of lateral wedging out of basal Belait Formation beds and intergrading to the Setap Shale Formations [4, 33]

The formation consists of conglomerate and pebbly sandstone at the base, passing upwards into alternating sandstone, shale and coal [3,4, 33]. Haile [34] suggested that Belait Formation was deposited in littoral to deltaic conditions in local isolated basins.

The sandstones have been described as mostly fluviatile [3, 4]. The lignites, cross-bedding and ripple marks, in combination with some foraminiferal micro-faunas (alternating with mostly barren strata) in some area, indicate clearly a paralic environment temporarily and locally developing into shallow marine i.e. littoral conditions [4]. Towards the coast the environment changes into fully marine, the Belait Formation merges gradually into the more marine Lambir or Miri Formation or the uppermost part of the Setap Shale Formation [4].

2.3.2 The Lambir Formation

The Lambir Formation (Middle–Upper Miocene) occupies about 220 square miles in the Lambir Hills, Bakong area, Teraja area and south-east of Marudi [27, 33, 34]. The formation is believed to be the more marine time-equivalent of the Belait Formation as they resemble nearly similar lithology [3, 4, 33]. Thickness of this Formation at Lambir Hill is estimated to be around 7000 feet [4, 33]. The Formation consists predominantly of sandstones and alternating shales with minor limestone and marl in some places [4, 27, 33, 34].

In the Lambir Hills, the base of the formation consists of sandstone and shale with locally abundant limestone lenses. Overlying this are shale, marl, thin limestone lenses, calcareous sandstone and sandstone, passing upwards into sandstone and shale [34]. The sandstones are fine to medium grained and lignitic with thin beds and are increasingly less consolidated towards the upper part of the formation, which consists of sandstones alternating with shales and clays, partly coarse grained or gritty, with quartz pebbles only [3, 4, 33, 34]. In the Ridan area northeast of Marudi, the Lambir Formation consists of regular alternations of sandstone and sandy clay, the sandstones are generally cross-bedded, medium-grained to coarse-grained and contain lenses with small quartz grains [3, 4, 34].

Depositional environment of the formation was more marine than during the deposition of the Belait Formation. Biohermal limestones indicate inner neritic to littoral conditions which towards the top became entirely littoral, as indicated by an increase in sandiness and lignites. The present of microfauna also indicates shallow marine conditions [4].

2.4 Physical Characterization

The physical characterization involved characterizing both Formations in terms of their physical properties. In this section, the porosity – permeability concept is explained along with the surface area and thermal conductivity of the rocks.

2.4.1 Porosity

Sandstones can easily act as a reservoir rock if the porosity inherited during deposition and throughout the diagenesis process was retained. Porosity (ϕ) is defined as the ratio of pore space volume, which is not occupied by the solid constituents, to the total volume [35]. Porosity can be expressed either as a decimal fraction or as a percentage.

$$\text{Porosity } (\phi) = [(\text{Pore Volume}) / (\text{Total Volume})] \text{ X } 100$$

(Equation I)

A sedimentary rock is considered porous when the rock consists of empty spaces located between the varying shapes of grains which are more or less cemented. Effective porosity is the amount of mutually interconnected pore spaces present in a rock [35, 36]. Presence of effective porosity creates permeability [35].

Generally for a reservoir rock, the most important factors that are affecting porosity are its depth of deposition and diagenesis of the rocks. This is mainly due to compaction [35-37]. It has been observed that porosity of a rock decreases with increasing depth, whereas porosity increases with better grain sorting, increasing grain size and decreasing clay minerals content [35].

Mercury porosimetry is an extremely useful characterization technique for porous materials as pores between 500μm to 3.5nm can be investigated [38]. Mercury porosimetry also provides a wide range of information, e.g. the pore size distribution, the total pore volume or porosity and specific surface area of the pores [39]. The principle of mercury porosimetry is based on the physical principle that a non-reactive, non-wetting liquid will not penetrate pores until sufficient pressure is applied to force its entrance [38]. Mercury is a non-wetting liquid for almost all substances and consequently it has to be forced into pores of the interested materials. Pore size and volume quantification are accomplished by submerging the sample into a confined quantity of mercury and then increasing the pressure of the mercury forcing it into the samples.

2.4.2 Permeability

Permeability is the ease of flow of fluids through rocks (by means of its void). It is a function of the pore size and shape, pore throat and/or channel diameter, grain size and shape, grain packing density, tortuosity, sorting, cementing, fracturing, and residual fluid saturation.

For a reservoir, the voids must be able to contain economically interested fluid or gas and allowing them to circulate and permeability in this case can be defined as the ability of the rocks to transmit fluid. Fine sediments such as clay exhibit low permeability compared to sedimentary rocks with larger grain sizes due to lack of connection between the clay particle fragments which are very tightly arrange.

Beside other petrophysics properties of a rock (i.e. bulk volume), permeability and porosity are used extensively as part of the rock characterization process during reservoir analysis studies in order to decide whether a prospect is economically viable to proceed.

2.4.3 Thermal Conductivity

Successful reconstruction of the paleotemperature in sedimentary basins requires detailed knowledge of the rock thermal properties, especially the thermal conductivity [40]. Paleotemperature regime of sedimentary basin is important to petroleum prospectivity for a number of reasons: (i) it controls the generation, expulsion and migration of hydrocarbons; (ii) it affects the viscosity of the hydrocarbons through time; (iii) it governs the rate of diagenetic reactions that is important to the physical properties of rocks in the basin [41]; and (iv) it influences the basin subsidence [42]. Heat flow data tell whether or not the rock has been buried to sufficient depth to have been in the "oil generation" window long enough for breakdown of organic materials and convert to become petroleum. In other words, if the rocks in a basin do not exhibit the properties expected for sufficient thermal maturity to have been reached, no petroleum can be expected to have been generated by source rocks in the basin.

Thermal conductivity of rocks can be determined based on Fourier's Law of conductivity (Equation II). It is usually expressed in $Wm^{-1}K^{-1}$.

$$\Delta Q/\Delta t = [\kappa A\ (T_1 - T_2)]\ /\ l$$

(Equation II)

Where by:

ΔQ = Heat flow

Δt = Time taken

K = Thermal Conductivity

A = Cross sectional area of the object

T_1-T_2 = Difference in temperatures between the two ends

l = Distance between the two ends

Thermal conductivity of sedimentary rocks is controlled by porosity; mineralogy and texture [43]. Of the most important factors, the later is the most difficult to measure because of its complexity with grain size and grain-size distributions [43].

Thermal conductivity can be measured in the laboratory on rock samples with the most prominent methods being the "divided bar" and "needled probe" [44]. The controlling factors of thermal conductivity in sedimentary rocks are porosity and its provenance [45]. Chemical sedimentary rocks formed by precipitation of dissolved materials or compaction of organic matter, and low porosity (less than 30 percent) physical sedimentary rocks formed by compaction and cementation of clastic materials have nearly similar thermal conductivity value ranges [45].

Similarly to other rock properties, thermal conductivity is characterized by a broad range of values within one rock type [45]. This range is primarily controlled by variations in mineral content, pores and cracks, their thermal properties and their volume fractions and spatial distributions within the rock [36]. Generally, the thermal conductivity increases with decreasing porosity [36, 45], increasing water content and improvement of grain bonds or cementation. Decreasing grain size increases the number of grain contacts per unit volume and thus, decreases thermal conductivity.

Study by Masnan et. al. [46] on thermal conductivity of shale and sandstone samples from Belait Formation suggested that thermal conductivity values drop in great values with increasing porosity of up to 10% and subsequently increases fairly after that point of porosity. These variations are attributed to porosity reductions and overburden pressure experienced by these samples. The thermal conductivity values also decreased at the clay-silt grain size range and continued to decrease until particle size approached range of fine sand. The thermal conductivity values then remained constant with particle size larger than very fine-grained sand. The authors then concluded that there is an inverse relationship between the thermal conductivity and porosity and particle size of the studied samples. These relationships are attributed to variations in the internal fabrics.

2.4.4 Surface Area Analysis

Surface area determines many physical and chemical properties of a material. Clays, soils and sediments vary widely in their reactive surface area because of mineralogical and organic composition and in particle size distribution. Such properties as water retention and movement, cation exchange capacity are closely related to the surface area [47]. Surface area is usually expressed in square meters per gram (m^2/g).

Substantial specific surface area in clay minerals has made this analysis very useful in characterizing the type of clay present. Nonswelling minerals, such as kaolinite, have only external surface, whereas swelling minerals like monmorilonite have a great deal of internal as well as external surface [47]. Natural clay deposits can have a wide range of total surface area since the combination of external and internal surface areas may vary simply because of the mixed layer minerals that may exist and the variations found in clay mineralogy of a sample.

Characterization of sedimentary rocks based on their clay minerals contents using the Ethylene Glycol Monoethyl Ether (EGME) method [47-49] can be proved useful because of the extreme differences in surface area properties between the nonexpanding and expanding silicates. Nonexpanding layer silicates such as kaolinite and some micas have only external surfaces [47]. Specific surfaces of these minerals range from 10 to 70 m^2/g [47]. Whereas expanding layer clay minerals such as monmorilonite, other smectites and vermiculites have extensive internal as well as external surfaces, recording surfaces up to 810 m^2/g [47]. It has also been reported that deep sea sediments possess a much higher values of surface area then other types of reservoir rocks due to their high clay and silt content [50].

Reliability of EGME method has been stated by Arnepalli et. al., [51] in their paper when they compared it with several other well established methods that are commonly used such as the Methylene Blue (MB) Absorption Technique, Nitrogen (N_2) Gas Adsorption Technique, Mercury Intrusion Porosimetry and Air-adsorption method. The authors also stated that the EGME method is also economical in terms of time and costs.

2.5 Mineralogical Characterization

Mineralogical and petrographical properties of a rock have been long used as part of the rock characterization. Knowledge on the mineral distributions and micro-features of a particular rock can be observed by making a thin section of the interested rock. The type of rock, textural features such as grain size, grain shape and its morphological fabric can also be observed and determined.

In addition to using petrographical thin section analysis, scanning electron microscope (SEM) is another versatile analytical analysis, capable of providing several different types of images, quantitative data relating to porosity and rock composition and the crystallographic structure of individual minerals [52]. Morphological identifications using SEM can further provide better information regarding the types of porosity in a rock. SEM is an extended analysis of petrographical image. It can be used to support the analysis using conventional polarized microscope as SEM allows large depth of field, which enables a large amount of the sample to be in focus at one time, and also the ability to obtain images in high resolution, which means that closely spaced features can be examined at a high magnification. X-ray diffraction analysis, on the other hand, is the most direct and accurate analytical method for determining the presence and absolute amounts of mineral species in a sample [53].

Previous mineralogical and petrographical observations available for the Belait Formation in Sarawak were conducted by Azimah Ali [13]. The study was conducted on several samples consisting of sandstone, siltstone and shale from the formation. The study revealed that the sandstone consists predominantly of quartz with clay matrix, and is texturally immature. The siltstone consists of angular to sub-angular quartz grains and sub-rounded to rounded rock fragments in matrix of clay mineral, mica flakes and sericite. Thin laminated and irregular cracks with burrows were also observed in the thin sections of siltstone from the Belait Formation. XRD analysis on the clay fractions revealed that they are composed of Kaolinite at 7Å, Illite/Muscovite at 10Å, Monmorilonite at 12-15Å and Chlorite / Vermiculite detected at 14Å.

2.6 Geochemical Characterization

Organic geochemistry techniques can be used to discover why, when and where petroleum is formed, how it migrates and, when used with other geosciences major, where it can be found [2, 54]. Petroleum geochemistry has been part of the major components and tools used in petroleum exploration. Advances in this field have led to a better understanding of exploration domain, mainly the hydrocarbon migration. Much of the geochemical analysis during hydrocarbon exploration accounts for the source rock evaluation during prospect maturation study.

The extend of hydrocarbons in the Belait Formation and Lambir Formation in the study area is unknown as much of the research and literature regarding this subject are unpublished or concentrated mainly on the offshore part. Occurrences of oil seeps at the Marudi area have been reported by Wilson [33] and Sandal [55] in their report. Drilling around the area however, yielded a dry well. Map of the early oil exploration in Sarawak compiled by Wilson [33] also indicated a few other drilling sites for the oil exploration which encompasses the study area in Miri and Marudi (Fig. 2.3).

In Miri, oil was first discovered at Miri 1 well which produced 88 barrels oil per day (BBOD) from sand at TD (total depth) of just 138 meters. Upon its completion in 1910, it produced from the marine counterpart of both formations, the Miri Formation.

2.6.1 Total Organic Carbon (TOC) Content

The amount and type of the organic matter preserved in sedimentary rocks are a function of several geological and biological processes such as organic productivity, level of anoxia and sedimentary processes of the depositional environment [56]. Quantity of the organic matter in a sediment / rock can be determined by Total Organic Carbon (TOC) analysis. TOC is measured in weight percent and indicates the organic richness of the rock [57]. TOC value of 0.5 % by weight is a good minimum estimate to identify a source rock [58]. Classification of TOC can be found in Peters [59] and Tissot and Welte [10].

This value reveals the amount of the organic matter present in the rock, but not the hydrocarbon potential, which depends on the type of organic matter, its thermal maturation, and its volume. TOC for the two studied Formations is also unknown due to similar reason that the literatures were not easily available and usually labeled as classified. However in a study conducted by Curiale et. al [60] which comprised of samples from the Belait Formation collected at Berakas Syncline, Brunei reported that the studied shales have TOC ranging from 0.84 – 6.23 percent [60].

2.6.2 Ultraviolet - Visible Light (UV-Vis) Spectroscopy

Ultraviolet spectroscopy is a well known and widely used tool for both quantitative and qualitative determination as well as characterization of changes in structures of humified components. Absorption of humic acids in the ultraviolet range is based on the aromatic groups that contribute to the molecular structure. Ultraviolet range is found at around 10nm till 400nm which continues with the visible light spectrum until 720nm. As with any other absorption spectroscopy, the goal of this method is to see how well the material can absorb the electromagnetic waves from each spectrum.

Schnitzer & Khan [61] stated that the light absorption of humic substances appears to increase when there is an increase in degree of condensation of the aromatic rings that these substances contain [62], the ratio of C in aromatic “nuclei” to C in aliphatic side chains [63], the total C content; and also molecular weight.

Absorbance at 465nm and 665nm is widely used by soil scientists for differentiating between Humic and Fulvic acids [61]. The ratio is usually referred to as E_4/E_6. This ratio has been reported to be independent of humic materials concentration extracted from different soil types [61, 62]. The E_4/E_6 is related to the degree of condensation of the aromatic C network Kononva [62]. The author furthermore added that low ratio of E_4/E_6 indicates a high degree of condensation of aromatic humic constituents whereas the high E_4/E_6 ratio reflects a low degree of aromatic condensation.

Schnitzer & Khan [61] do not agree with this conclusion and stated the E4/E6 ratio is directly related to molecular weight. He suggested that sample with high ratio of E4/E6 have higher molecular weight i.e. aromatic dominated compounds. It has also been stated that the UV-Vis adsorption spectroscopy for evaluation of petroleum has been strongly underestimated [64] as E4/E6 ratio from the UV-Vis, has been used widely as a measure of aromacity or humification [65].

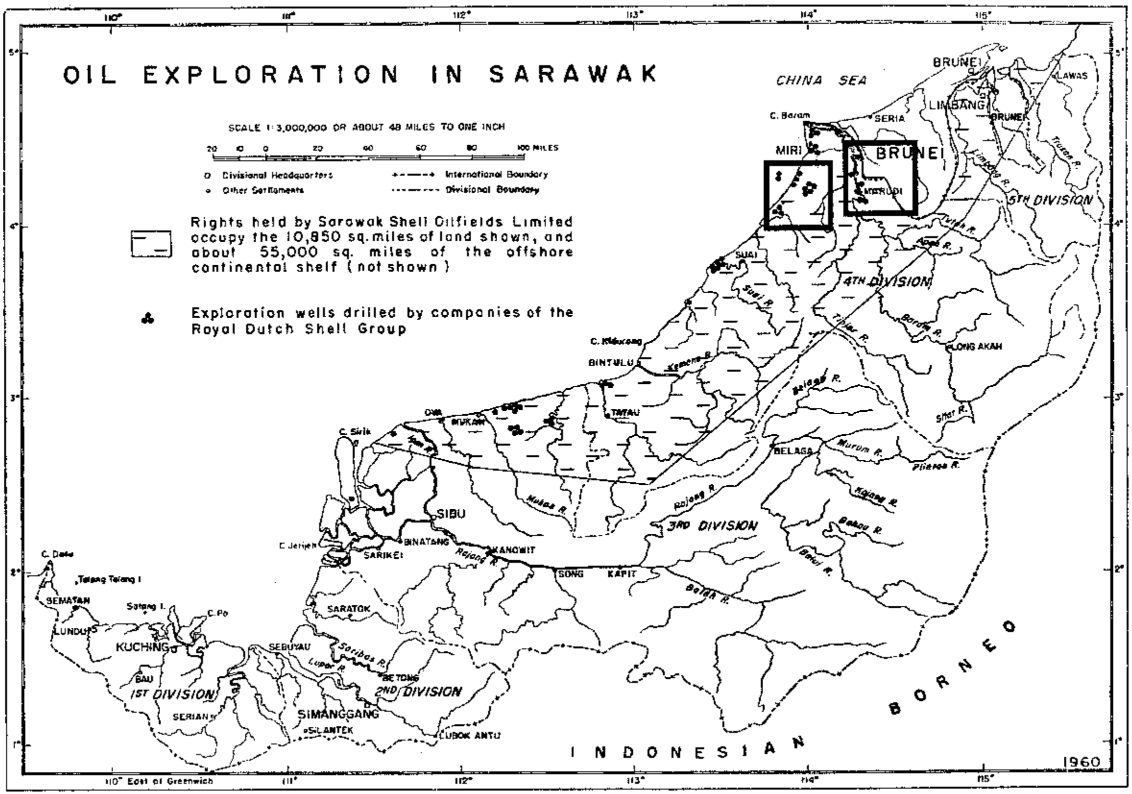


Fig. 2.3 – Map of previous oil exploration in Sarawak as compiled in Wilford [33]. It can be seen from this map that the area activities studied is also explored. Here the location of the current study areas is roughly represented by the red boxes on the map.

2.6.3 *Fourier Transform Infrared (FTIR) Spectroscopy*

Infrared spectroscopy has been used since post World War II period by several major chemical manufacturing companies as part of their quality control. It was later that the technology evolved for the quantitative measurements of components in polymeric and petroleum products [66]. With development of recent technologies, much of the published works using FTIR focused on the identification and characterization of materials and the development between the measured spectrum and molecular structure and chemical functionality [66].

In infrared spectroscopy, IR radiation is passed through a sample. Some of the infrared radiation is absorbed by the sample and some of it passes through (transmitted). The resulting spectrum represents the molecular absorption and transmission, creating a molecular fingerprint of the sample. Like a fingerprint, no two unique molecular structures produce the same infrared spectrum something that made infrared spectroscopy useful for several types of analysis [67].

Soil scientists have long been using the FTIR as part of the characterization of organic matter particularly the humic substances. Schnitzer and Khan [61] stated that although infrared spectroscopy tells little regarding the chemical structure of humic nuclei, infrared spectroscopy does provide worthwhile information on the distribution of the functional groups. Schnitzer and Khan [61] also stated that, infrared spectroscopy is nevertheless useful for the gross characterization of complex humic materials of diverse origin.

In the context of rock characterizations, a study by Ganz and Kalkreuth [68] discusses the potentiality of infrared spectroscopy particularly the FTIR to classify source rocks and oil shales as an additional tool along the arrays of conventional geochemical analysis (rock-eval pyrolysis, vitrinite reflectance measurements etc.). Ganz and Kalkreuth [68] also compared the classification of conventional O-C and H-C ratio of Van Krevelen diagram method with a new set of parameters found using the FTIR. The parameters which are known as the A Factor (aliphatic) and C Factor (carboxylic) represents the peak changes in the aliphatic groups of measured intensities and changes in the peak of measured intensities for the carboxyl/carbonyl groups respectively. These formulas were based on the knowledge regarding the increasing and decreasing ratio of aliphatic and carboxyl/carbonyl ratio during migration [10]. Similar method was performed by Ballice et. al., [69] to classify kerogen types and Boukir et. al., [70] to characterize crude oil asphaltenes with the aid of UV-Vis spectroscopy.

CHAPTER 3

MATERIALS AND METHODS

3.1 Chapter Overview

This chapter is divided into two parts whereby the first part will elaborate and answers some of the questions regarding where and how the samples were collected and what materials were involved. This is followed by brief information regarding the experimental techniques performed for the samples in order to characterize the studied formations.

3.2 Fieldwork

Fieldwork was conducted for one week on both Formations in Northern Sarawak around late April until early May of 2010. The rocks from both formations were sampled for lab analysis. All Belait Formation samples were collected within Marudi district while samples representing Lambir Formation were collected around Miri Town.

3.3 Sampling and Samples

Systematic sampling was conducted in-situ and collected rocks were ensured to be fresh. Rock samples were break using geological hammer to ensure that samples taken at the field are indurated. The selected section of the outcrops that contained fossils or possessed any structures that can assist this study was hammered to obtain a hand size rock samples that weight approximately 1kg. Rock samples obtained were labelled, stored and sealed in hard containers. These samples were then subjected to further lab analysis.

Sampling was conducted based on the map prepared by previous researchers [3, 4, 14, 15, 71, 72] and geological map prepared by the Mineral and Geoscience Department Malaysia [73] (Fig. 3.1). Explanations regarding the samples collected during the fieldwork and the features it possessed in the outcrop scale will be discussed in this section.

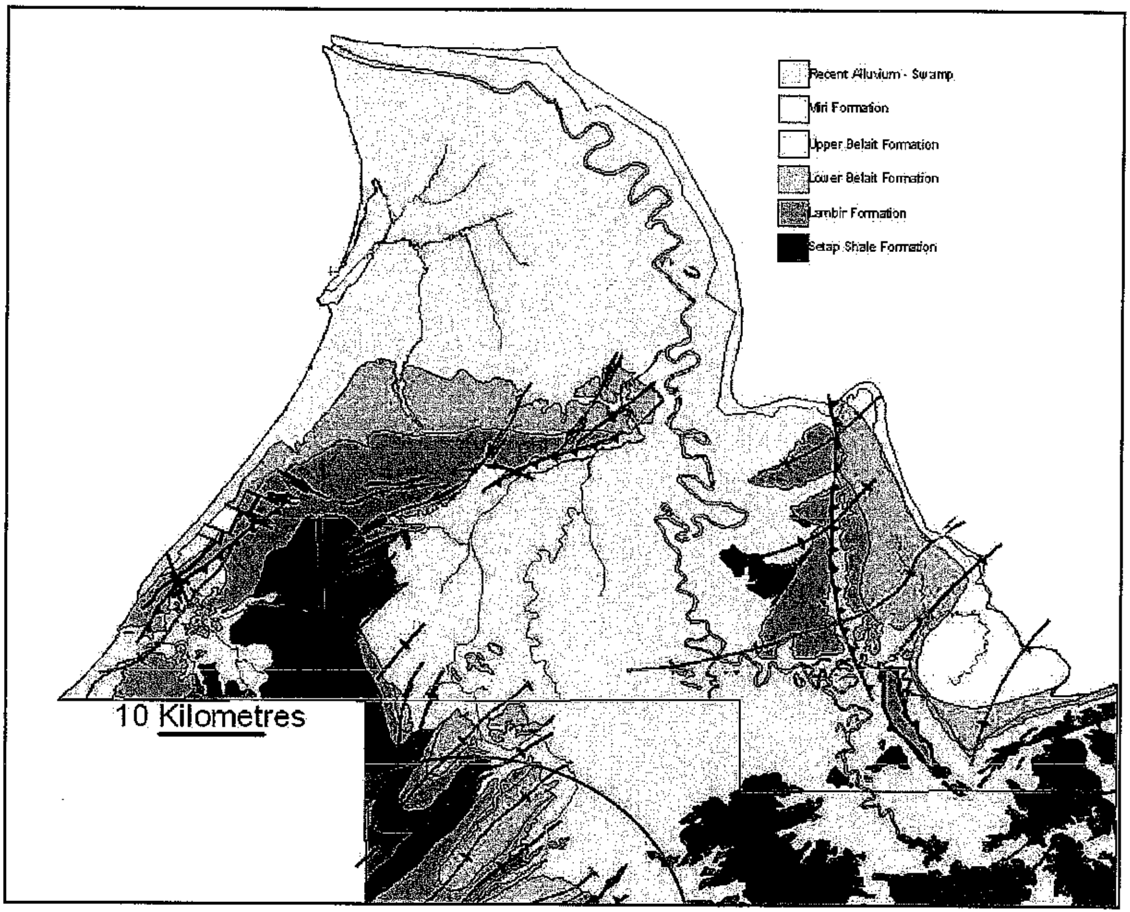


Fig. 3.1 – Geological map of the area based on the Mineral and Geoscience Department Malaysia [73].

A total of nine samples were collected during the fieldwork with five samples (B1 – B5) representing the Belait Formation and four samples (L1-L4) from the Lambir Formation (Table 3.1). Samples B6 - B9 were given by Dr. Padmanabhan in powdered forms. These samples were collected during one of his field visits around Marudi area. Due to hazard and time constraints, rock samples for these samples could not be collected during the fieldwork. As these samples are available in limited quantity, only FTIR analysis could be performed on the samples. The Belait Formation samples were collected from Marudi area of Northern Sarawak (Fig. 3.2) and the Lambir Formation samples were collected at from the onshore outcrop bordering the Miri coastal area to the South China Sea (Fig. 3.3).

Table 3.1 – List of samples used for the study.

Sample Label	**Formation**	**Lithology [74]**
B1	Belait Formation	Mudrock
B2	Belait Formation	Mudrock
B3	Belait Formation	Mudrock
B4	Belait Formation	Sandstone
B5	Belait Formation	Sandstone
B6	Belait Formation	Sandstone
B7	Belait Formation	Shale
B8	Belait Formation	Sandstone
B9	Belait Formation	Shale
L1	Lambir Formation	Sandstone
L2	Lambir Formation	Sandstone
L3	Lambir Formation	Sandstone
L4	Lambir Formation	Sandstone

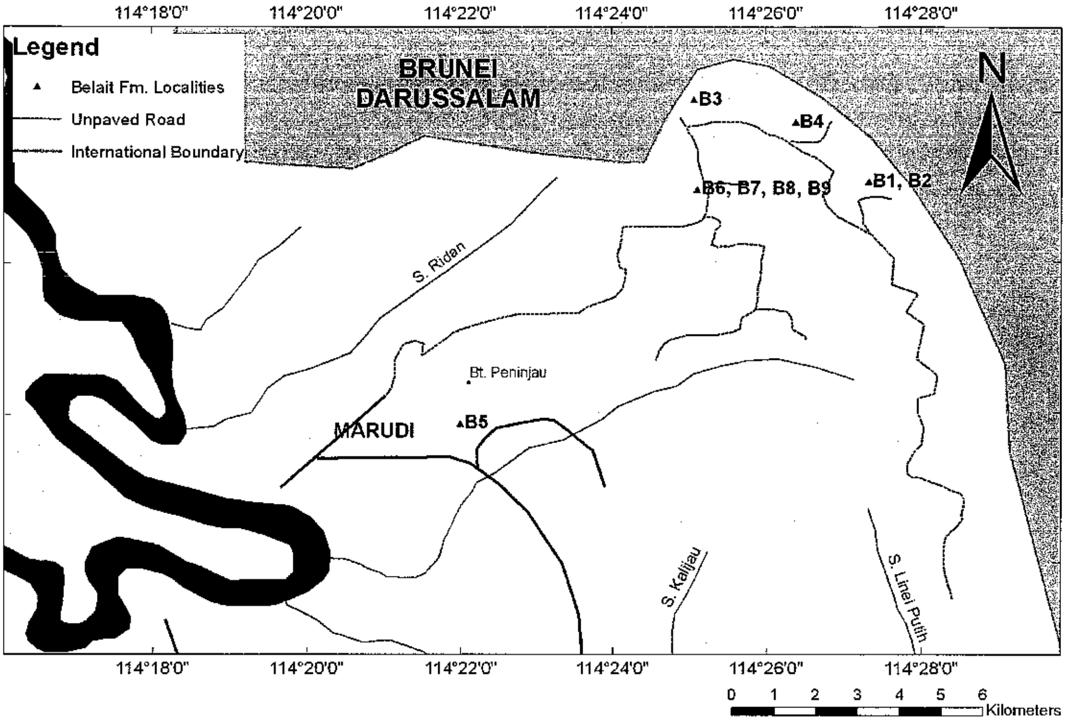


Fig. 3.2 – Sampling map for the Marudi area. Samples that are collected here represent the Belait Formation as mapped by previous researchers [4, 14, 15, 71, 72, 75].

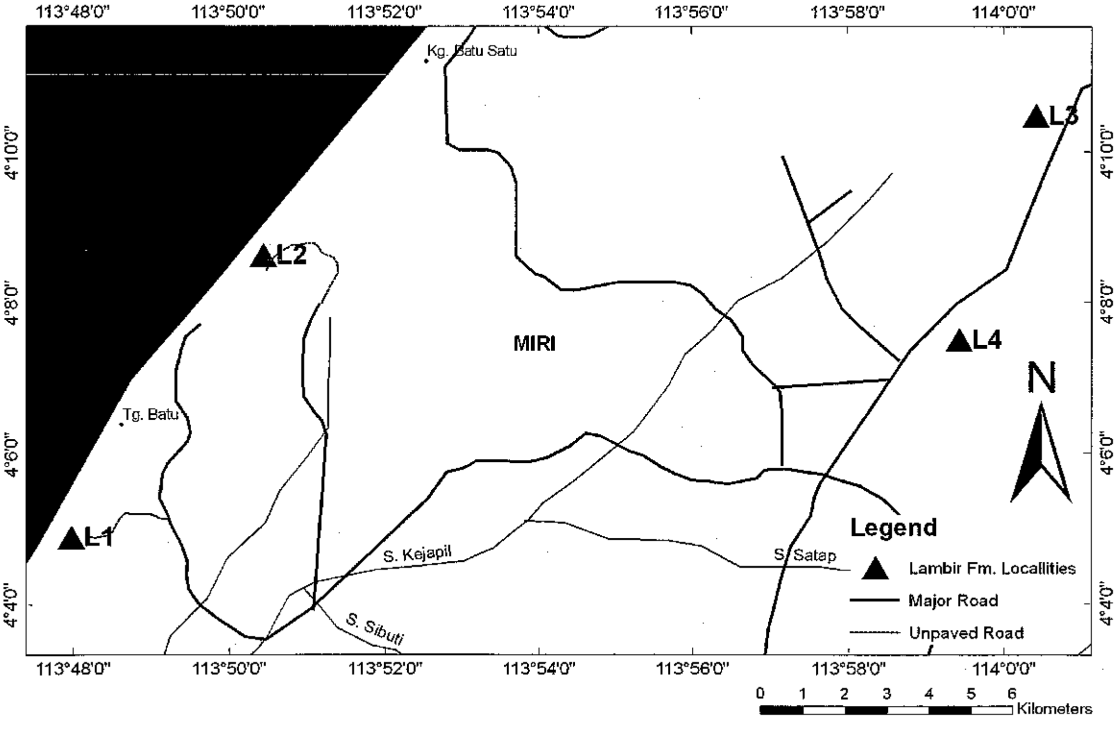


Fig. 3.3 – Sampling map for the Lambir Formation at Miri, Sarawak. Sampling was conducted based on availability of outcrops and map produced by previous researchers [4, 71, 76].

Sample B1 and B2 were collected at the same area located in the interior of Marudi, Sarawak fringing the border to Brunei. The outcrop is an example of a typical heterolithics sequence belonging to the Belait Formation (Fig. 3.4). The heterolithics sequence consists of ~26 meters in vertical height of sand and shale interval. Presence of coal in the form of clasts and laminations can be seen along the shale sections of this heterolithics sequence.

Similar to the heterolithics sequence of the first outcrop, B4 was collected at 15 meters height in Belait Formation outcrop that consists of sand and shale heterolithics sequence, alternating with orange-whitish coloured medium-grained sandstone (Fig. 3.5). Cross laminations can be observed in the sandstone section (Fig. 3.6A). The whole outcrop was logged. Sample for this outcrop was collected at one of the sandstone sections. Soft-style deformation features can be found in the shale and sand of the heterolithics part of this outcrop with thinning upward trends (Fig. 3.6B) between the grains. Coal in the form of clasts and laminations was also detected within the shaly sections of the heterolithics sequence.

The last sandstone from the Belait Formation is represented by sample B5 that was collected at an exposed roadside outcrop at Jalan Marudi – Rumah Gadong (Fig. 3.7). The outcrop was logged and studied. Similar to all other Belait Formation outcrops, the heterolithics sequence in this outcrop recorded 1:1 ratio of sand and shales. Presence of bioturbated mud in the heterolithics sequence could also be observed at the outcrop (Fig. 3.8). The sequence then continues with massive medium-grained white pinkish sandstones where sample for this outcrop was collected. The sandstone is featureless with presence of vertical burrows in the mid-section. Cross bedding structures could be seen clearly at the basal section of this outcrop (Fig. 3.8). On the beds where these channels are present, thin laminations of carbonaceous materials with thickness of around 1cm and coal dusts could also be found (Fig. 3.8).

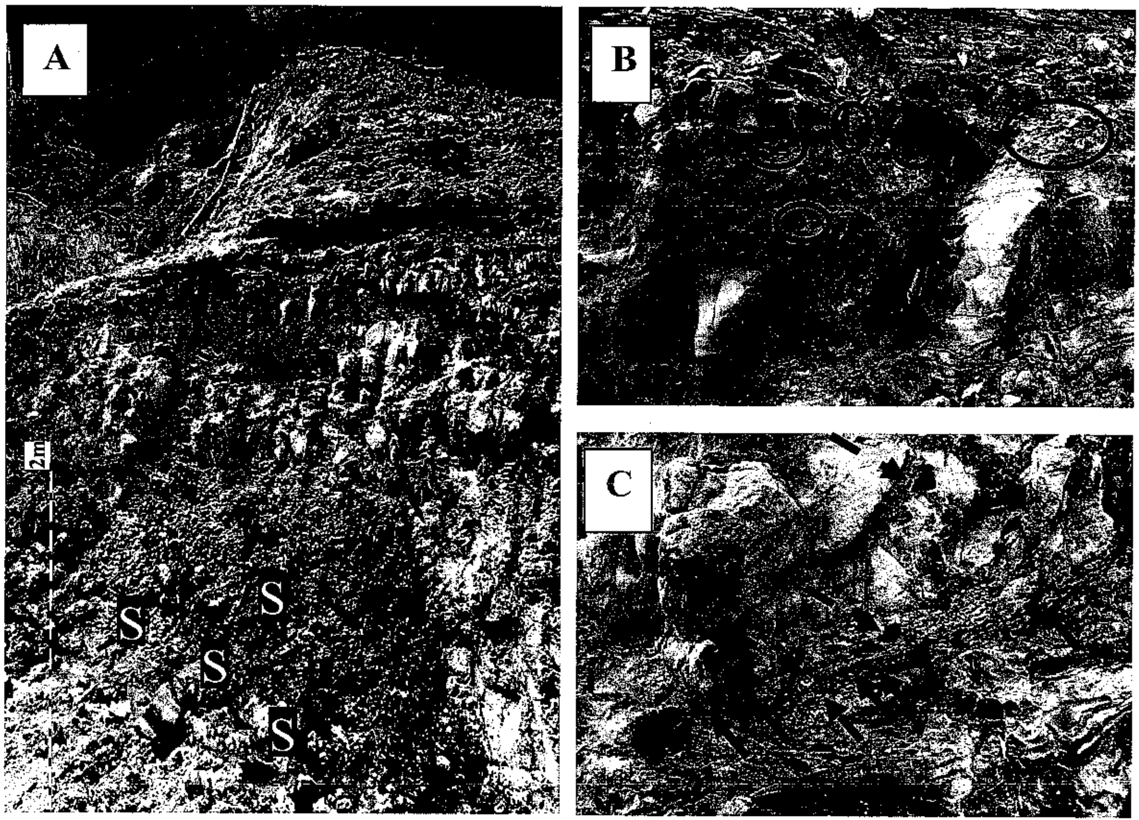


Fig. 3.4 – B1 and B2 outcrop pictures. **A** – The bottom part of the picture showed where the seepage location (approx. 2m in height) and the upper section which consists of heterolithics with mud to sand ratio of 2:1. **B** - *Ophiomorpha Nodosa* (circled) that have been detected nearby the studied sequence. **C** - Presence of coal in forms of thin laminations (average of 1-5cm in length) and clasts are marked by the red arrows.

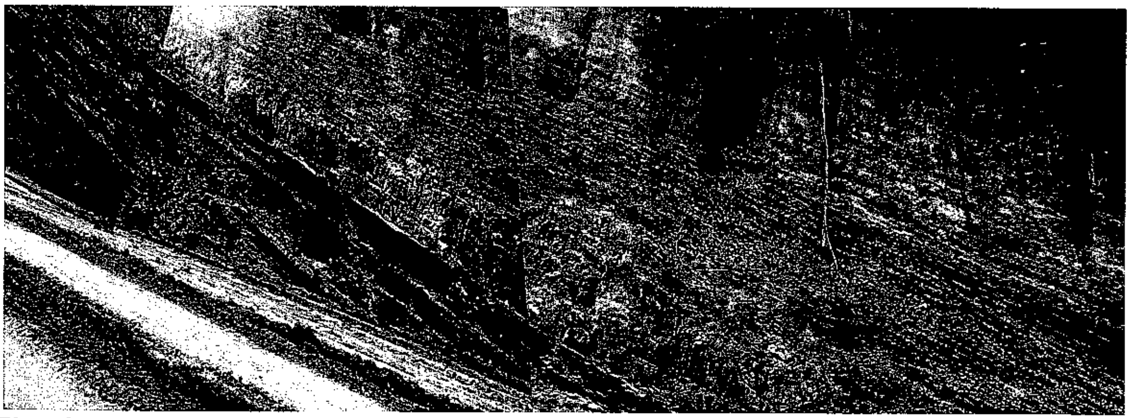


Fig. 3.5 – The outcrop for sample B4 from the Belait Formation. The outcrop is located in the interior of Marudi, North Sarawak. The outcrop consists of sand – shale heterolithics sequence alternating with orange - whitish sandstones.

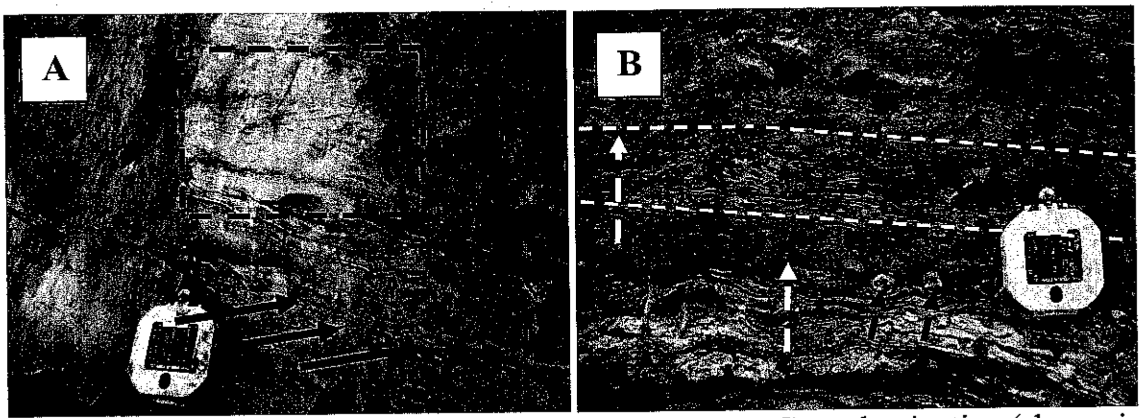


Fig. 3.6 – B4 outcrop sedimentary structure pictures. **A** – Cross lamination (shown in the red box) and parallel lamination (pointed by the red arrows) are found in the sand sections of the Belait Formation B4 outcrop. **B** – Soft-style deformation as seen in the B4 outcrop of the Belait Formation. Ball and pillow structures as pointed by the red arrow. Syn-depositional features such as convolute laminations and contorted laminations can also be seen (orange arrows). The sequence is also noticed to be coarsening upward (white arrows).

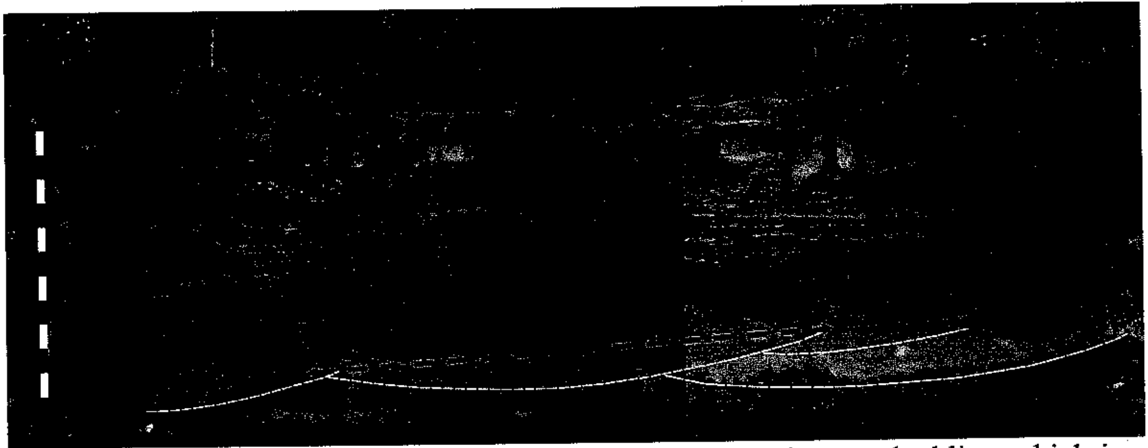


Fig. 3.7 – The B5 outcrop of the Belait Formation. Trough cross bedding which is a fluviatile feature can be found in the outcrop. The individual through are overlapping each other as seen here and it was measured (red lines) having just less than 5 meters laterally, whereas the total height of the outcrop is around 2.1 meters vertically.

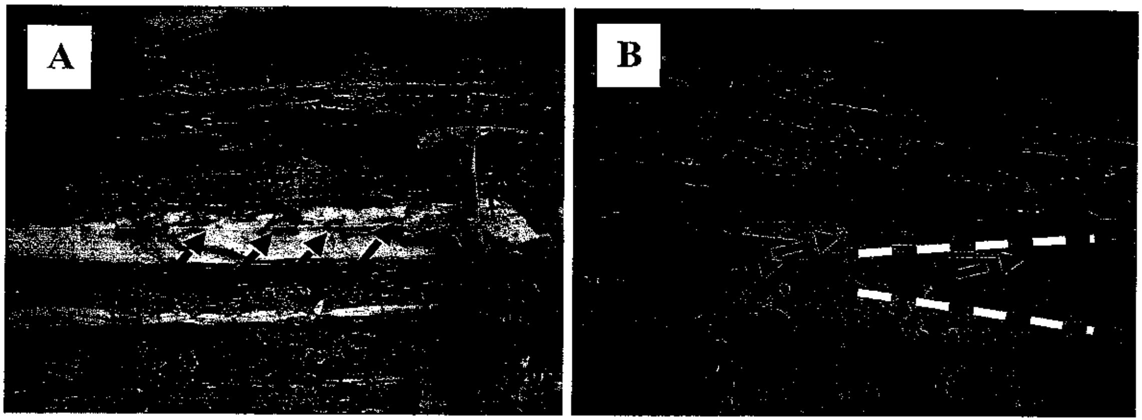


Fig. 3.8 – The sedimentary features in B5 outcrop. **A** – Bioturbated mud can be found in the heterolithics sequence of the Belait Formation B5 outcrop. Much of the replaced materials are reddish in colour (red arrows). **B** – Fine cross laminations in the medium-grained sandstone beds of the outcrop (blue dotted line). Here, thin laminations of carbonaceous materials (thickness around 1cm) can also be observed (red arrows).

Much of Lambir Formation outcrops were sampled along the Miri coastal area and consisted of very fine grained sandstone samples. Occurrences of massive sandstones bedding is also common within the Lambir Formation outcrops [77]. The heterolithics of the Lambir Formation although look the same compared to the Belait Formation outcrop is quite different on closer looks. One clear example is that the individual thickness of the sand to shale ratio in the Lambir Formation heterolithics in most cases is sandier, having ratio of more than 1:1 (sand : mud) [77].

Sampling was conducted at one of the Tusan Beach sandstone outcrop, the sample is represented by L1 (Fig. 3.9). The second sample was collected in an outcrop at the beach of. Kampung Masjid (L2) which is the continuation from the Tusan Beach outcrop. Although sampling was conducted to all of the outcrops visited but due to time and unpredictable weather conditions, only the last outcrop, L3 which is a brownish orange sandstone outcrop alternating with 1:1 sand and shale heterolithics sequence at an exposed outcrop near Jalan Miri – Bintulu (Fig. 3.9) was sampled. Sample from this outcrop was collected on the top section which is a brownish-orange massive sandstone. L4 outcrop is located alongside the same road of the previous L3 outcrop but furthering more to the direction towards Bintulu.

Fig. 3.9 – Example of Lambir Formation outcrops. **A** – The massive sandstone outcrop at Tusan Beach (Sample L1). **B** – Sample L3 outcrop. The sandstone can be considered as part of the massive bedding because there is no structure present. This feature is very common in Lambir Formation.

3.4 Mineralogical and Petrographical Analysis

Thin sections were made for all of the collected samples and examined for petrographical analysis. Petrographical analysis includes; thin section analysis and X-ray diffraction (XRD).

3.4.1 Thin Section Analysis

Petrographical and mineralogical analysis was conducted in order to characterize the rock samples from its mineralogical point of view. Hand samples brought from the field were first treated using mixture of epoxy and hardener to ease cutting the rock samples into smaller fragment. The latter were then placed in a plastic cup where a mixture of epoxy and hardener in 2: 1 by parts ratio was poured into the cup leaving a 2 cm height space. The cup was then placed under vacuum for 30 minutes and left for up to a week for hardening.

Hardened fragments were cut using METKON Geocut into billet sized of ~30 mm to approximately 50 mm length, 25 mm wide and 5 mm thick. METKON Micracut 175 Precision Cutter was used for trimming the billet samples to as thin as possible (possibly ~50 μm). Sample lapping and polishing to 35 μm thick were made by METKON Forcipol 300-1V attached to Forcimat–TS head. At this thickness, the thin section will easily transmit light for further petrographical analysis. Petrographical and mineralogical observation was conducted on the thin sections viewed with OLYMPUS BX51-P polarizing microscope at Microscopy Division, Mineral and Geoscience Department, Ipoh, Perak. Thin sections of these rock were samples viewed under polarizing microscope with both plane polarized light (PPL) and cross-polarized light conditions (XPL). VIS Plus version 3.0 software was used to capture the images viewed in the microscope. Thin sections were made based on the procedures from Tucker [78] with descriptions from the aid of illustrations given by Adams *et. al.*, [79] and MacKenzie & Adams [80].

3.4.2 XRD Analysis

XRD was performed using slide oriented specimens whereby the rock samples were crushed into powder and water was added to form a slurry mixture. This mixture was then transferred to a glass slides (size of 5cm x 2cm) using a dropper and air drier for a day. The dried slide representing the sample was then attached to a slide holder for its XRD mineral compositions. The XRD was performed using a Philips Xpert X-ray Diffractometer at Universiti Pertanian Malaysia (UPM), Serdang with CuKα radiation at scanning speed of 0.04°/s. Slide oriented experiment was then conducted on these rock fractions with smear-glass techniques based on the methods described by Gibbs [81], Drever [82] and Hardy & Tucker [83]. Peaks obtained were identified from the database provided by International Centre for Diffraction Database (ICDD) and descriptions from Brindley [84].

3.5 Physical Analysis

Physical analysis was performed in order to characterize the physical properties of the samples. Among the analysis and lab works performed are the mercury porosimetry analysis, thermal conductivity analysis and EGME retention.

3.5.1 Mercury Porosimetry Analysis

Mercury (Hg) porosimetry techniques were also used to determine porosity and mean pore sizes of the studied rocks. Air- then oven-dried samples were cut using a small-sized bow saw into a known dimension of 1cm x 1cm x 1cm before being analyzed with Pascal 240 Thermo Fischer Mercury Intrusion Porosimeter. Samples were first degassed and then intruded by Hg. Apparent density, bulk density, porosity and open pore size distribution (pore diameter between 3.7 and 58000 nm) of each sample were computed using the PASCAL (Pressurization with Automatic Speed-up by Continuous Adjustment Logic) method and the Washburn equation. This equation assumes: cylindrical pores, a contact angle between mercury and sample of 140°, a surface tension of mercury vacuum of 0.480 N/m and mercury density equal to 13.5 g/cm^3.

3.5.2 Thermal Conductivity Analysis

Samples were air dried for one week and then dried in the oven (60°C) for one day before being cut into small blocks with varied dimensions depending on the samples availability. Thermal conductivity estimation was carried out by supplying constant heat to the rock sample at 40W and 30°C room temperature until thermal equilibrium had been achieved. Measurements were taken using Omega steel probe connected to Omega HH506RA thermal-logger based on descriptions given by Somerton [85] and Clauser & Huenges [45]. Measurements were performed at Universiti Teknologi Petronas (UTP) Geochemistry Lab. The coefficient of thermal conductivity, k [W/(m·K)], is a measure of the rate q (W) at which heat flows through a material. It is the coefficient of heat transfer across a steady-state temperature difference ($T_2 - T_1$) over a distance. These differences between the readings were referred and measured as ΔT. The distances between the positions of the two readings were measured as L. The area (A) of the rock when heated is also measured (Fig. 3.10).

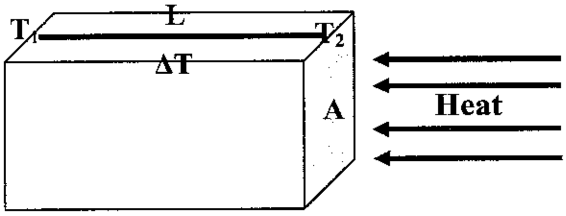


Fig. 3.10 – Equipment setup and the parameters involved when measuring the thermal conductivity of a rock sample.

Thermal conductivity of the rock sample was calculated using the formula shown below (Equation I). Thermal conductivity is denoted as k with measurement units of $Wm^{-1}K^{-1}$ and represents the measure of heat flow per unit temperature gradient.

$$k = Q*L / (A*\Delta T)$$

(Equation III)

Q = Heat flow across the material

k = Thermal conductivity of the material

L = Length / Distance

A = Cross-sectional area of the material where heat is supplied

ΔT = Temperature differences between the point measured ($T_2 - T_1$)

3.5.3 *Specific Surface Area - Ethylene Glycol Monoethyl Ether (EGME) Retention Method*

Specific surface area (SSA) analysis was conducted on dime-sized rock chips broken from collected rocks to further characterize the presence of clay minerals within the studied samples. Specific surface of a porous material is defined as the interstitial surface area of the pores per unit of bulk volume of porous materials [86]. EGME Retention method was used to determine the total surface area for the clay portion of samples [47, 49] based on the EGME method proposed by Carter *et. al.* [47, 48]. In this analysis, samples dried over Phosphorous Pentoxide (P_2O_5) were then saturated with EGME. A monomolecular layer of EGME was then established by desorbing the EGME by vacuum over EGME-saturated $CaCl_2$. The weight of a monomolecular layer of EGME on the sample is determined by weighing the dried sample. EGME is determined by weighing the sample and sample plus EGME.

$$\text{Retention of EGME (mg g}^{-1}\text{)} = (Wt_1 - Wt_2) \times (1000/Wt_3)$$

(Equation IV)

Where:

Wt_1 = Sample weight with monomolecular layer of EGME + tare weight of bottle

Wt_2 = Sample weight after drying with P_2O_5 + tare weight of bottle

Wt_3 = Sample weight after drying with P_2O_5 - tare weight of bottle
1000 = conversion factor (mg g^{-1})

The surface area in units of EGME per g of samples is converted to m^2g^{-1}; the conversion is as follows (Equation V):

$$\text{Surface area } (m^2g^{-1}) = \text{EGME Retention } (mg\ g^{-1}) / 0.286$$

(Equation V)

Where:
0.286 = Conversion factor (mg EGME m^{-2}), the constant, 0.286, is the amount of EGME (mg) that is required to cover a m^2 of clay.

3.6 Geochemical Analysis

Organic characterizations of the studied rocks were determined from powdered rock samples by a series of geochemical methods. In addition to determining the total organic carbon contents (TOC), Ultraviolet- Visible Light (UV-Vis) spectroscopy was performed to study the ratio of optical densities or absorbance of the solutions at 465nm and 665nm. Fourier Transform Infrared (FTIR) spectroscopy was performed to determine types of functional group present in the studied samples. X-ray Fluorescence (XRF) was also performed to determine the elemental compositions of the studied samples.

Hydrocarbon interpretations of these samples is explained in its chemical terms. It is therefore considerate to enlighten some of the terms that will be encountered in the text. Aliphatic generally represents straight chain bonded / single bonded compounds (C-C) known as paraffins; the double bonded (C=C) compounds known as olefins. Hydrocarbons can also be present as cyclic (ring shaped) compounds that are available in two conditions. The aliphatics equivalents of cyclic compound are also known as naphthenes. Another important cyclic compound is the aromatic compound. Aromatics (Aryl) are cyclic hydrocarbons which begin with benzene ring and contain carbon-carbon double bonds. Aromatic is also known to be denser than the aliphatic (lipid-like) compound [87]. Just for comparison purposes, the density of water is known to be 1g/cm^3. Hydrocarbons however are generally less denser than water but aromatic in its simplest forms is much denser than the longer chain aliphatics counterparts. A triacontane ($C_{30}H_{62}$) straight chain aliphatic has density of 0.81g/cm^3; an aliphatic cyclic, cyclo-octane (C_8H_{16}), has density of 0.83g/cm^3; an olefin, 1-decane ($CH_3(CH_2)_7$-C=CH_2), has density of 0.74g/cm^3. Aromatic compounds however, a benzene (C_6H_6), has density of 0.88g/cm^3.

3.6.1 Total Organic Carbon (TOC) Analysis

Due to the unavailability of pyrolysis method (Rock Eval), TOC was carried out as an approximate indicator of source rock potential in the argillaceous rock. The TOC was also done on the sandstone in order to link with the FTIR and UV-Vis results so that some inference can be made regarding the migration of hydrocarbon in the reservoir quality rocks.

Powdered samples of 100-200mg were weighed and placed in an inert (porcelain) boat before being analyzed for their TOC contents at 1200°C using O.I Analytical 1030S Solids TOC Module. TOC values were then obtained from IR detector at different temperature interval and displayed through WinTOC interface for data acquisition of analyzed samples. Further details on the TOC procedure is explained elsewhere [59, 88]. Classifications of organic carbon content were made based on the descriptions given by Tissot & Welte [10]. The experiment was conducted at the Civil Engineering Environmental Lab Universiti Teknologi Petronas (UTP).

3.6.2 X-ray Fluorescence (XRF) Analysis

X-ray fluorescent (XRF) can be complimented with the results obtained in the XRD analysis as XRF provides highly accurate information about the elemental composition of a sample. Samples were crushed and then air- and oven-dried before analyzed using Bruker S4 Pioneer X-ray fluorescence spectrophotometer for their elemental compositions.

3.6.3 UV-Vis Spectroscopy

This method is used to determine the degree of condensation of aromatic network of humic structures based on the E4/E6 ratio which is used to evaluate the nature of the humic substances. E_4 is the absorbance measured at 465 nm and E_6, the absorbance at 665 nm of the UV-VIS Spectrum. This method uses UVIKON 923 UV-VIS Spectrophotometer. Fine resolution of UV-VIS Spectroscopy allows the study of the spectral behaviour observed in the humic substances. The loss of aromatic structures of humic acid results in significant changes in the UV-VIS spectrum for these substances. This behaviour is monitored through the extinction value, which is the measure of electronic radiation absorbed at a particular wavelength and peak maxima which is the highest point at the peak of absorption.

Powdered rocks were diluted in test tubes with 0.5M hydrogen peroxides (H_2O_2) and put to rest for one night before extraction. The extracted water-powdered samples were then placed in a quartz cuvette of 10mm thickness and analyzed using Shimadzu UV-3150 UV-VIS spectrophotometer.

The spectrophotometer was set to acquire spectra in the range of 200-800nm with scanning interval of 0.5nm at medium scan speed. The data acquired by the spectrophotometer was then viewed in Shimadzu UV Probe 2000 software to identify the spectral at E4 (465nm) and E6 (665nm). The values obtained at these spectra were then compared to established literature [61, 65]. The UV-Vis analysis was performed at the Chemical Engineering Department Lab, Universiti Teknologi Petronas (UTP).

3.6.4 Fourier Transform Infrared (FTIR) Spectroscopy

Samples for FTIR were prepared by pressing homogenous mixture of powdered samples (2mg) and KBr (100mg) into micro-disc pallet. These micro-disc pallets were then analyzed using a Shimadzu 8400S Fourier Transform Infrared (FTIR) Spectroscope to determine the types of stretching bonds presence. The spectroscope was set to Happ-Ganzel apodisation with resolution of 4.0 and the wavelength acquired was in the range of 400-4000cm^{-1}.

Shimadzu IRsolution version 1.1 software was used to view the acquired spectra from the spectroscope. The spectral data were then re-plotted back by DPlot software ver. 2.2.9.8 [89] and peaks from the spectra were assigned manually. Interpretations of the FTIR spectra were made by comparing to the values from available literature [61, 66, 68, 90-93]. The analysis was performed at the Chemical Engineering Department Lab, Universiti Teknologi Petronas (UTP).

The FTIR spectra can be interpreted based on the mentioned literature [61, 66, 90-93] alone but confusion in certain peaks in different literatures has led this research to look at new ways of translating the peaks represented in the complex region. Complex region is a region where many of the assigned peaks are located and provide confusions.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Chapter Overview

This chapter discusses the overall results regarding the characterization of the Belait and Lambir Formations. Important debates regarding the overall studies are also discussed in this particular chapter.

4.2 Some Field Differentiating Characteristics between the Belait and Lambir Formations, North Sarawak

Similarities between the general appearances of the Belait and Lambir Formation in the field have led to difficulties in distinguishing one from the other. This differentiation is important as there is an ongoing exploration for oil and / or gas in this part of Sarawak. Selected outcrops from the northern and central Sarawak have been inspected in the field to evaluate the difference between these formations. Field observations suggest that there are at least five differentiating characteristics between these formations.

4.2.1 Field Observations

Most of the Belait Formation outcrops contain iron stains which are reddish in colour (10R6 6) due to the presence of Fe-oxyhydroxides (Fig. 4.1). The heterolithics facies of the Belait Formation have larger proportions of clay compared to the Lambir Formation. The heterolithic sections are also thicker than what is observed in Lambir Formation reaching up to 5m in some outcrops.

At the field level, all sandstones from the Lambir Formation look similar. These rocks are yellowish grey in colour (5Y7 2) and do not have any common sedimentary features as expected in near-shore sediments.

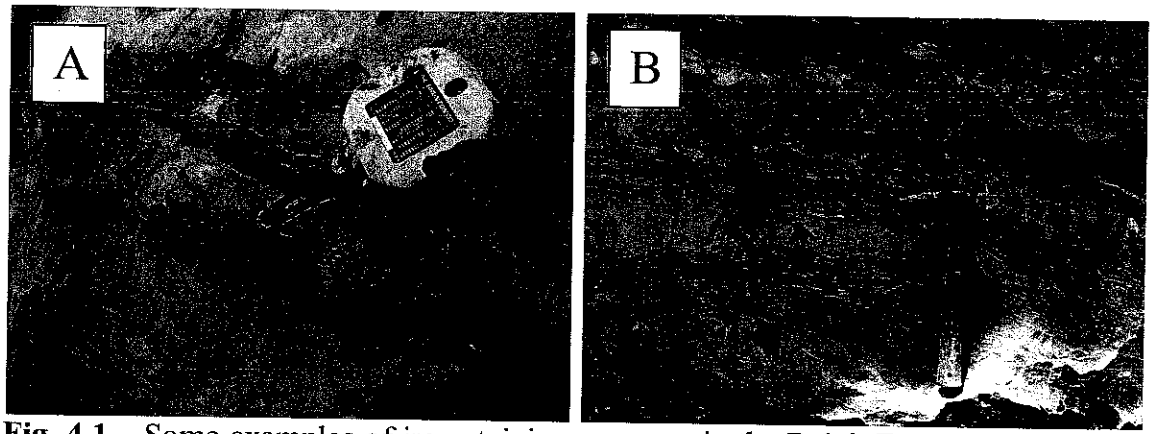


Fig. 4.1 – Some examples of iron staining presence in the Belait Formation outcrops. **A and B** - The colour of these iron staining ranges from reddish to oranges and is very commonly found in the outcrops of Belait Formation, Northern Sarawak.

Field observations from the selected outcrops suggest that there are some differentiating characteristics between the two Formations (Table 4.1). Characterizations of these formations were based on the differentiation of their sedimentological aspects. This is because sedimentary structures are very important in interpreting the depositional environment of a facies [94]. These differentiating characteristics are described in the following paragraphs;

4.2.1.1 Sedimentary Features

Pre-depositional sedimentary structures occurred on surfaces between beds, formed before the deposition of the overlying bed and these structures are mostly of erosional origin [35]. Examples of these structures include ripple marks, flutes and channels [35]. In this subtopic, the types of ripple marks observed in both formations are discussed.

Ripple marks are quite common as sedimentary features in the Belait Formation [15]. Asymmetrical ripple marks (Fig. 4.2) as found in the Belait Formation characterize fluviatile environment as they are commonly generated by both unidirectional current [95-97]. The symmetrical shape ripple marks, on the other hand (Fig. 4.1), which indicate near-shore environment (marine) is a characteristic of the Lambir Formation [15] as it is usually generated by diagnostic of oscillatory flow [35, 95-97].

Presences of cross-beddings/strata are also commonly found within the Lambir Formations and rarely in the Belait Formation[14]. Cross-beddings form when particles settled on the inclined surfaces of the depositional bedforms while they migrate beneath currents [14, 95, 98]. Presence of this feature in Lambir Formation is believed to be an indicator of a near-shore type of depositional environment.

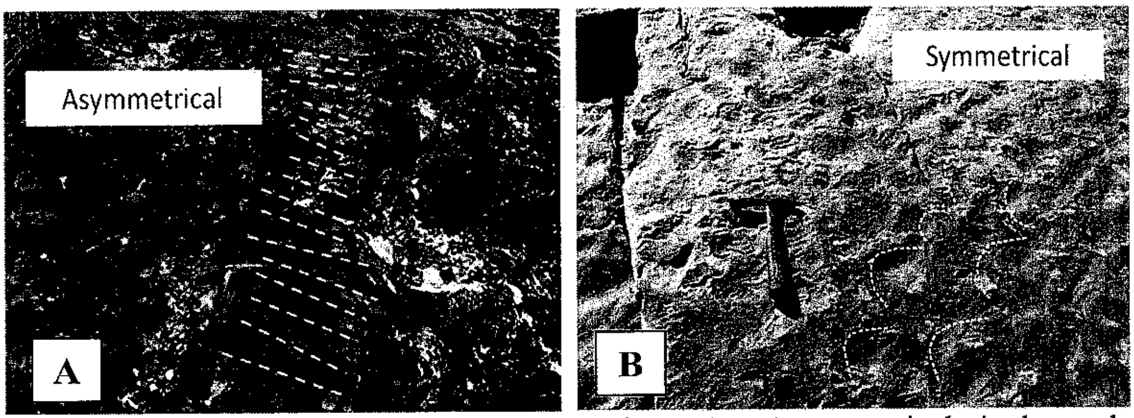


Fig. 4.2 - Ripple mark styles in both formations. **A** - Asymmetrical ripple marks found in the Belait Fm. is characteristic of fluviatile environment [15]. **B** - The symmetrical shape ripple marks in the Lambir Fm. is characteristic of a more marine environment.

4.2.1.2 Fossils

Fossils are important components of many sedimentary rocks and even when present in small numbers, they can provide useful, often critical, information [78]. Majority of the fossils found on both formations during the field visit are in the form of trace fossils. Trace fossils are the tracks, trails and burrows that are common in so many sedimentary rocks [35, 97]. Trace fossils can provide information on both palaeoecology and environment (Fig. 4.3) and is especially valuable where body fossils are limited or absent [78].

Burrows represent the activity of an organism within the sediment, after the sediment has been deposited. Because of this temporal relationship, burrows normally cross-cut other deposition-related sedimentary structures like bedding and laminations. The type of burrows usually yields information on the depositional environments, water depth of the sediments as well as markers for environmental change [99].

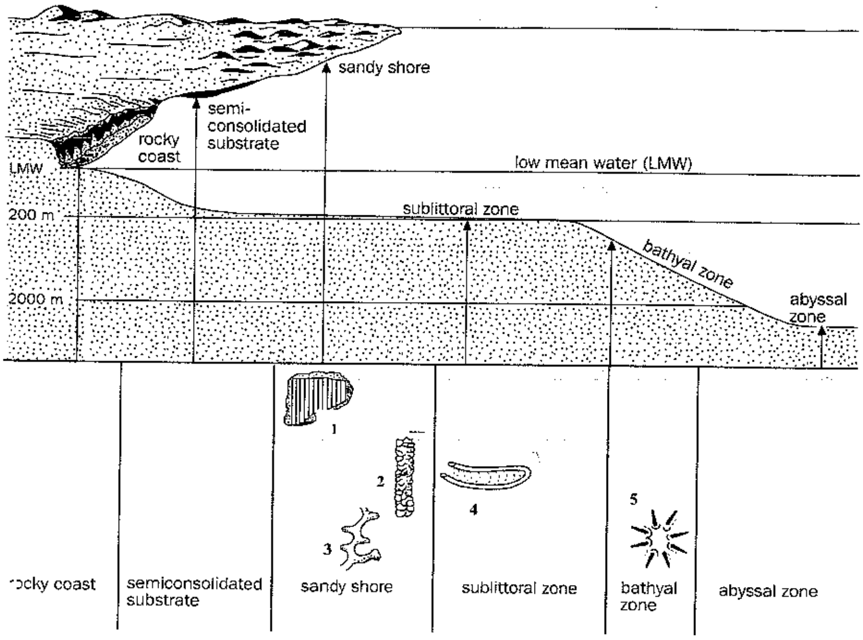


Fig. 4.3 – Palaeoecology and environmental depositions of trace fossils (from Stow [99] after Frey & Pemberton, in Walker [100]). Trace fossils are as follows: 1– *Skolithos*; 2- *Ophiomorpha;* 3– *Thalassinoides*; 4- *Rhizocorallium*; 5- *Zoophycus.*

In the case of the studied area, burrows of *Ophiomorpha Nodosa* (Fig. 4.4) are abundant in the Lambir Formation [3] but occurred lesser in the Belait Formation. Other forms of burrows mentioned in here from previous studies could not be found during the field visit. Abundances of this burrow in Lambir Formation indicate that it is a much more marine formation than Belait Formation.

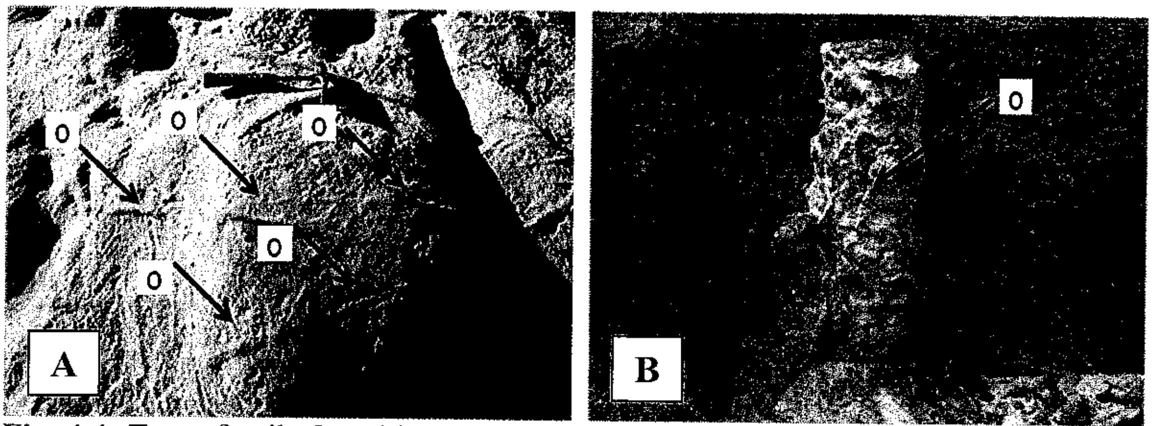


Fig. 4.4- Trace fossils found in the studied formations. **A** - Burrows of *Ophiomorpha Nodosa* (O) in the Lambir Formation at Tusan Beach outcrop, Miri, Sarawak. Burrow is measured to be having length of 5 – 7 cm in this picture. **B** – Sediments mixing with the fecal of *Ophiomorpha Nodosa* (O) forming burrow-like shaped found at the outcrop of Belait Formation in the interior of Marudi, North Sarawak.

4.2.1.3 Flow Pattern

Channels are the largest pre-depositional inter-bed structure which range from kilometers wide and hundreds of meters deep, it can also occur in diverse environments as well (i.e. alluvial plains to submarine continental margins) and are indicated by localized linear erosion by fluid flow added by erosive bed load [35]. Some of the factors that determine the type of channels include improved sorting and fining grain size as they go seawards [35, 99].

Features such as mud- and/or sand-filled channels are also found within the studied Belait Formation outcrops where occurrences of this feature are pretty much rare to none in the Lambir Formation outcrops [14].

Coarse-grained gravelly / conglomeratic deposits are found within vast ranges of environments but usually more commonly associated with types of fluvial (or of high energy) characteristic deposits. In the Belait Formation conglomerates deposits are found much more in southern part of Sarawak. It was first classified as a terrace [4] but reclassified as conglomerate [14]. All these flow patterns derived features which are found in the Belait Formation suggest a fluviatile / high energy environment.

4.2.1.4 Bedding / Stratigraphy

Due to the differences in the environment that these two formations possessed, heterolithics sequences as a result of changing environment are generally found within the Belait Formation outcrop. This structure, also known as tidal flats are sandy-muddy depositional system along marine and estuarine shores periodically submerged and exposed in the course of the rise and fall of the tide [101]. It is believed based on the feature, Belait Formation has been deposited as an isolated infilling basin oscillating between littoral and deltaic-paralic (i.e. lagoon, protected inlet) [4, 14].

Observation on the proportions of sand and mud in these heterolithic sequences (Fig. 4.5 and Fig. 4.6) between the two formations suggests that the Belait Formation possesses a much sandier sequence than the Lambir Formation. These proportions of sand and mud are attributed to the types energy of the environment possesses during deposition with sandier composition representing a high energy environments and muddy compositions caused by low-energy environment setting [101].

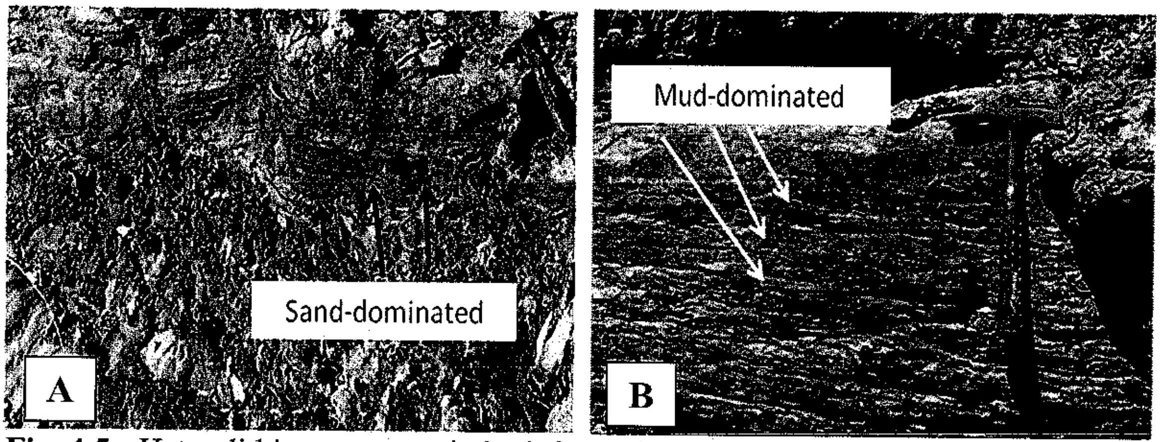


Fig. 4.5 - Heterolithics sequence in both formations. **A** - Sand-dominated heterolithics sequence from the Lambir Formation outcrop at Kampung Masjid in Miri, Sarawak. **B** - Mud-dominated heterolithics sequence / flaser bedding in the Belait Formation outcrop.

Occurrences of massive sandstone facies (Fig. 4.5) are much more common in the Lambir Formation rather than in the Belait Formation [14]. Deposition of massive sand beds results from sudden failure of capacity and competence of flow and also as a product of rapid deposition from high concentration sandy suspension flows as its particles are prevented from being reworked after reaching the depositional surface due to process of quick burial [95, 96].

Carbonaceous sandstone (Fig. 4.5) more commonly in the Belait Formation as opposed to the Lambir Formation. Carbonaceous materials deposition is a result of partial anaerobic decay of organic matter in a reducing setting in which water circulation is restricted and deposition is slow [102]. Coals, though present in various extend in both Formations cannot be used as a differentiating factor simply because they are found in both Formations as well as they formed in an environment alienated and older to these Formations.

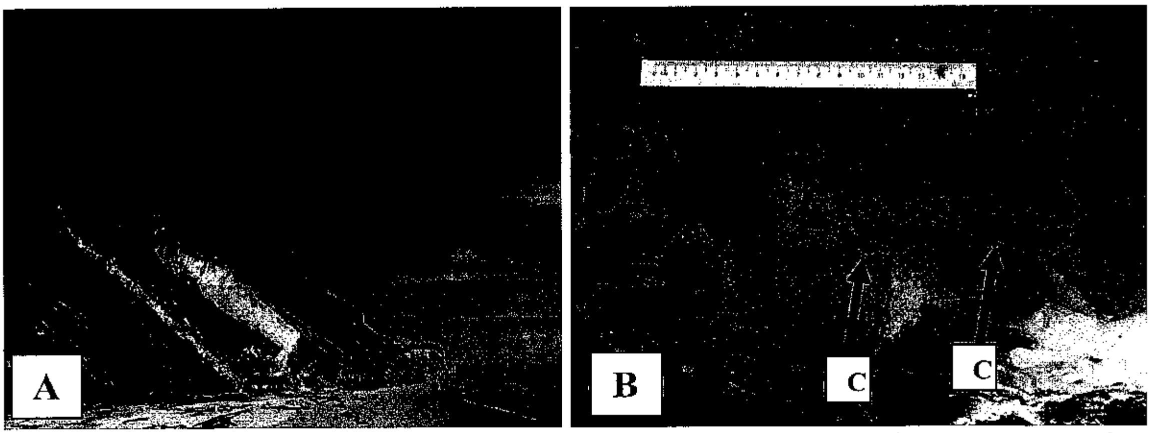


Fig. 4.6 – The bedding and stratigraphy features of both Formations. **A** – Massive sandstone outcrops are quite common features of the Lambir Formation. Height of the model in this figure is 1.80 meter. **B** - Medium fine-grained carbonaceous laminations in the sandstone from the Belait Formation outcrop, Marudi, Northern Sarawak.

4.2.2 Summary

Based on these observations, it is concluded that despite identifying some differentiating characteristics between both formations, there still remains some outcrops where such characteristics are absent. Linking such outcrops to the two formations will remain a challenge.

Table 4.1 – Field characteristics summary table between the Belait and Lambir Formations (NB ***** = More / Common; * = Less / Rare.

Type / Characteristics	**Feature**	**Belait Formation**	**Lambir Formation**
Sedimentary Features	Ripple mark	Asymmetrical [14]	Symmetrical [14]
	Cross-bedding	NIL [14]	***** [14]
Trace Fossils	*Ophiomorpha*	* [26]	***** [26]
	Rhizocorallium	* [26]	***** [26]
	Skolithos	*** [26] (Basal of the Formation)	*** [26]
	Thalassinoides	* [26] (Brunei)	Not detected [26]
Flow pattern	Channels	***** [14, 72, 116]	* [14, 72, 77]
	Conglomerate	**** [14, 26, 72]	NIL [14, 26, 72]
Bedding/ Stratigraphy	Heterolithics sequence	***** Mud-dominated sequence [14, 77]	*** Sand-dominated sequence [14, 77]
	Carbonaceous shale	***** [77]	*** [77]
	Massive SST	** [77]	***** [77]
Coals	Laminations	***** [77]	*** [77]
	Fragments	**** [77]	*** [77]

4.3 Differentiation of the Microfabrics of Sediments in a Fluviatile Grading to Shallow Marine Setting in North-eastern Sarawak

Rock microfabric refers to the mineralogy, orientation, arrangement, packing and the nature of contact of the minerals at a micro-scale [103-105]. Observations on this internal architecture allow us to make inferences and statements on the makeup of the sediments [106]. As a result, microfabric analysis can provide us a better understanding of the process involved in a sedimentary environment and the process occurring during deposition, deformation and/or emplacement [107, 108].

The Lambir Formation (Early to Mid Miocene) and the Belait Formation (Early to Late Miocene) are seismic-time equivalent. The difficulty in distinguishing between these two formations can be encountered in the field too. Thickness of the Lambir Formation at Bakong Valley, Northern Sarawak has been estimated to be around 2000 meters whereas the total thickness of the Belait Formation is estimated to be in excess of 6000 meters. Although the environment of deposition for these two Formations are different [3, 4], distinguishing both formations remain a challenge. Variations between the formations have been demonstrated earlier [14, 15, 72, 77, 109]. However there are lacks of comparison studies on the microfabric characteristics between the two formations.

4.3.1 Microfabric of the Belait Formation

Most of the sandstones and mudrocks from the Belait Formation showed dominance of quartz while the shales have dominance of clay minerals. Sample B1 showed quartz as the predominant mineral at 70% of the total mineralogy whereas clay and iron oxides acquired 25% percent as the matrix counterpart of this thin section. The rest of percentage is dominated by the sample porosity. Quartz grains are generally sub-angular to sub-rounded in shape. In terms of grain sizes, the grains are mostly measured to be around 0.25 mm in diameter or lesser in size (medium to fine-sand) Grains are poorly distributed and in random orientation.

Although some of the quartz grains did not show any signs of strain there are a few fractures detected within the grains (Fig 4.8A). Fracturing of sand grains has been recognized by many researchers for a variety of naturally and experimentally deformed quartzose sedimentary rocks [110, 111]. Fractures occur as a result of overloading pressure during diagenesis, particularly at the mep8sogenesis stage [112, 113] resulting in the subsequent fracturing of bigger grains. This produces fragments of quartz grains of high degree of angularity.

On the other hand, sample B2 showed that the majority of the quartz grains observed are relatively small. The diameter of this secondary quartz is measured to be at around 0.1–0.5 mm in size. The big grains show clustering effects of which individual clusters form quartz aggregates of around 0.3- 0.4mm in size. These aggregates are cemented by either clay or iron. Sample B2 consists of 50 % quartz with an estimated 5–10 percent of void and pores. Iron staining within the matrix can also be observed within the thin sections. Mudclasts (Fig. 4.8B) were also detected indicating that the deposition of the Belait Formation in a medium consisting of mixed materials (sand-sized grains with clay-sized grains). Fine laminations occurred made of carbonaceous materials (Fig. 4.8C) can be observed in these rocks indicating deposition of terriginious materials.

It can be seen in sample B3 that the arrangements between the mineral grains are more compact than the previous Belait Formation samples. Although orientations of the mineral are in random order, individual grains were also finer than the previous samples (Fig. 4.8D). The main mineralogy of the coarse fragments are still quartz which occupies 5-10 percent of the overall mineralogy with 1 percent opaque minerals.

In sample B4, the grains are well sorted and have grain sizes around 0.5-1mm, medium sand. Porosity can be described as good to very good, represented by micro-pores (Fig. 4.9A). The grains are angular to sub-rounded grain in shape without any signs of strain within the viewed sections. Fine interstitial pores filled with opaque minerals (iron oxides) could be observed in the thin sections.

Sample B5 showed lesser porosity, estimated to about 5 percent from the thin section. The quartz grains of the sample are sub-rounded and much similar with the previous sandstones (B4), there are no sign of strains presence or fracturing detected on the quartz grains. The quartz grains consist of 95 percent of the entire slides mineralogy having largest grain size than of all the previous Belait Formation thin sections measuring at 1.5mm in diameter (Fig. 4.9B).

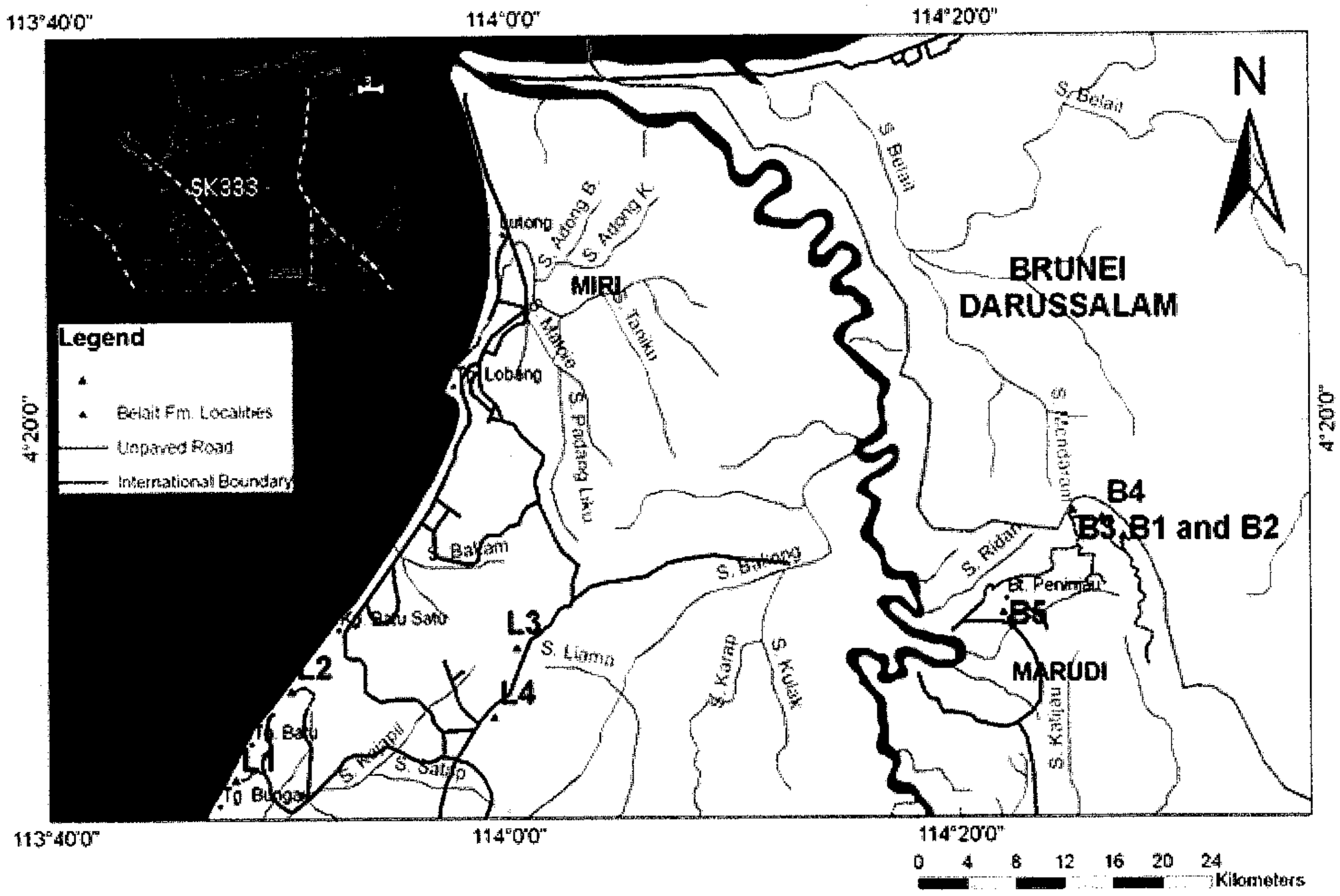


Fig 4.7 - The sampling map of the Belait and Lambir Formation, North-eastern Sarawak. The small red box on the top left indicates the area of current oil exploration block (SK333) encircled in black line which is part of the studied area.

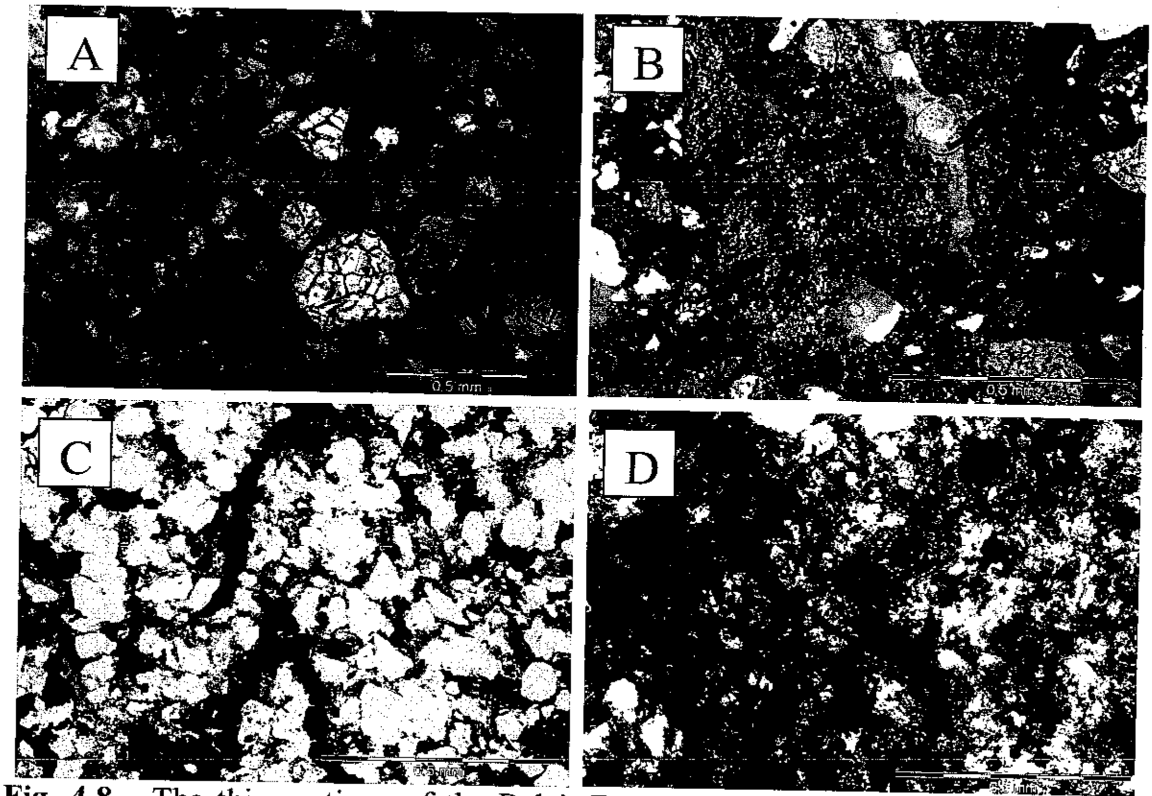


Fig. 4.8 - The thin sections of the Belait Formation samples B1, B2 and B3. **A** - Fracturing in the quartz grains in sample B1. Magnification 40X, XPL. **B** – Mudclasts at the central part of this picture consists of finer grain materials, viewed at 40X magnification, XPL. **C** – Fine striations / laminations of carbonates found in the B1 thin section, viewed at magnification of 40X, PPL. **D** – The silt – clay matrix part of B3 outcrop with presence of micro-pores (red arrow) measured to be in the range of 0.1–0.3mm in average diameter. Magnification at 100X, XPL.

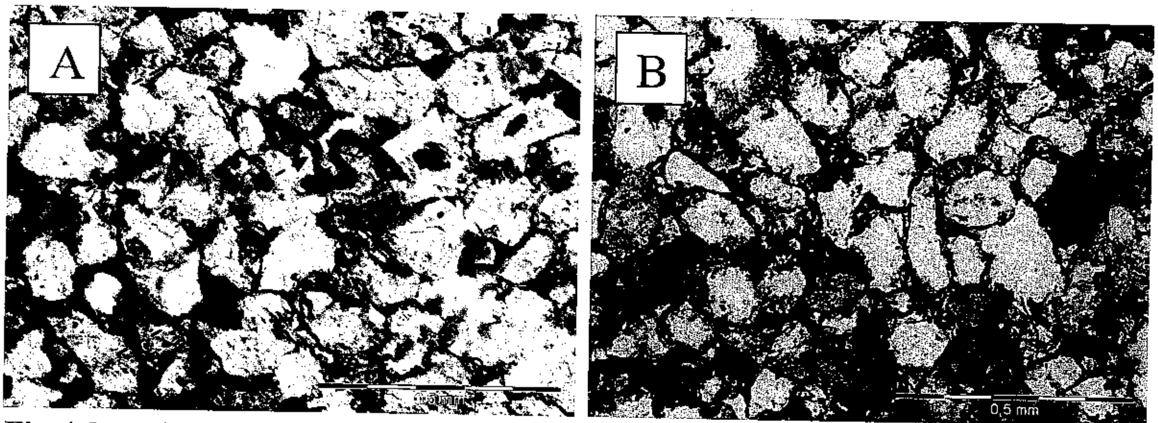


Fig 4.9 – The thin sections of the Belait Formation samples B4 and B5. **A** – Picture showing connected pores (red arrows) in the B4 thin section although a bit reduced by the compact grain arrangement. **B** – The quartz grains of B5 sample from the Belait Formation showing random distributions with compact grain arrangement. Shape of the grains is much similar to B4 outcrop where here it is sub-rounded although there are presence of angular grain-shaped but in lesser extends, viewed at 40X magnification in PPL.

Abundance of quartz grains and the lack of metastable grains (feldspar) in some samples of the Belait Formations samples indicates mineralogical maturity. However, high contents of clay of up to 25% in other samples of the Belait Formation suggest mineralogical immaturity [114, 115]. As such, mineralogical maturity in Belait Formation is complicated.

4.3.2 Microfabric of the Lambir Formation

Three sandstones from the Lambir Formation were collected near Miri. The first two sandstones (L1 and L2) were collected at the beach along the Miri coastal road. The third sample (L3) was collected at Jalan Miri- Bintulu. At the field level, these samples were similar in appearances and texture. All the Lambir Formations rocks are yellowish grey in colour (5Y7 2).

Microfabric analysis shows that all the sandstones are very fine- to fine-grained. Quartz dominates the mineralogy. In sample L1, the quartz grains are 0.1mm in average size with estimated porosity at around 2–3 percent. Quartz content is estimated to be 95% set in a matrix of finer grained minerals consisting of iron and phyllosilicates. The quartz grains are sub-rounded in shape (Fig. 4.10A) with medium sorting between the grain sizes although orientation is still random. Much of the quartz grains show signs of strains and fracturing within the samples. In area where grains are loose and packed, stains and fracturing are generally absent.

In L2 sample, the quartz grains are in the range of 0.1 to 0.2 millimeter in average diameter. Sorting of the grain is moderate. Quartz grains are sub-angular to rounded in shape. Porosity is estimated at 5 percent. Grains of less than 0.1 millimeter in average diameter occupy 5 percent of the entire thin section. Sub-parallel arrangement of the quartz grain can also be observed within the sample (Fig. 4.10B).

Sample L3 thin section analysis showed the composition of the sample consisted of mixture between fine sands and silt sizes grains (Fig. 4.11A). Porosity of the sample is similar to the two previous samples from the Lambir Formation. The grains are also sub-angular in shape and with medium sorting (Fig. 4.11B).

Similar to the sandstones of Belait Formation, sandstones of the Lambir Formation are also mineralogically matured. Clay minerals account for less than 5% of these sandstones. The sandstones have grains that are more rounded compared to the Belait Formation suggesting the grains may have been transported over long distances prior to deposition. Fracturing in the quartz grains was also observed in some samples but the strains in the Lambir Formation sandstones were not as extensive as in the Belait Formation.

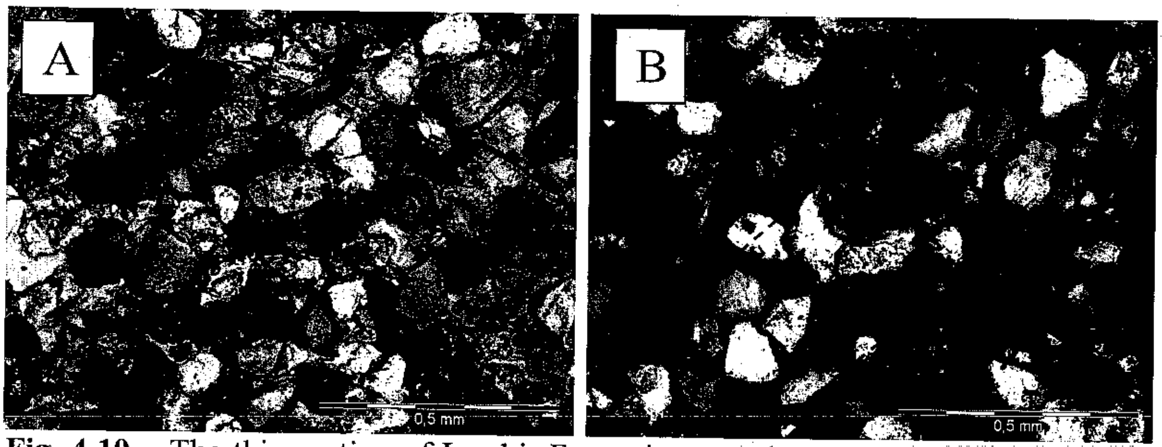


Fig. 4.10 – The thin section of Lambir Formation sample L1 and L2. **A** – The sub-rounded quartz grains in the Lambir Formation L1 thin section viewed in XPL at magnification of 40X. **B** – Sub-parallel arrangement observed in the thin section of L2 outcrop (red lines across the pictures) viewed at 40X magnification in XPL.

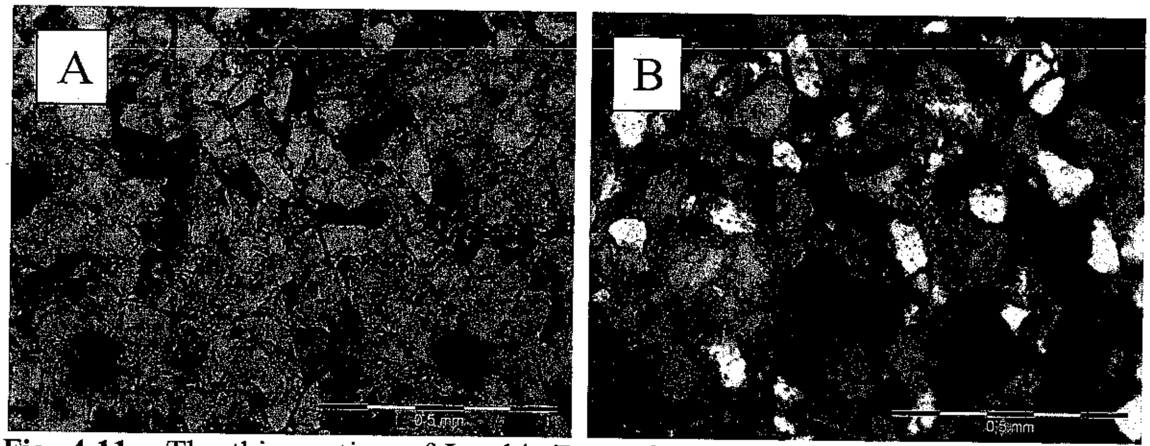


Fig. 4.11 - The thin section of Lambir Formation sample L3. **A** – Mixture of fine sands and silt-grained mineralogy as observed in the L3 thin section. Viewed at 40X magnification (PPL). **B** – Sub-angular grain shape and medium sorting of the grains in the L3 sample as observed in XPL with 40X magnification.

4.3.3 Summary

The presence of sub-rounded grains in the Lambir Formation suggests that the Formation was probably deposited in a high energy setting environment whereas the Belait was deposited in a predominantly much lower energy as indicated by then presence of mudclasts. The high degrees of angularity of the sand grains of Belait Formation suggest a short transportation and fast depositional setting, which is a characteristic for fluvial deposits. Variations in the degree of fracturing of quartz in both formations were probably caused by high compaction experienced during diagenesis of Belait Formation. This suggests that the Belait Formation comprises areas where geopressure anomalies may be present.

Both formations may have also experienced differences in the rate of diagenesis and different compaction rates. This study shows that despite both formations are seismicly equivalent, there may be differences at the field up to microfabric level of observation. In addition to this, differences in geopressure anomaly also warrant a strict differentiation factor for the two formations.

4.4 Spatial and Temporal Variability of the Hydrocarbon Distribution in the Northern Sector of the Belait Formation

Traditionally the Belait Formation has been accepted as barren. However it has been discovered recently that hydrocarbons can be present in various forms in the Formation [109]. The purpose of this study is to investigate further the occurrence of hydrocarbon and to characterize this aromatic hydrocarbon in the northern sector of the Belait Formation in Sarawak.

Four representative samples were selected from an outcrop that had a stratigraphic height of about 100m. These samples were subjected to a full range of mineralo-chemical and petrographical analyse. There is currently insufficient information on the mineralo-chemical variations within this Formation [15]. This information is very important as there is an ongoing exploration and production at SK333 for oil and or gas.

4.4.1 Field Characteristics of the Belait Formation

The outcrop (280m) comprises five facies (Table 4.2), the heterolithics facies, (f_1), sandstone with mud-draped facies (f_2), sandstone with closely spaced channels facies (f_3), massive sandstone facies (f_4) and dark grey shales facies (f_5). According to Padmanabhan [15] sandstones with mud-draped facies, f_2 (at 230m) exhibits literally continuous and discontinuous mud-drapes, with varying degrees of thickness, lengths and density per square metre while another facies comprising sandstone showing coarsening upward sequence, f_3 with closely spaced migrating channels with fills of sand and high carbon contents occurs in high geomorphic positions. Top stratigraphic position facies (f_5), revealed presence of some medium-grained sandstones [15].

Samples studied represent the f_2 sequence of the outcrop. This part consists of sandstone with mud-draped alternating with shales and shows no presence of trace fossils. The coarsening upward sequence was the result of the period where sea level rises [3] and resulted in delta prograding (Fig. 4.12). The alluvial Belait Formation is believed to be part of a deltaic setting [14] with braided river network system.

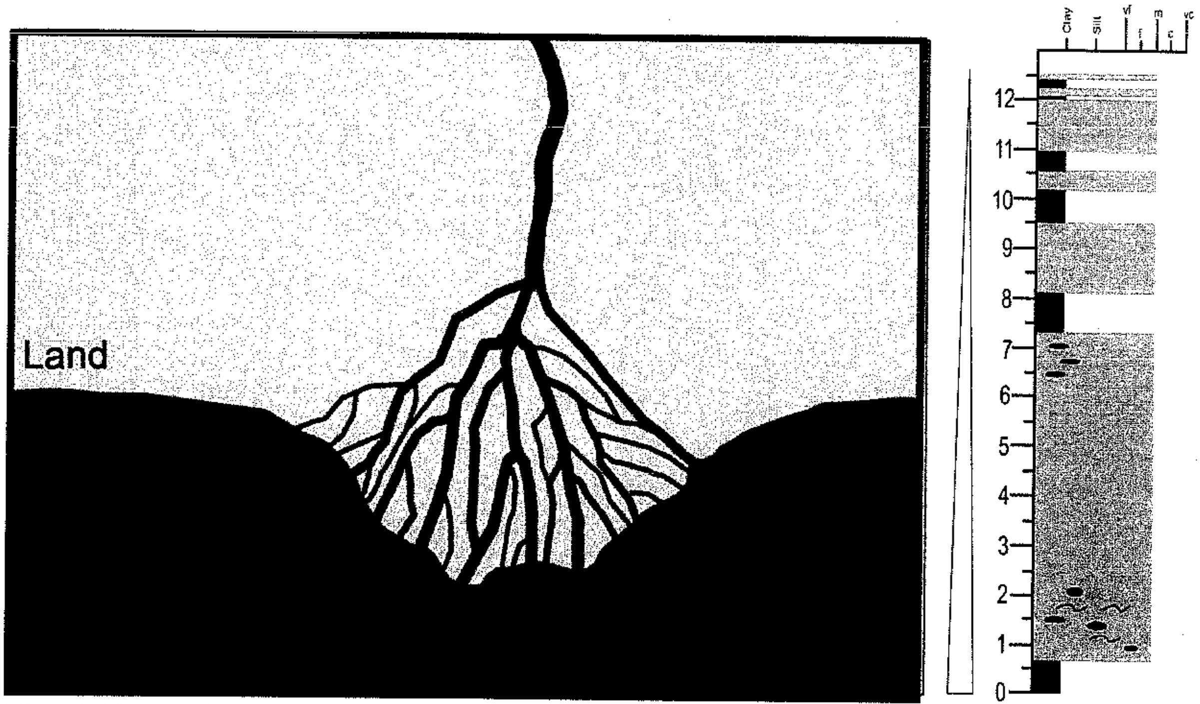


Fig. 4.12 – Paleoenvironment reconstruction of the inferred prograding delta in the northern-sector of the Belait Formation. The fining upwards of the sequence is as seen in the outcrop. N.B. litholog is not in scale.

In this study, two carbonaceous shale and two sandstone layers were selected for sampling from an outcrop located at the Northern-Sector of Belait Formation (Fig 4.13). The samples were labelled respectively as B6 and B8 for carbonaceous shales, B7 and B9 for sandstone. The outcrop studied extends from 4° 15.94' N; 114° 26.271' E to 4° 15.855' N; 114° 26.268' E and comprises five facies (Table 4.2). The selected rock samples were then subjected to a full range of mineralo-chemistry analysis.

Table 4.2 – The studied outcrop facies and its descriptions. (based on Mokhtar [116]).

Facies	Descriptions
f_1	Heterolithics sequence (with remnants of boulders)
f_2	Sandstones with mud-drapes and shales
f_3	Sandstones with closely spaced channels and shales
f_4	Massive sandstones
f_5	Massive dark grey shales

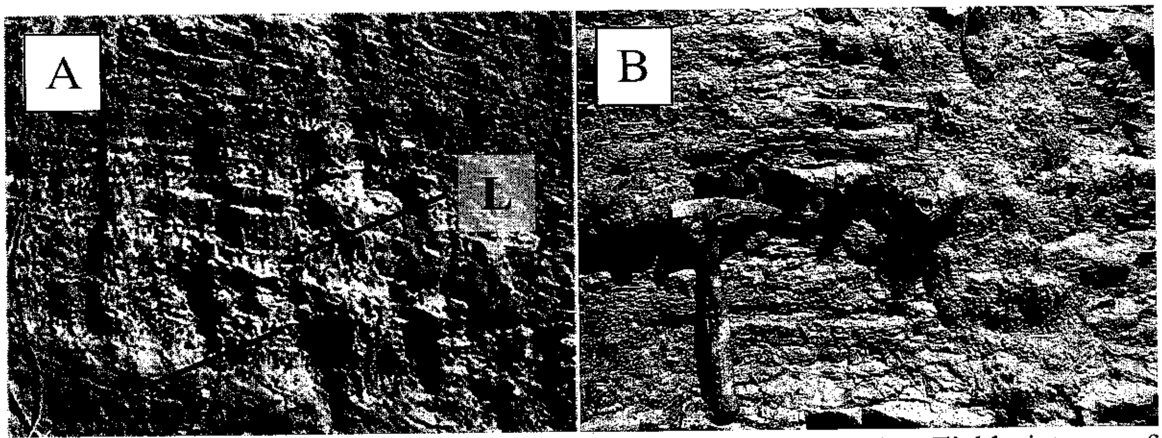


Fig. 4.13 – Features of some of the Belait Formation outcrops. **A** – Field pictures of the outcrop with sand filled laminations (L) and mud drape (m) (0.5m – 1.5m from the section). **B** - Heterolithics sequence (ranging from 0-0.5m of the log section).

4.4.2 Mineralo-chemical Analysis of the Belait Formation

XRF analysis of sandstones (B7 and B9) and shales (sample B6 and B8) showed that Al element in shales is four times higher than in sandstones (Table 4.3). This indicates the presence of clay minerals Kaolinite in these shales. Silicate contents are slightly high in sandstones samples which indicates the higher contents of Quartz, SiO_2. Irons in these samples most probably occur as Goethite FeOOH as confirmed by XRF and FTIR data.

The UV-Vis scans of all samples from 200 – 800nm showed low ratio values around 1.43 to 1.52 (Table 4.3). A low E4/E6 value reflects the pre-dominance of aliphatic structures while a high E4/E6 indicates the pre-dominance of aromatic constituents (Stevenson, 1982). E4/E6 ratio of sandstones showed that the Arenite possesses the E4/E6 value of 1.56 while the ferruginous sandstone E4/E6 is valued at 1.49. The carbonaceous shales of B6 and B8 possess E4/E6 value of 1.41 and 1.48, respectively. From the E4/E6 ratio it can be said that the carbonaceous shales possess a slight pre-dominance of aliphatic structures than the sandstone samples.

Results from FTIR (Table 4.3, Fig. 4.14 and Fig. 4.15) showed that both sandstones and shales contained mixture of aromatic and aliphatic compounds which are acquired by the IR range at around 400-4000cm^{-1}. Various aromatic structures were detected in both samples prominently displayed by the Aryl C=C and Aryl-H at different intensity and throughout the ranges of 400-625cm^{-1} and 900-1100 cm^{-1} respectively. The pre-dominance of aliphatic structures which contributes to the low E4/E6 samples in carbonaceous shales is well represented by paraffin group CH/CH_2 in the samples. Sample B6 also showed aliphatic olefin compound that is found at 1606.59 cm^{-1} which further proves the low E4/E6 ratio of the sample itself. The aliphatic on sample B8 are represented by the shared peaks of CH / Aryl-CH at 694.33cm^{-1}, 775.33cm^{-1} and 796.55cm^{-1}.

Table 4.3 – Mineralo-chemical analysis of the rock samples from the Belait Formation

Label	Lithology	FTIR		XRF						UV-Vis
		Functional group	Band (cm^{-1})	Percentage (%)						E_4/E_6
				O	Al	Si	Mg	Ca	Fe	
B6	Carbonaceous shale	Aryl C=C	432.02, 501.46, 534.25	51.00	8.31	35.51	0.60	0.13	1.16	1.41
		C-H (Str.) / Aryl C-H	694.33							
		C-H (Str.) / Aryl C-H / Aryl-H	775.33, 796.55							
		Aryl-H / Silicates	912.28, 950.84, 1008.70, 1033.77							
		CH_2 (Str.)	1434.94							
		C=O / Aliphatic C=C	1606.59							
		C=O	1785.96							
		CH / CH_2	2925.81							
B7	Arenite	Aryl C=C	426.24, 468.67	52.00	6.60	39.16	0.19	6.6	0.30	1.56
		C-H (Str.) / Aryl C-H	690.47							
		C-H (Str.) / Aryl C-H / Aryl-H	777.26, 796.55							
		Aryl-H / Silicates	912.27							
		C=O	1787.89, 1874.68							
B8	Carbonaceous shale	Aryl C=C (ring bend)	432.02, 501.46, 534.25	51.00	8.42	33.52	0.51	3.40	1.90	1.48
		Aryl-H / Paraffin	694.33							
		C-H (Str.) / Aryl C-H / Aryl-H	775.33, 796.55							
		Aryl-H / Silicates	912.28, 1008.70, 1033.77							
		C=O	1863.10							
B9	Ferruginous sandstone	Aryl C=C	468.67, 536.17	52.00	2.75	41.66	-	0.12	2.40	1.49
		C-H (Str.) / Aryl C-H	690.47							
		C-H (Str.) / Aryl C-H / Aryl-H	777.26, 796.55							
		Aryl-H / Silicates	1031.85, 1085.85							
		C=O	1787.89, 1874.68							
		CH / CH_2	2852.52, 2921.95							

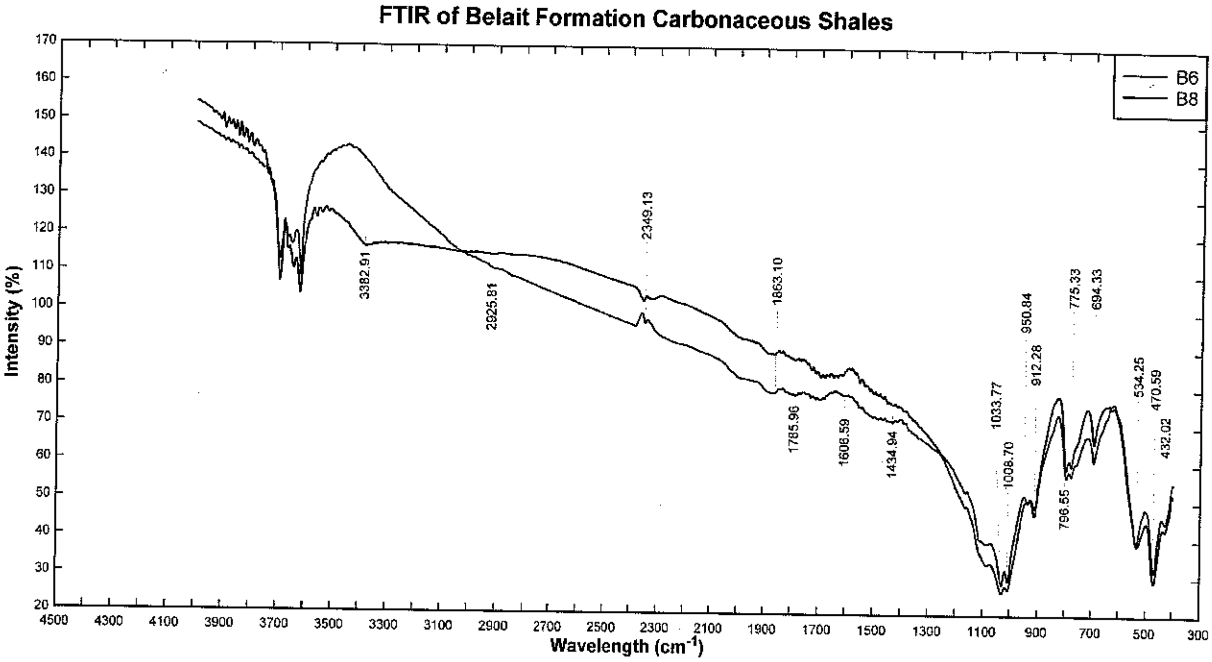


Fig. 4.14 – FTIR spectra for the Belait Formation carbonaceous shales for sample B6 and B8.

The sandstone sample B9 possess much of the aliphatic compounds found in the carbonaceous shales such as the paraffin CH as well as CH / CH_2 compounds which are well represented at 2852.52 cm^{-1} and 2921.95cm^{-1}. The arenite (B7) aliphatic components were only represented by peaks shared between the CH / Aryl-CH and CH / Aryl-CH / Aryl-H at 690.47cm^{-1} and 777.26cm^{-1}, 796.55cm^{-1} respectively resulting in slightly high E4/E6 value. Carbonyl compound was also detected throughout the whole samples which ranges at 1680 – 1900cm^{-1}. Arenite and ferruginous sandstones showed presence of oxygen and hydrogen bond. While the free-OH bonds, at 3600-3200cm^{-1} frequency in these samples indicate presence of goethite.

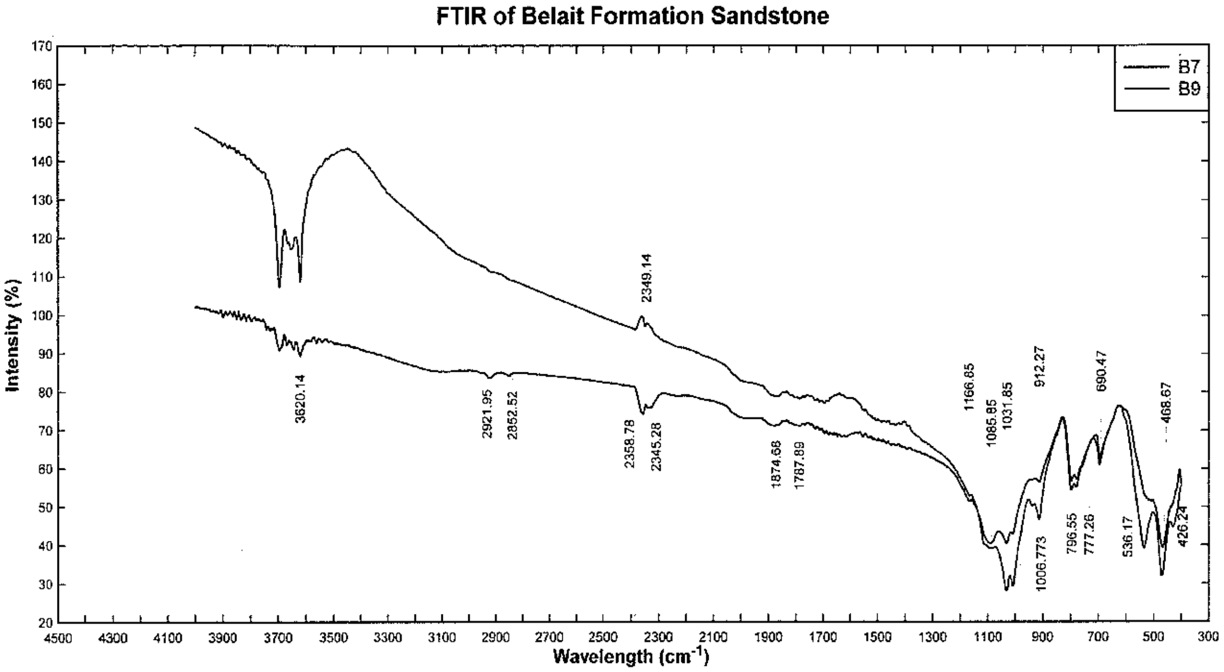


Fig. 4.15 – FTIR spectra for the Belait Formation sandstones for samples B7 and B9.

4.4.3 Summary

FTIR has shown that there are spatial and temporal variability which accounts for the differences in the same sections for different temporal succession within the studied samples. It can then be concluded that there is a spatial and temporal variability of appreciable sense of the hydrocarbon distribution in the samples studied from the northern sector of the Belait Formation.

Presence of hydrocarbon as indicated by the FTIR and UV studies reaffirms the current strong belief that the reservoir potential of the Belait Formation, contrary to the earlier interpretations of the formation as being barren [4], may have been underestimated. It is also worth mentioning that the study shows that the northern sector of the Belait Formation appears to contain mixture of aromatic and aliphatic components.

4.5 Spatial Temporal Variability of the Hydrocarbon Distribution within the Lambir Formation

The Lambir Formation which is the time-seismic equivalents of the Belait Formation has been a proven reservoir for oil and gas in the past. Characterization between these two formations has been performed by various researchers [14, 15, 46, 71, 72, 76, 77, 116]. As most of these characterizations were proposed based on the sedimentary features of these two formations, the current knowledge regarding these formations is restricted to their differences in origin and depositional settings.

Current oil and gas exploration in the SK333 which comprises of the two formations has revived the interests to take a look in the mineralo-chemical contents of these two sedimentary sequences. This is in addition to the presence of aliphatic and aromatics mixture as detected in previous studies conducted on the Belait Formation [14, 109]. This current study aims to further characterize the hydrocarbon distribution in the Lambir Formation and its mineralo-chemical variations as performed on the Belait Formation.

4.5.1 Field Characteristics of the Lambir Formation

Three sandstones from three outcrops (L1 – L3) were collected from the Middle to Late Miocene Lambir Formation around Miri area. The first outcrop (L1) which records a stratigraphic height of around 20 meters was collected from a massive sandstone outcrop facies at Tusan Beach. No structural features were present within the outcrop although occurrences of Ophiomorpha could be seen.

The second outcrop collected at the Kampung Masjid Beach is part of the Lambir Formation that stretched out from the outcrop at Tusan Beach. Sample L2 was collected from the sandstone facies at this outcrop. The outcrop which is around 5 meters in stratigraphic height consists of sand and clay heterolithics sequence facies alternating with sandstone facies.

Sample L3 was collected from an outcrop located at Jalan Miri – Bintulu. The outcrop which is about 6 meters in stratigraphic height consists of two facies, the sand dominance heterolithics facies and massive yellowish sandstone facies. The heterolithics facies was measured to be having thickness which ranges from 1 – 1.5 meters. It comprises sand sequences of 1 – 5 cm thickness alternating with grey shales of less than 1.5 cm thick. The massive sandstones sequence is measured to be no less than 1 meter in height from the total outcrop thickness.

4.5.2 Mineralo-chemical Variations of the Lambir Formation

There is a high percentage of Al, Mg, Si and Ca in all the studied samples (Table 4.4). This might represent clay minerals presence but variations in the amount might suggest a specific clay mineral presents in the samples. Sample L1 contains a high amount of Al and Si with low Ca that might represent kaolinite. While presences of Mg, Al, and Si with Ca might indicate presence of both kaolinite and monmorilonite types of clay in sample L2 and L3.

In the UV-Vis, the three samples recorded variation with sample L1 projected a value that represents aliphatic and aromatic mixtures but with slight aromatic pre-dominance at E4/E6 value of 1.16. Samples L2 and L3 showed E4/E6 ratio of 0.21 and 0.65 respectively. The high E4/E6 value (more than 1.00) in sample L1 indicates pre-dominance of aromatic compounds whereas the low E4/E6 value (less than 1.00) indicates pre-dominance of aliphatic compounds.

The findings on E4/E6 ratios of the studied samples are also supported by the FTIR spectra recorded at 400 - 4000cm^{-1} (Fig. 4.16). Sample L1 recorded presence of aliphatic components such as the CH compound at 2945.01 cm^{-1}, CH3 compound at 1317.30cm^{-1}, 1342.36cm^{-1}, 1361.65cm^{-1} and 2881.45cm^{-1} region. Shared peaks of CH / Aryl-CH / Aryl-H were detected at 692.40 cm^{-1}, 779.19cm^{-1} and 784.97cm^{-1}. Aryl C=C (Olefins) bonds were also detected in a shared peak with carbonyl compound at 1508.23cm^{-1} and 1604.67cm^{-1}.

Table 4.4 – Mineralo-chemical analysis of the rock samples from the Lambir Formation

Label	Lithology	FTIR		XRF (%)						UV-Vis
		Functional group	Band (cm^{-1})	O	Al	Si	Mg	Ca	Fe	E_4/E_6
L1	Sandstone	Aryl C=C	424.31, 489.89, 532.32	51.00	3.95	40.61	0.44	0.13	0.32	1.16
		C-H (Str.) / Aryl C-H	692.40							
		C-H (Str.) / Aryl C-H / Aryl-H	779.19, 798.48							
		Aryl-H / Silicates	912.27, 943.13, 1006.77, 1031.85, 1085.85							
		CH_3	1317.30, 1342.36, 1361.65, 2881.45							
		C=O / Aryl C=C	1508.23, 1604.67							
		C=O	1681.81							
		CH	2945.01							
L2	Sandstone	Aryl C=C	424.31, 470.60, 532.32	54.00	7.01	38.32	0.20	0.12	0.30	0.21
		C-H (Str.) / Aryl C-H	646.11, 692.40							
		C-H (Str.) / Aryl C-H / Aryl-H	784.97, 798.48							
		Aryl-H / Silicates	912.27, 941.20, 1006.77, 1031.85, 1085.85							
		CH_3	1176.78, 1396.37, 1450.37							
		CH_2	1342.36							
		C=O / C=C	1604.67							
		C=O / Aryl C=C	1681.81							
		CH / CH_2	2845.45, 2923.88							
L3	Sandstone	Aryl C=C	424.31, 470.60, 532.32	52.00	5.81	39.81	0.16	0.12	0.28	0.65
		C-H (Str.) / Aryl C-H	692.40							
		C-H (Str.) / Aryl C-H / Aryl-H	779.19, 798.48, 850.55							
		Aryl-H / Silicates	916.12, 941.20, 1006.77, 1031.85, 1085.85							
		CH_3	1317.30, 1342.36, 1361.65, 1396.37, 2881.45							
		CH_2	1473.51							
		CH / CH_2	2923.88							

Aromatic compounds were detected in all studied samples represented by the Aryl C=C bonds occurring at 400 – 600cm^{-1} region in the Infrared (IR) spectra. Mixtures of aliphatic / aromatic peaks (CH / Aryl C-H) compounds were also observed in all samples in the IR spectra region around 690-850cm^{-1}. Low E4/E6 values from L2 and L3 were caused by the pre-dominance of aliphatic components found throughout the samples. These aliphatic dominance samples (L2 and L3) were observed on the IR spectra to be having higher intensity in terms of their aliphatic compounds than sample L1.

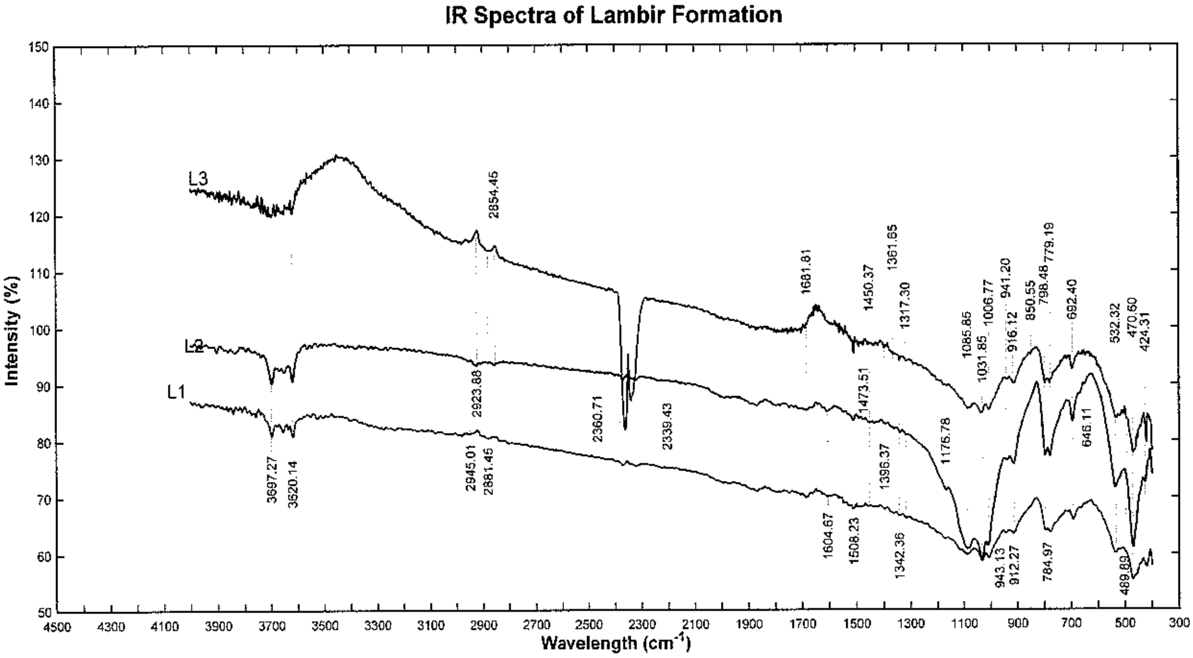


Fig. 4.16 – The Lambir Formation Infrared spectra for the studied sample (L1, L2 and L3).

In sample L2, aliphatic groups such as the CH_2 compounds were detected at 1342.36cm^{-1} whereas the CH3 compounds were detected at 1176.78cm^{-1}, 1396.37 cm^{-1} and 1450.37cm^{-1}, respectively. Shared peaks of CH / CH2 were also detected within the L2 sample at 2845.45cm^{-1} and 2923.88cm^{-1}.

Similarly in sample L3, aliphatic compounds could also be observed within the sample IR spectra at 1473.51cm^{-1} for CH_2 and 2923.88cm^{-1} for the CH / CH2 compounds. Presence of high intensity sharp wagging structures of CH_3 observed at 1317.30cm^{-1}, 1342.36cm^{-1}, 1361.65cm^{-1}, 1396.37cm^{-1} and stretching at 2881.45cm^{-1}

might be the cause of low E4/E6 ratio of this sample. Summary of molecular bonds presence from the FTIR of these samples is displayed in Table 1.1. The C=O peaks detected in samples L1 and L2 at 1508.23cm^{-1}, 1604.67 cm^{-1}, 1681.88cm^{-1} is attributed to the presence of coal. Coals in the forms of laminations, boulders as well as forming part of beds were observed in the Lambir Formation outcrop during field visit (Fig. 4.17). This further suggests deposition of Lambir Formation in an environment where presences of terriginious materials are greatly available within anoxic conditions.

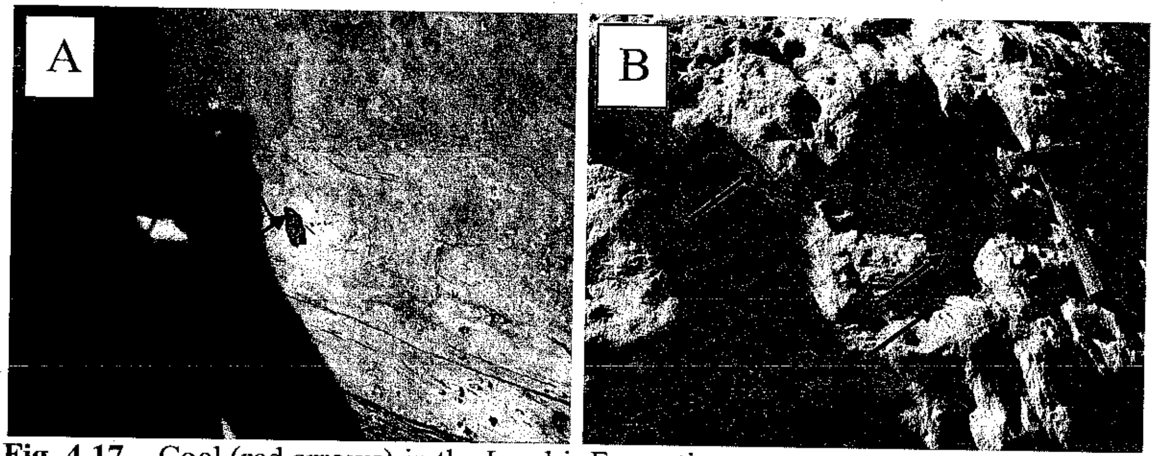


Fig. 4.17 – Coal (red arrows) in the Lambir Formation outcrops can be seen occurring in various forms.

4.5.3 Summary

It can be concluded that the presence of aliphatic compounds in all sample is attributes to the low E4/E6 ratio observed in the samples. Differences in the intensities of the compounds cause variations in the distributions of the hydrocarbons within the samples which suggest the possibility of differential migration in the reservoir of Lambir Formation. Presence of coals in various forms indicate deposition of Lambir Formation in a setting where in-flux of terriginious materials is greatly available and in constant supply with a high energy and slow depositions (i.e. estuarine, littoral setting) with anoxic conditions which are in favor of the deposition of carbonaceous materials.

4.6 Heterogeneity of Hydrocarbon Distribution in Tertiary Sediments of North East Sarawak.

As mentioned earlier in the text, tremendous spatial and temporal variability has been detected within the sedimentary rocks of the Belait and Lambir Formations. Also it has to be mentioned again that the renewed interests for oil and / or gas exploration in this part of Malaysia have been responsible for initiating more research work in this area. Therefore, evaluating the distribution of hydrocarbon resources of both Lambir and Belait Formations will be of valuable interests for the industry.

The primary focus of this study is to observe the quality and the hydrocarbon distributions in both the Belait and Lambir Formations. This study will makes use of geochemical characterization method coupled with some physical properties analysis of the rocks in order to characterize the hydrocarbon distribution in these rocks.

4.6.1 TOC Content

The samples show similar quantitative values for TOC (Table 4.5). Samples B1, B2, and B3 (Belait Formation) have TOC values of 3.48, 3.12 and 2.80% respectively. It can, therefore, be interpreted as a possible source rock material in terms of its TOC contents [1]. The Belait Formation sandstones (B4 and B5) with a TOC ranging from 2.25 – 2.76% and Lambir Formation sandstones (L1 – L4) with a TOC ranging from 2.26 – 2.82% indicating a good organic matter content.

4.6.2 Hg-Porosity and Pore Size

Porosity in the studied samples from the Belait Formation mudrocks (B1, B2 and B3) can be ranged from good to excellent with values of 15, 28 and 17 respectively. In the Belait sandstones, sample B4 and B5 porosity values were recorded at 35 and 37 respectively. Lambir Formation sandstones (L1-L4) porosity values were observed at values around 15 – 36.

Variations were also observed within the pore sizes between both formations. Mudrocks from Belait Formation were observed to have the smallest modal pore sizes which ranges around 30-60nm. The Lambir Formation sandstones (sample L1, L2, L3 and L4) on the other hand were observed to have modal pore sizes of 155nm, 138nm, 146nm, and 144nm respectively. Sandstones samples from the Belait Formation (B4 and B5) recorded the highest modal pore sizes among all samples with values of 165nm and 276nm, respectively.

Table 4.5 – TOC, E4/E6, Porosity and Pore Size of the studied samples.

Sample	TOC (wt. %)	Hg-Porosity (ϕ)	Average Pore Size (nm)	E4/E6 ratio
B1	3.48	15	51	1.58
B2	3.12	28	61	1.79
B3	2.80	17	30	1.70
B4	2.76	35	165	2.13
B5	2.25	37	276	2.69
L1	2.34	36	155	1.16
L2	2.26	36	138	0.21
L3	2.82	24	146	0.65
L4	2.76	15	144	0.89

4.6.3 UV-Vis Analysis

On the E4/ E6 ratio (Table 4.5), the Belait Formation showed that there is a pre-dominance of aromatic components within the samples. Less aliphatic components in the results also indicates that migration of aliphatics might have occurred, Samples B4 and B5 appeared to have retained the aromatics behind during a past migration event as both E4/E6 values for these samples are much higher compared to the rest of the samples. Secondary migration of aliphatics might account for the disappearance of the aliphatics. However migration of aliphatics might have not been extensive in the shales (mudrocks) of the Belait Formation.

Pre-dominance of aliphatic compounds can be seen in the L2, L3 and L4 samples with E4/E6 ratio values of 0.21, 0.65 and 0.89 respectively [61, 65, 93]. Of all the Lambir Formation samples only L1 yielded dominant aromatics based on its E4/E6 ratio values. This heterogeneity as observed within samples in the same formation suggests that different rates of migration from the source may have occurred within the samples in the formation.

4.6.4 Relation of E4/E6 ratio with Porosity and Pore Sizes

It can be observed that with increasing E4/E6 in the Belait Formation samples, the median pore sizes and porosity of the samples also increases. Similar trends were also observed within the Lambir Formation samples E4/E6 ratio with both parameters (porosity and pore size). Trends of these parameters with E4/E6 ratio can be observed in Fig. 4.18A and Fig. 4.18B for the Belait Formation. Lambir Formation samples, however, showed a much lower gradient relationship between these parameters with its E4/E6 ratio (Fig. 4.18C and Fig. 4.18D).

The variations in gradient between these parameters among samples from both Formations could possibly relate with the variations in E4/E6 ratio. This suggests the disappearance of aliphatic components in certain samples with bigger pores which are more likely to have migrated out from the samples during diagenesis resulting in higher values in E4/E6 (value more than 1.0).

4.6.5 FTIR

Differences between the FTIR spectra of the Belait Formations (Fig. 4.19) can be observed within the mudrocks and sandstone samples. In the mudrocks samples, (B1, B2 and B3) it can be observed that although all three samples have similar peaks, differences were observed in terms of the peak intensity.

Carbonyl compounds (C=O) were detected in both formations at the range of 1500 – 1900cm^{-1}. Strong intensity peaks of free-OH compound were also detected in both formations at 3618.21cm^{-1}, 3620.14cm^{-1}, 3705.00cm^{-1} and 3697.27cm^{-1}. These peaks are often associated with presence of either water or oxide minerals in the samples. Sharp prominent peaks were observed around the ranges of 2339.49cm^{-1} - 2376.71cm^{-1}. This represents the presence of multiple bond compounds in both formations.

As indicated by the UV-Vis from E4/E6 ratio, most of the samples from the Belait Formations are aromatic dominated compounds. In the Belait Formation samples (Table 4.6), aromatics hydrogen bond / aromatics group (Aryl-H) were observed to dominate most of the FTIR spectra peaks occurring at the range of 900 – 1250cm^{-1}. Peaks in this region are also attributed to the presence of silicate compounds (900 – 1100cm^{-1}). In terms of hydrocarbon, generally, most of the Belait Formation samples were observed to contain the mixture of aliphatic and aromatic with various proportions. Aliphatic compounds in the mudrock samples (B1, B2 and B3) are well represented by CH peaks at 665.40cm^{-1} and 2925.81cm^{-1} and CH / CH2 peaks at 2854.45cm-1. Shared peaks of CH / Aryl C-H / Aryl-H were observed in all Belait Formation samples with peaks occurring at 772.26cm^{-1} and 796.55cm^{-1} in all samples except B4. CH / Aryl H peaks were present in all samples except B2 occurring at 694.33cm^{-1}. A series of wagging peaks was also observed in most of the samples except in B2 at 1442.66cm^{-1} and 1454.23cm^{-1} representing the CH2 / CH3 compound.

From the Lambir Formation FTIR spectra (Fig. 4.20, Table 4.7), it is observed that there are greater presence of aliphatic compounds throughout the samples (LI, L2, L3 and L4). Aryl C=C (olefins) groups can be observed within the samples stretching at around the 400-600cm^{-1} region. Other occurring regions of aromatic compounds can also be observed together with aliphatic paraffin (CH) and Aryl-H at the region around 690 – 900cm^{-1} as well as within the shared peaks with carbonyl group (C=O) around 1480 – 1680cm^{-1}.

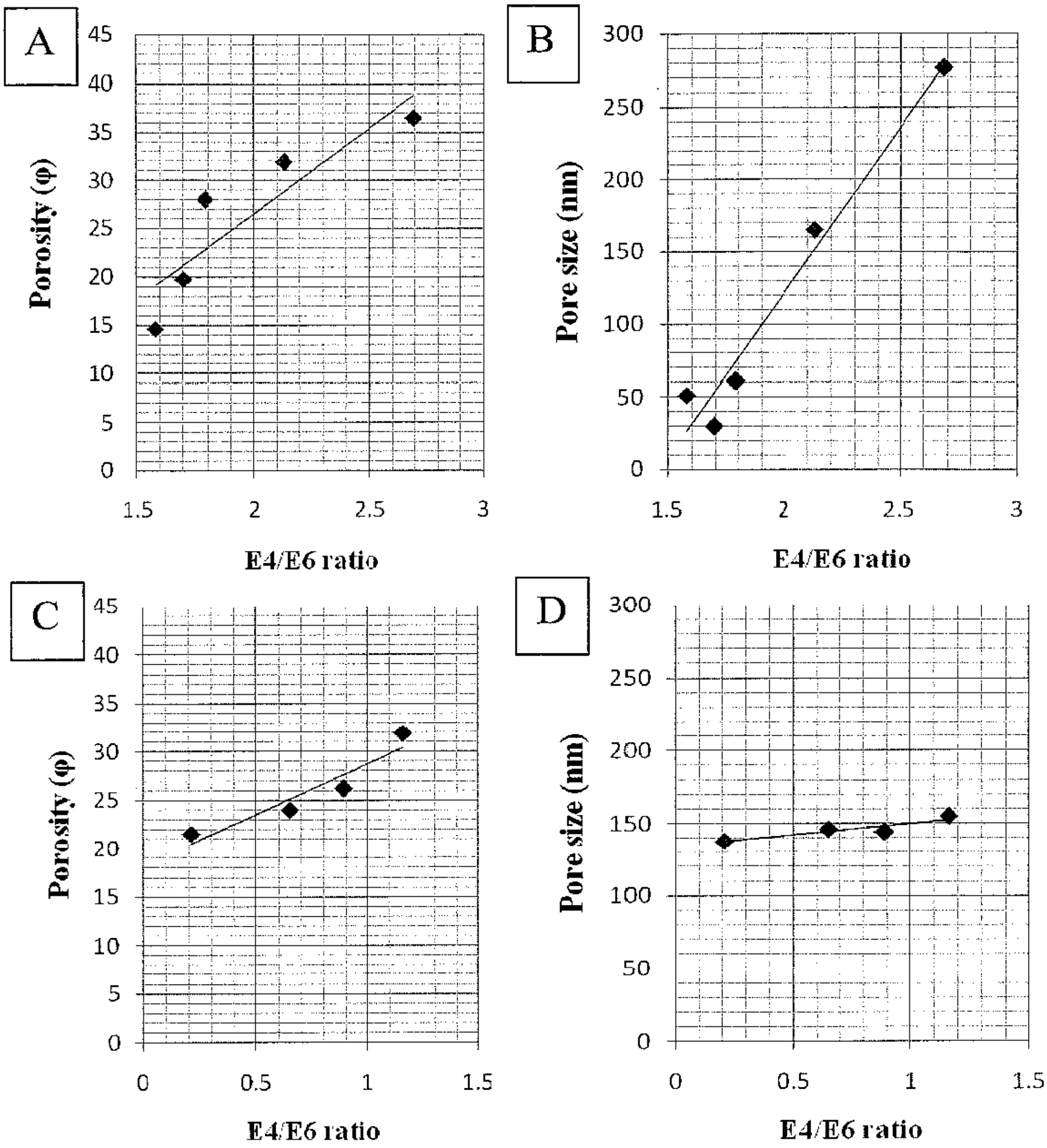


Fig. 4.18 – Relationship between E4/E6 ratio with pore radius and porosity. **A** - Relationship of Belait Formation sandstones E4/E6 values with porosity (ϕ). **B** – Relationship of Belait Formation samples (B1, B2, B3, B4 and B5) E4/E6 values with average pore size. **C** - Relationship of Lambir Formation sandstones E4/E6 values with porosity (ϕ). **D** – Relationship of Lambir Formation sandstones (L1, L2, L3, L4) E4/E6 values with average pore size.

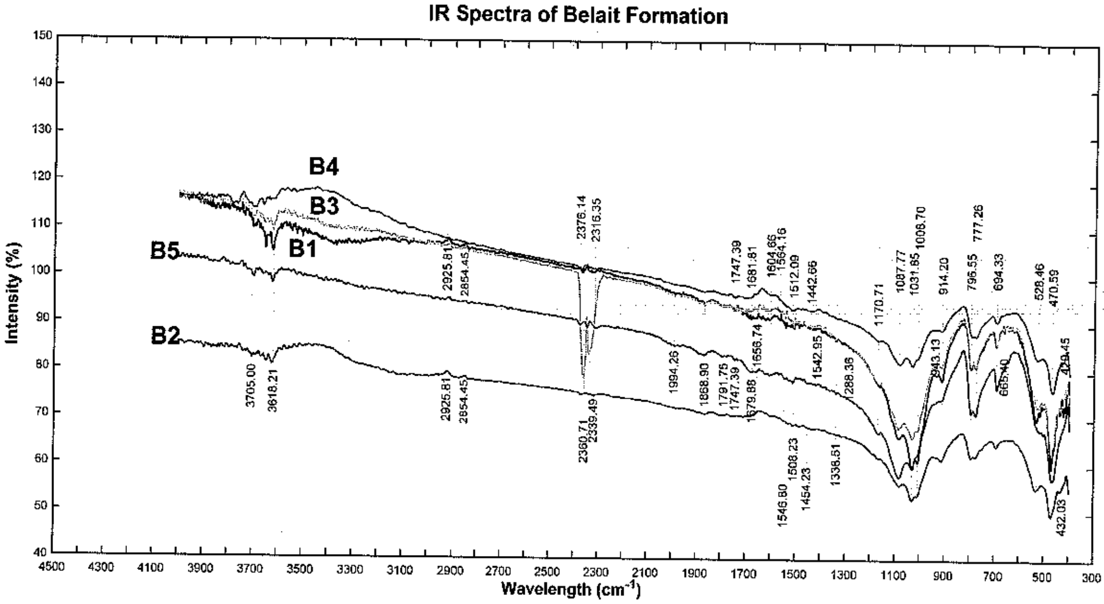


Fig. 4.19 – FTIR spectra for the Belait Formation samples.

Presences of CH_3 (methyl functional group) can be observed in all samples at wavelengths around 1370 – 1390cm^{-1} and 2880 – 2890cm^{-1} regions. Other aliphatic paraffin compounds such as CH were also detected in all samples occurring either independently at 2945.01cm^{-1} or sharing peaks with ethyl (CH_2) at regions around 2840 - 2870cm^{-1} and 2910 – 2940cm^{-1}.

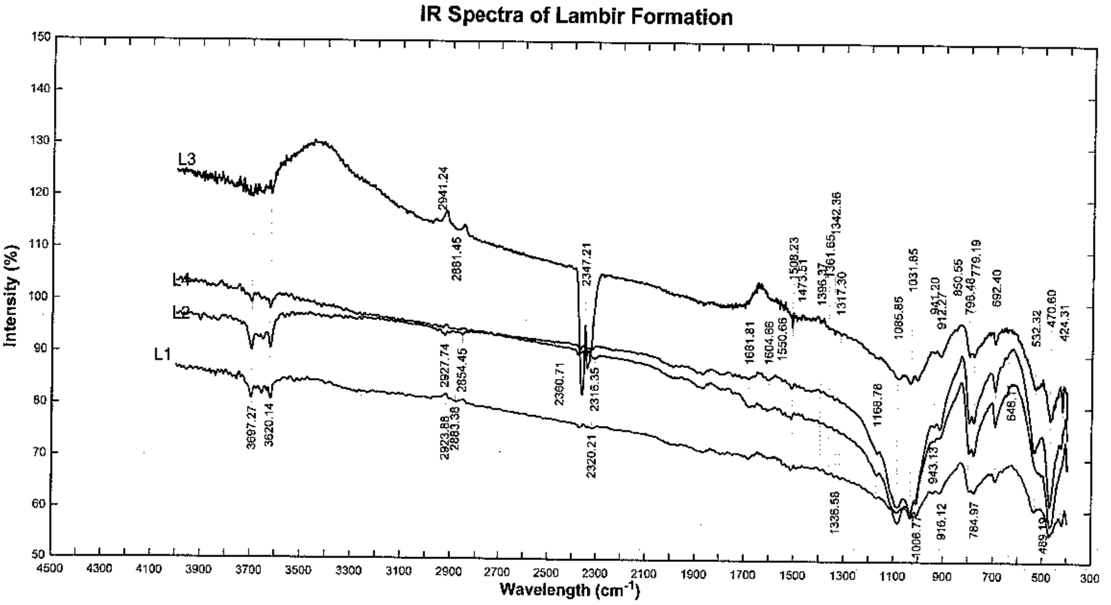


Fig. 4.20 – FTIR spectra for the Lambir Formation samples.

Table 4.6 – Belait Formation analysis of FTIR spectral peaks and UV-Vis E4/E6 ratio

Label	Lithology	FTIR		UV-Vis
		Functional group	Functional group	E_4/E_6
B1	Sandstone	Aryl C=C	420.45, 470.89, 528.46	1.58
		CH	665.40, 2925.81	
		CH / Aryl-CH	694.33	
		CH / Aryl-CH / Aryl-H	777.26, 796.55	
		CH / CH_2	2854.45	
		CH_2 / CH_3	1442.66	
		Aryl-H / Silicates	914.20, 943.13, 1008.70, 1031.85, 1087.77, 1170.71, 1288.36, 1338.51	
		C=O	1681.81, 1868.90	
		C=O / Aryl C=C	1512.09, 1542.95, 1546.16, 1604.66	
B2	Sandstone	Aryl C=C	432.03, 470.59, 528.46	1.79
		CH	2925.81	
		CH / Aryl-CH / Aryl-H	777.26, 796.55	
		Aryl-H / Silicates	914.20,1008.70, 1031.85, 1087.77, 1170.71	
		C=O	1546.80, 1604.66	
		CH / CH_2	2854.45	
B3	Sandstone	Aryl C=C	420.45, 470.89, 528.46	1.70
		CH	665.40, 2925.81	
		CH / Aryl-CH	694.33	
		CH / Aryl-CH / Aryl-H	777.26, 796.55	
		CH / CH_2	2854.45	
		CH_2 / CH_3	1442.66	

Label	Lithology	FTIR		UV-Vis
		Functional group	Band (cm^{-1})	E_4/E_6
B3	SST	Aryl-H / Silicates	914.20, 943.13, 1008.70, 1031.85, 1087.77, 1170.71, 1288.36, 1338.51	
		C=O	1868.90	
		C=O / Aryl C=C	1512.09, 1542.95, 1546.16, 1604.66	
B4	Sandstone	Aryl C=C	470.59, 528.46	2.13
		CH / Aryl-CH	694.33	
		CH / Aryl-CH / Aryl-H	779.19, 798.48	
		Aryl-H / Silicates	914.20, 943.13, 1008.70, 1031.85, 1087.77, 1170.71	
		CH_3	1317.30, 1361.65, 1396.37	
		CH / CH_2	2845.45, 2927.74	
		CH_2 / CH_3	1442.66	
		C=O	1747.39	
		C=O / Aryl C=C	1512.09	
B5	Sandstone	Aryl C=C	470.59, 528.46,	2.69
		CH / Aryl-CH	694.33	
		CH / Aryl-CH / Aryl-H	777.26, 796.55	
		Aryl-H / Silicates	914.20, 1031.85, 1087.77, 1170.71	
		CH_2 / CH_3	1454.23	
		C=O	1679.88, 1747.39, 1791.75	
		C=O / Aryl C=C	1508.23, 1546.80, 1604.66, 1656.74	
		-	-	
		-	-	
		-	-	

Table 4.7 – Lambir Formation analysis of FTIR spectral peaks and UV-Vis E4/E6 ratio

Label	Lithology	FTIR		UV-Vis	Label	Lithology	FTIR		UV-Vis
		Functional group	Band (cm^{-1})	E$_4$/E$_6$			Functional group	Band (cm^{-1})	E$_4$/E$_6$
L1	**Sandstone**	Aryl C=C	424.31, 489.89, 532.32	**1.16**	**L3**	**Sandstone**	Aryl C=C	424.31, 470.60, 532.32	**0.65**
		CH / Aryl-CH	692.40				CH / Aryl-CH	692.40	
		CH / Aryl-CH / Aryl-H	779.19, 798.48				CH / Aryl-CH / Aryl-H	779.19, 798.48, 850.55	
		Aryl-H / Silicates	912.27, 943.13, 1006.77, 1031.85, 1085.85, 1168.78				Aryl-H / Silicates	916.12, 941.20, 1006.77, 1031.85, 1085.85	
		CH_3	1317.30,1342.36, 1361.65, 2881.45				CH_3	1317.30, 1342.36, 1361.65, 1396.37, 2881.45	
		C=O / Aryl C=C	1510.16, 1604.67				CH_2	1473.51	
		C=O	1681.81				C=O / Aryl C=C	1508.23	
		CH	2945.01				CH / CH_2	2923.88	
L2	**Sandstone**	Aryl C=C	424.31, 470.60, 532.32	**0.21**	**L4**	**Sandstone**	Aryl C=C	424.31, 470.60	**0.89**
		CH / Aryl-CH	646.11, 692.40				CH / Aryl-CH	646.11, 692.40	
		CH / Aryl-CH / Aryl-H	784.97, 798.48				CH / Aryl-CH / Aryl-H	779.19, 798.48	
		Aryl-H / Silicates	912.27, 941.20, 1006.77, 1031.85, 1085.85, 1168.78				Aryl-H / Silicates	912.27, 1006.77, 1085.85, 1168.78,	
		CH_3	1176.78, 1342.36, 1396.37, 1450.37				CH_3	1317.30, 1361.65, 1396.37	
		C=O / C=C	1604.66				CH / CH_2	2854.45, 2927.74	
		C=O	1681.81				C=O / C=C	1550.66, 1604.66	
		CH / CH_2	2854.45, 2927.74				C=O	1681.81	

4.6.6 Summary

These findings from the FTIR, UV-Vis and E4/E6 ratio suggest that samples B1-B5 are possibly type-I reservoir rocks, with B1-B3 being possibly good source rock materials and B4 and B5 being possibly good reservoir quality rocks. L1 is probably comparable to a type-I reservoir quality rock. Due to low E4/E6 ratios, L2, L3 and L4 are probably comparable with a type-I or type-II reservoir quality rocks.

4.7 Comparison between Fluviatile - Shallow Marine Settings in the Tertiary Sediments of North-eastern Sarawak, Borneo.

Earlier interpretation of Sarawak geology (Fig. 4.21) has been extensively compiled mainly for the purpose of oil exploration and its mineral resources. Geological maps have been published [3, 4, 33] and these provide a general framework of the distributions of the main rock types. However, the Lambir Formation (Early to Mid Miocene) and the Belait Formation (Early to Late Miocene) are indistinguishable in seismic sections (Fig. 2.2). The difficulty in distinguishing between these two formations can be encountered in the field too. Although the environment of deposition for these two formations were known to be different [3, 4], equal grain distributions, lack of paleontological data and structural features have further complicated the effort of distinguishing them.

It is the aim of this work is to examine both Formations in terms of their sedimentary structures and a series of lab analysis involving microfabrics observations, petrophysical and geochemical analysis of these rocks with the aim to produce a list of differentiating characteristics. The list produced is hoped to help future works to distinguish both formations. A total of twelve samples were collected (Fig. 4.22; Table 4.8) and subjected to a number of analysis to achieve this objective.

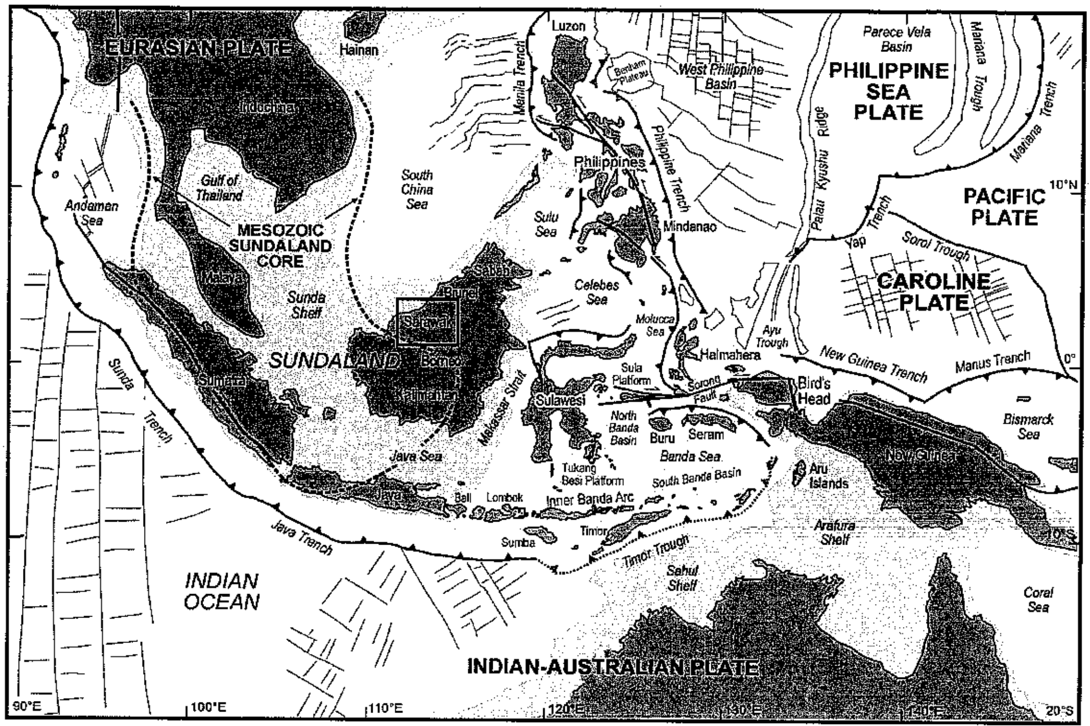


Fig. 4.21 – Sarawak in its regional context [from 117].

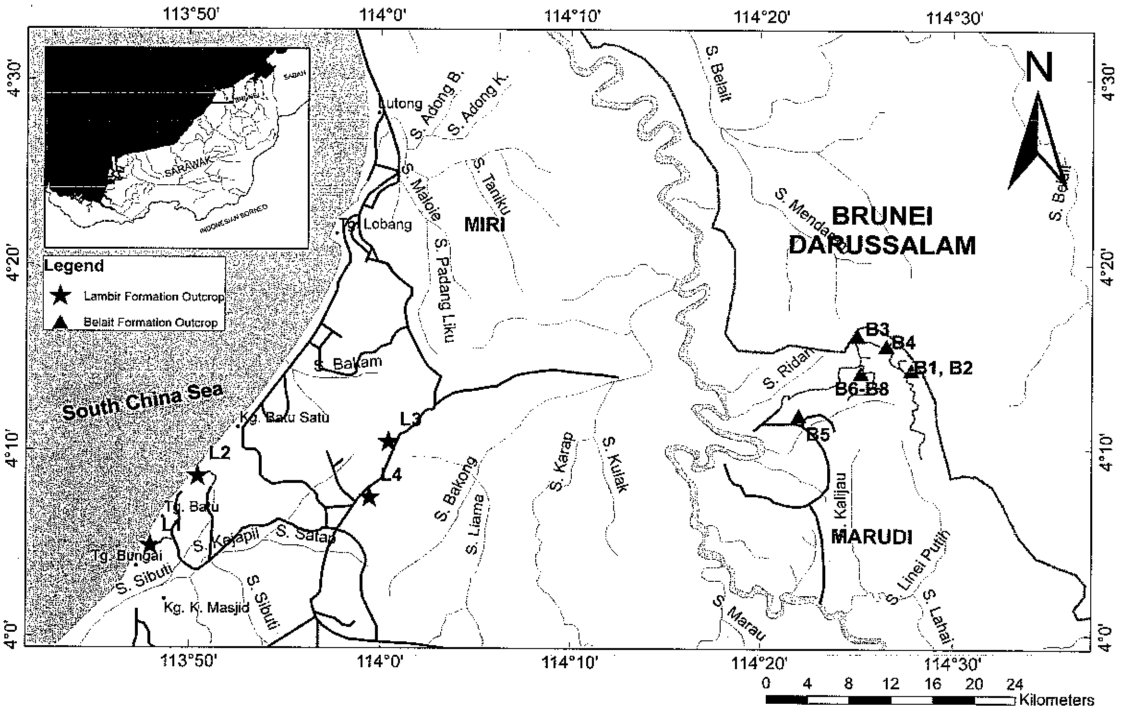


Fig. 4.22 – Map of the study area. Inlets (on top corner left indicates the current area for oil exploration block SK333 in the proximity of both Formations).

Table 4.8 – Sample label, Formation, Lithology [74] and coordinates for the samples collected.

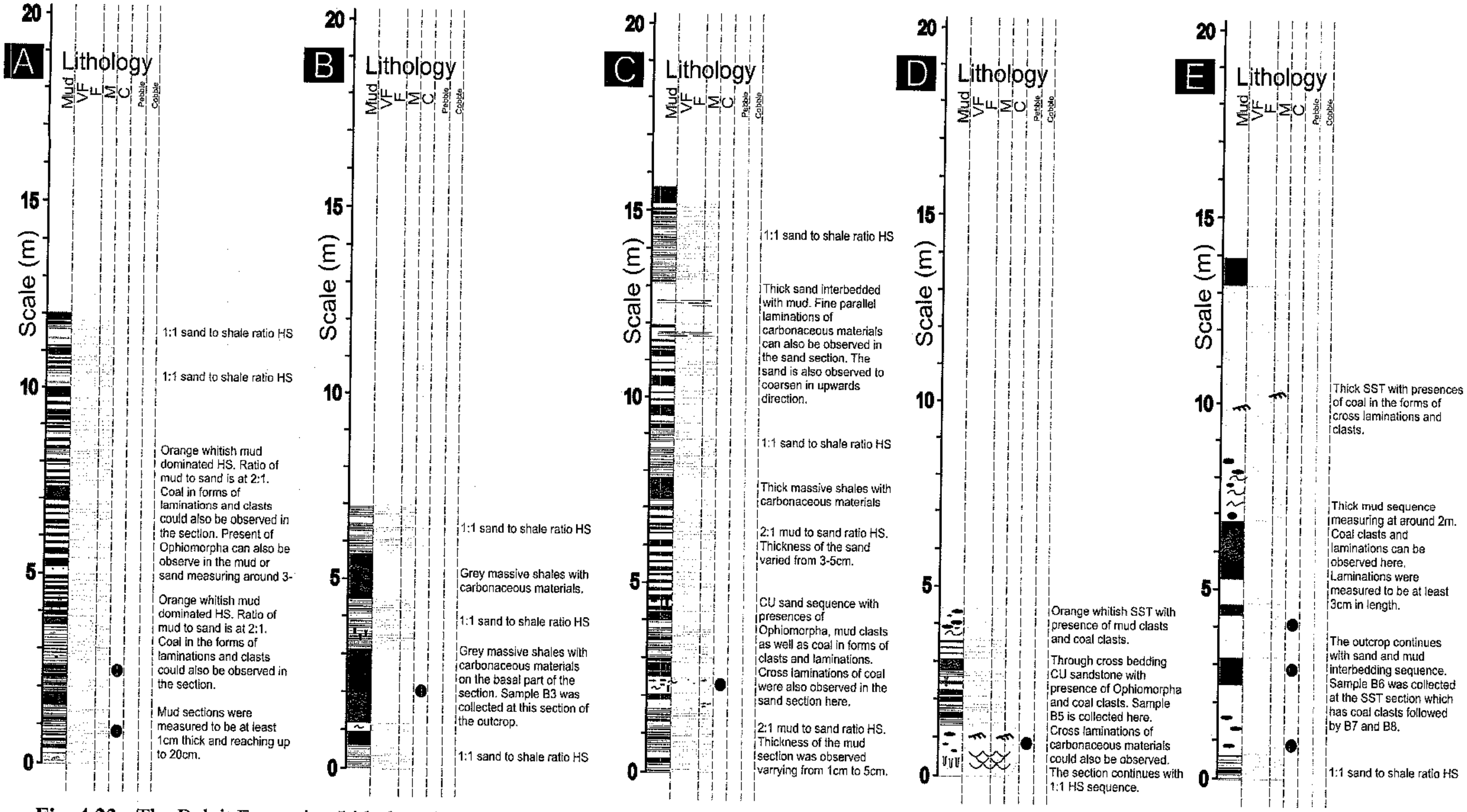
Sample Label	Formation	Lithology [74]	Coordinates
B1	Belait Formation	Mudrock	N 4° 16.265', E 114° 26.426'
B2	Belait Formation	Mudrock	N 4° 16.265', E 114° 26.426'
B3	Belait Formation	Mudrock	N 4° 16.209', E 114 26.311'
B4	Belait Formation	Quartz Arenite	N 4° 15.701', E 114° 26.267'
B5	Belait Formation	Quartz Arenite	N 4° 11.581', E 114° 22.118'
B6	Belait Formation	Quartz Arenite	N 4° 14.977', E 114° 25.112'
B7	Belait Formation	Mudrock	N 4° 14.977', E 114° 25.112'
B8	Belait Formation	Quartz Arenite	N 4° 14.977', E 114° 25.112'
L1	Lambir Formation	Quartz Arenite	N 4° 7.304', E 113° 49.114'
L2	Lambir Formation	Quartz Arenite	N 4° 11.086', E 113° 52.497'
L3	Lambir Formation	Quartz Arenite	N 4° 21.6167', E 114° 0.550'
L4	Lambir Formation	Quartz Arenite	N 4° 24.6167', E 114° 1.480'

4.7.1 Discussion on the Field Characteristics of the Belait and Lambir Formation

Based on the discussion in section 4.2, it is evident that both formations cannot be really distinguished from each other in the field. In addition, the following subtopics will discuss the differentiating characteristics of these two formations.

This study shows that based on the sand to mud ratio that the Belait Formation is fluviatile (Fig. 4.23) whereas the Lambir Formation is shallow marine (Fig. 4.24). In principle, both Formations should show different sedimentary features [95, 96, 192, 115, 118-120].

In this respect, it is noted that the conglomerate is found in scattered locations in the Belait Formation. However this may not be totally suitable as a universal field distinguishing characteristics since many part of the Belait Formation do not have basal conglomerate. As noted earlier, the presence and type of ripple marks could assist in differentiating between these Formations. However the occurrence of such feature is again limited in some exposure only.



A

1:1 sand to shale ratio HS

1:1 sand to shale ratio HS

Orange whitish mud dominated HS. Ratio of mud to sand is at 2:1. Coal in forms of laminations and clasts could also be observed in the section. Present of Ophiomorpha can also be observe in the mud or sand measuring around 3-

Orange whitish mud dominated HS. Ratio of mud to sand is at 2:1. Coal in the forms of laminations and clasts could also be observed in the section.

Mud sections were measured to be at least 1cm thick and reaching up to 20cm.

B

1:1 sand to shale ratio HS

Grey massive shales with carbonaceous materials.

1:1 sand to shale ratio HS

Grey massive shales with carbonaceous materials on the basal part of the section. Sample B3 was collected at this section of the outcrop.

1:1 sand to shale ratio HS

C

1:1 sand to shale ratio HS

Thick sand interbedded with mud. Fine parallel laminations of carbonaceous materials can also be observed in the sand section. The sand is also observed to coarsen in upwards direction.

1:1 sand to shale ratio HS

Thick massive shales with carbonaceous materials

2:1 mud to sand ratio HS. Thickness of the sand varied from 3-5cm.

CU sand sequence with presences of Ophiomorpha, mud clasts as well as coal in forms of clasts and laminations. Cross laminations of coal were also observed in the sand section here.

2:1 mud to sand ratio HS. Thickness of the mud section was observed varrying from 1cm to 5cm.

D

Orange whitish SST with presence of mud clasts and coal clasts.

Through cross bedding CU sandstone with presence of Ophiomorpha and coal clasts. Sample B5 is collected here. Cross laminations of carbonaceous materials could also be observed. The section continues with 1:1 HS sequence.

E

Thick SST with presences of coal in the forms of cross laminations and clasts.

Thick mud sequence measuring at around 2m. Coal clasts and laminations can be observed here. Laminations were measured to be at least 3cm in length.

The outcrop continues with sand and mud interbedding sequence. Sample B6 was collected at the SST section which has coal clasts followed by B7 and B8.

1:1 sand to shale ratio HS

Fig. 4.23 - The Belait Formation Litholog. **A** - Sample B1 and B2 outcrop. **B** - Sample B3 outcrop. **C** - Sample B4 outcrop. **D** - Sample B5 outcrop. **E** - Sample B6, B7 and B8 outcrop. Sample from each outcrop is collected at the point labelled by the star at the log. HS in the description refers to heterolithics. SST here refers to sandstone.

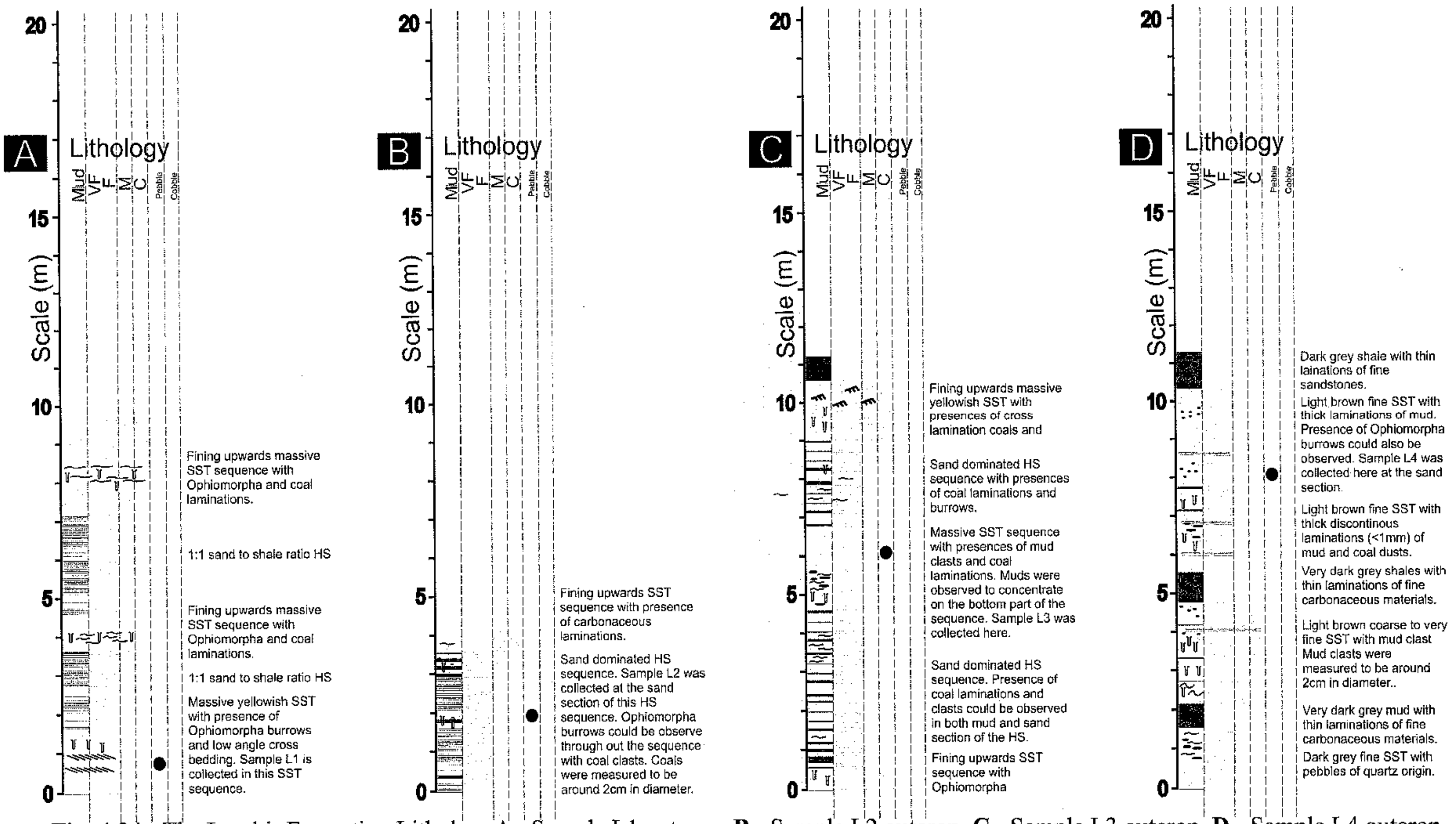


Fig. 4.24 - The Lambir Formation Litholog. **A** - Sample L1 outcrop. **B** - Sample L2 outcrop. **C** - Sample L3 outcrop. **D** - Sample L4 outcrop. Sample from each outcrop is collected at the point labelled by the star at the log. HS in the description refers to heterolithics. SST here refers to sandstone.

The preceding discussion indicates that the field observations from selected outcrops can be summarized as key differentiating characteristics to distinguish between these two formations. Ten features could be observed and are proposed as to aid in differentiating the two formations in the field (Table 4.1).

4.7.2 Microfabric Characteristics

Microfabric observation on both formations revealed that all samples are dominated by presence of quartz and clay minerals. Abundance of quartz grains and lack of metastable grains suggest that these formations are mineralogically mature [74, 115]. The Belait Formation sandstones are made of fine to medium grains of quartz.

Grains are poorly distributed and in random order. Quartz grains are generally sub-angular to sub-round in shape (Fig. 4.25A). This suggests a very short distant transportation. Similarly, quartz dominates the mineralogy of the Lambir Formation. Contrarily, these grains are generally sub-rounded in shape having fine-grained size (Fig. 4.25B). This is as opposed to the short transportation suggested for the sediments of Belait Formation. These grains also possess medium sorting although their orientation within the whole microfabric structure remains random. Mudrocks of Belait Formation were observed to have more compact arrangements. Grain size of these mudrocks was measured to be less than 0.625mm. Fine striations of carbonaceous materials could also be observed within the mudrocks fabric.

Another important feature from microfabric observation of both formations is the fracturing of quartz grains. The effect of quartz fracturing was observed to be more extensive in the Belait Formation samples rather than the Lambir Formation (Fig. 4.25C and Fig. 4.25D). Fracturing of quartz grains have been recognized by many researchers for a variety of naturally and experimentally deformed quartzose sedimentary rocks [110, 111]. Quartz fracturing occurred as a result of overloading pressure during diagenesis, particularly during the mesogenesis stage [112, 113] resulting in the subsequent fracturing of bigger grains. This produces fragment of quartz grains of high degree of angularity, as has been observed in the Belait Formation. The variations in the degree of fracturing between both formations possibly point to high compaction experienced by Belait Formation due to differences in thickness between the two formations. This also suggests that the Belait Formation possibly comprises areas with geopressure anomalies.

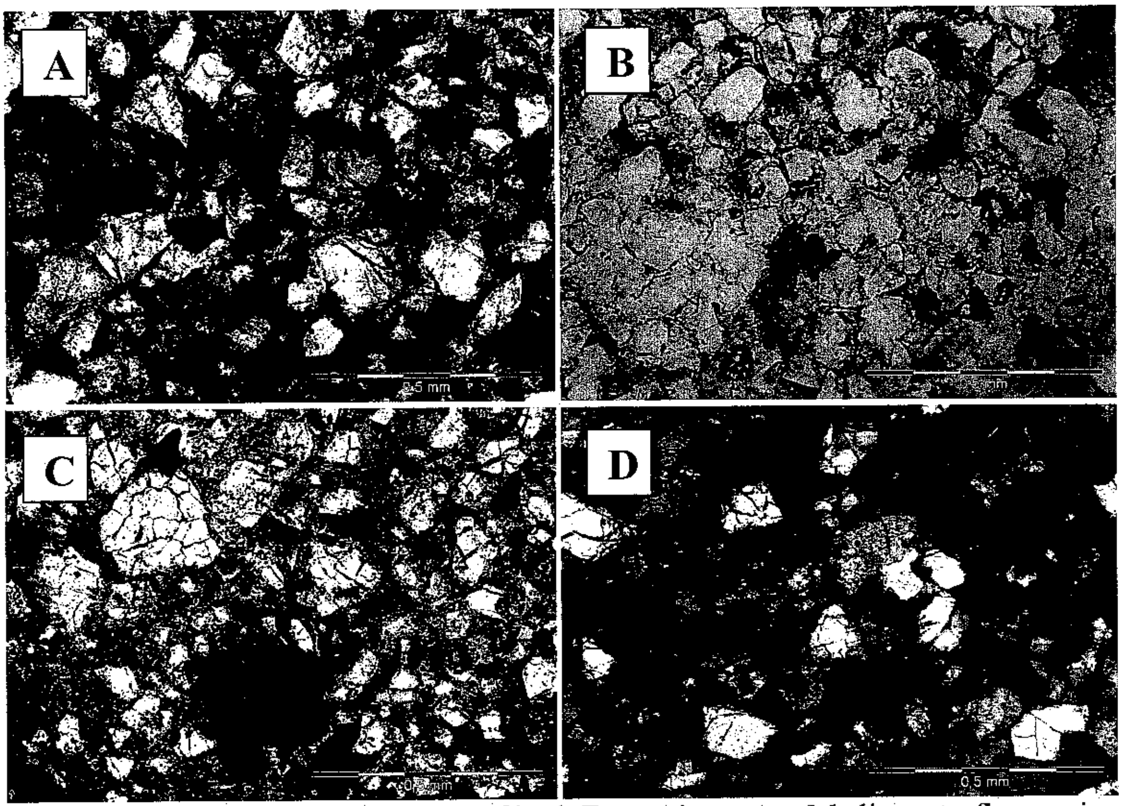


Fig. 4.25 – The microfabric features of both Formations. **A** – Medium- to fine-grained sub-angular quartz in the Belait Formation sandstone sample B4. **B** – Sub-rounded shaped grains in the Lambir Formation sandstone sample L1. **C** – Fracturing of quartz grains in a sandstone from the Belait Formation (sample B3). **D** – Fracturing of quartz grains in a sandstone from the Lambir Formation (sample L2).

4.7.2.1 Mineralogy

XRD analysis from both formations revealed that all samples are composed dominantly of quartz. Occurrences of quartz were detected at 0.424 – 0.428nm for the medium intensity peaks. The maximum intensity peaks occurred at around 0.333 – 0.336nm. The peaks position and values obtained from quartz peaks of both formations were very similar to each other. This suggests that the source materials of both formations could be from the same origin but experienced different depositional setting.

The Belait Formation contains clay minerals such as Kaolinite and probably Illite (Fig. 4.26). These phyllosilicates groups were detected in all samples except B5, which showed only presence of quartz. Likewise, the Lambir Formation contains Kaolinite and probably Illite as well (Fig. 4.27). Presence of kaolinite in all the samples from both formations generally suggests a continental deposition [114, 115]. This is since kaolinite is stable at continental conditions, fresh water deposits and in soils undergoing weathering [115]; whereas presence of illite and kaolinite together indicates shallow level of burial stage experienced by both formations [115]. Most samples in both formations have well developed peaks of phyllosilicates and tectosilicates. This shows that there has been minimum to nil alteration of the phyllosilicates.

4.7.2.2 Clay Minerals from EGME Specific Surface Area

Sandstones from both formations displayed surface area values varying around 23 - 29 m^2/g (Table 4.5). Higher values for surface area were recorded from the mudrock samples (B1, B2 and B3) of the Belait Formation which ranges around 32 - 37 m^2/g. These values suggest presences of micas and / or kaolinite group of phyllosilicates [47] in the samples. Similar values in the surface area from sandstone of both formations suggest similar presence of phyllosilicates within the samples.

4.7.3 Petrophysical Properties

4.7.3.1 Hg-Porosity and Pore Size

Porosity greater than 25% is considered to be good to excellent; 15-25% porosity is considered to be fair to good and less than 15% porosity is considered poor. Sample B4 and B5 from the Belait Formation recorded porosity values of 35% and 37% respectively (Table 4.5). Lambir Formation sandstones (sample L1-L4) were observed of having porosity values varying from 15% to 36%. This means that Belait Formation sandstone have porosity that can be considered as excellent while Lambir Formation sandstones have porosity that ranges from fair to excellent rating. Lambir Formation sandstones (sample L1-L4) were also observed to have smaller range in average pore sizes comparing to the Belait Formation sandstones (sample B4 and B5). The Lambir Formation sandstone pore sizes have values of 155nm, 138nm, 146nm, and 144nm, respectively. Sandstones samples from the Belait Formation (B4 and B5) have higher pore size with values of 165nm and 276nm.

These variations suggest possibilities of higher trends in geopressure anomalies experienced by the thicker Belait Formation with bigger grains size than the Lambir Formation. Alteration of porosity with increased geopressure anomalies could cause extensive mineral dissolution. Combined reaction by the sediments and connate water may have dissolved unstable grains of the Belait Formation to yield higher porosity. Higher initial porosities and permeability due to poorly sorted sediments in Belait Formation may have also provided rapid movement of the interstitial water and resulting in a greater chance for the dissolution of unstable grains.

Mudrocks from Belait Formation (sample B1-B3) were observed to account for smallest values in both pore sizes and porosities (Table 4.5). Higher porosity however was observed for sample B2 at 28% than the 15% and 17% in sample B1 and B3 respectively. This varies greatly from poor to excellent in rating. Variations between the porosity and pore sizes in these mudrocks possibly suggest differential compaction trends experienced by Belait Formation. Reduction of porosity in the mudrocks could also be possibly caused by dissolutions of unstable minerals. The Belait Formation which contains substantial amount of compacted mud/shales section would discharge a large volume of water. This water with increases in geopressure anomalies could possibly cause the dissolution of unstable framework in the mudrocks.

4.7.3.2 Thermal Conductivity Estimations

Thermal conductivity values between the sandstone samples from both formations are very similar (Table 4.5 and Table 4.9). Sandstones from the Belait Formation showed a range of values from 2.2 to 4.2$Wm^{-1}k^{-1}$. Sandstones from the Lambir Formation showed a narrower range around 2.4 to 3.9$Wm^{-1}k^{-1}$. The Belait Formation mudrock samples however seem to possess higher range of values in thermal conductivity.

This suggests that samples which have a much more compact arrangement in their fabric tend to have higher conductivity. This can be explained by good grain contacts in compact samples (i.e. mudrocks), which create a better conductance bridge for heat to transfer than samples which have looser grain arrangement. It could also be observed that mono-mineral sample (B5) possesses lesser thermal conductivity than samples which have multi-minerals content. The lowest thermal conductivity value however was recorded by sample has multi-minerals content but possesses highest porosity. Presence of porosity / void between the grains reduces grain to grain contact resulting in lower thermal conductivity. The subsequent subtopic discusses the relation of thermal conductivity and porosity among the samples.

4.7.3.3 Thermal Conductivity versus Porosity

This trend observed between the two parameters implies that samples with lower porosity have higher conductivity. The porosity and thermal conductivity values of these samples can be observed in Table 4.9. A graph was plotted using these parameters, and a best-fit line was drawn to justify the relationship between the thermal conductivity and porosity values (Fig. 4.28). The graph suggested that there is an inverse relationship between the porosity and thermal conductivity of the studied samples. This relationship is expressed by $y = 4.8402x^2 -42.946x=109.62$.

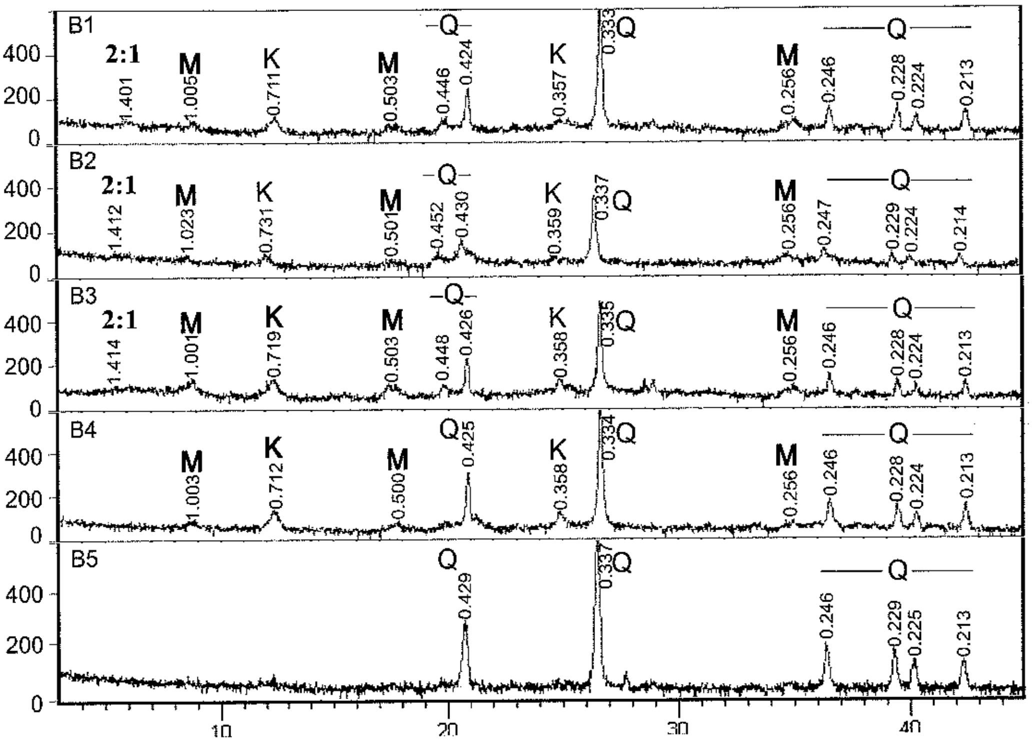


Fig. 4.26 - The XRD results of oriented specimens from the Belait Formation (K= Kaolinite, M= Illite and Q=Quartz.

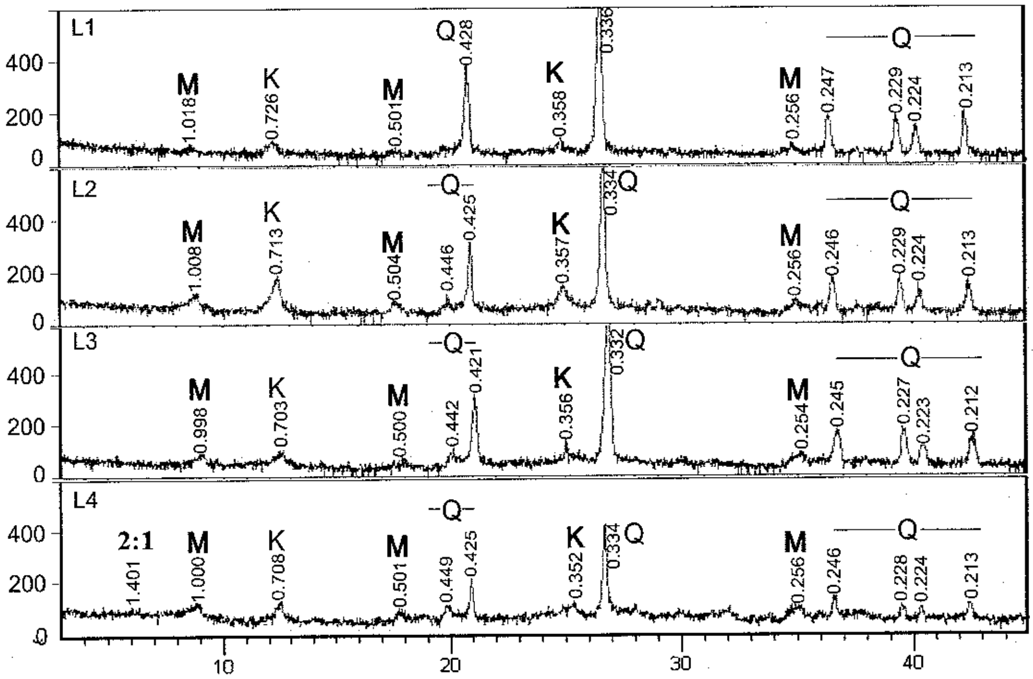


Fig. 4.27 - The XRD results of oriented specimens from the Lambir Formation (K= Kaolinite, M= Illite and Q=Quartz.

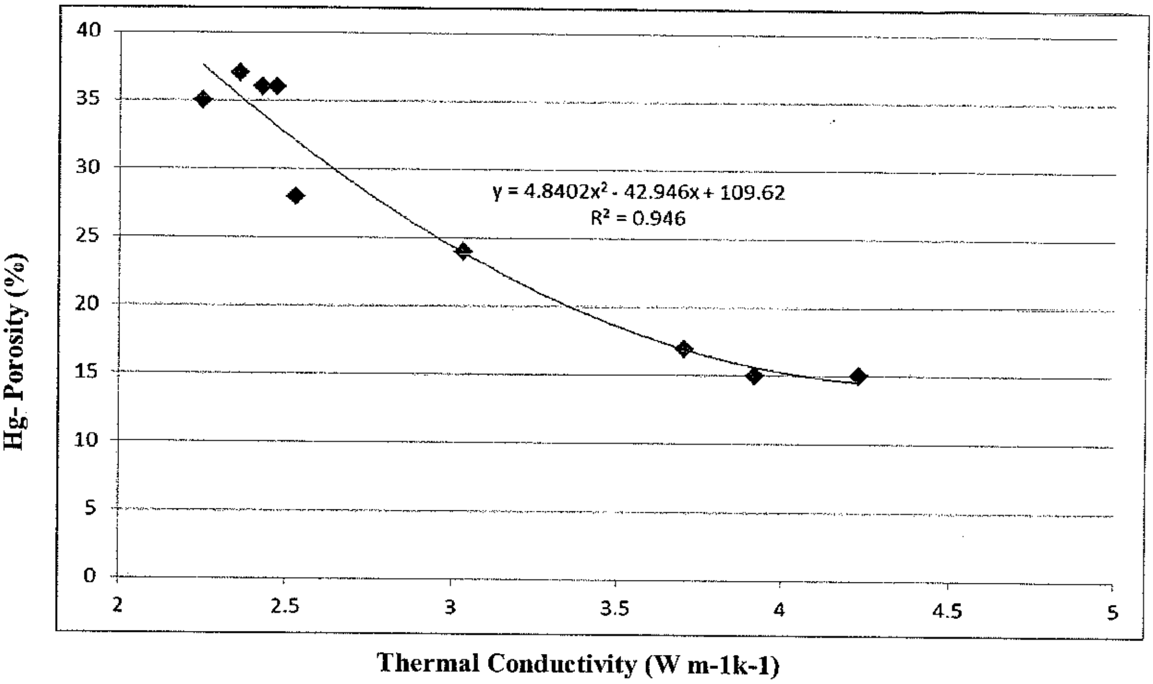


Fig. 4.28 - The thermal conductivity vs. porosity relationship for samples from the Belait and Lambir Formations.

4.7.4 Variations in Hydrocarbon in terms of the Total Organic Carbon (TOC) and Ultraviolet-Visible Light (UV-Vis) E4/E6 ratio

Amount and type of the organic matter preserved in sedimentary rocks are a function of several geological and biological processes. Primarily preservation of organic matter depends on the level of organic productivity, anoxia and sedimentary processes of the depositional environment [56]. Quantity of organic matter in a sedimentary rock can be determined by its Total Organic Carbon. TOC is measured in weight percent and indicates the organic richness of a rock [10, 57, 59]. As been addressed by Tissot & Welte [10], a rock with TOC which less than 0.5% is not considered as source rock; 0.5-1.0% is considered as poor; 1.0-2.0% is considered fair; 2.0-4.0% is considered as good and more than 4.0% TOC is considered excellent. The result of this study indicated that the Lambir Formation has provided a pathway for the hydrocarbons to migrate. This reference is supported by the findings in FTIR and UV-Vis.

Table 4.9 – Total Specific Surface Area and Thermal Conductivity (K), for the samples studied.

Sample	Total Specific Surface Area (m^2/g)	Thermal Conductivity ($Wm^{-1}k^{-1}$)
B1	32	4.233
B2	37	2.525
B3	35	3.704
B4	25	2.247
B5	23	2.358
L1	25	2.424
L2	25	2.469
L3	29	3.030
L4	27	3.921

Belait Formation E4/E6 ratio showed dominance of aromatic components within the samples (B1-B5). It is to be noted that the samples used for this analysis were devoid of coal dusts or laminations. Less aliphatic components in the results also suggest that migration of aliphatics might have occurred, Samples B4 and B5 appeared to have retained the aromatics behind during a past migration event as both E4/E6 values for these samples are higher compared to the rest of the Belait Formation samples. Secondary migration of aliphatics might account for the absence of the aliphatics as they are much lighter than the aromatics. Aliphatic migration in the Belait Formation is also aided by the larger pore sizes especially in B4 and B5 samples which ease the much lighter aliphatics to migrate away. However migration of aliphatics might have not been as extensive in the mudrocks of the Belait Formation with their smaller pore sizes.

Dominance of aliphatic compounds could be seen in Lambir Formation samples L2-L4 which have E4/E6 ratio values of 0.21, 0.65 and 0.89 respectively. Of all the Lambir Formation samples only L1 recorded dominance of aromatics based on its E4/E6 ratio values. The variation between the E4/E6 values between both formations might possibly account for the retaining of aliphatic compound caused by lesser geopressure anomalies experienced in Lambir Formation.

4.7.5 Fourier Transform Infrared (FTIR)

Generally, most of the Belait Formation samples were observed of having aromatic dominated compounds in an aliphatic and aromatic mixture. Lambir Formation FTIR spectra however were observed to have greater presence of aliphatic compounds throughout the samples (LI, L2, L3 and L4). Breakdowns of these interpretations are described in the succeeding sections. The section is divided into three main regions from the infrared spectra of the acquired FTIR analysis. The discussed regions are the 420-900cm^{-1} region, 1370–1680cm^{-1} and the 2700-3000cm^{-1}. These regions were known as the "hydrocarbon detection" regions [61, 66, 90-93] as all the hydrocarbons in the samples if present will be detected by the FTIR here. Some of the functional groups were grouped together i.e. CH / Aryl-CH / Aryl-H because of the similar ranges they possess. When grouped, the samples could be represented or interpreted as to possess one or more functional group.

4.7.5.1 The 400 – 900cm^{-1} FTIR region

Peaks in this range are usually associated with presence of aromatic olefins as well as aliphatic and aromatic paraffins (Fig. 4.29). Analysis on the FTIR of this range reveals presence of Aryl-olefins in all samples with stretched peaks occurring at around 400-600cm^{-1} region. Olefin compounds were detected with much frequency and with transmittance as low as around 30% in some Belait Formation samples (Table 4.10). Lower transmittance on the FTIR reflects higher absorption of the compounds by the samples. This suggests higher presence of olefins in the Belait Formation compared to the Lambir Formation.

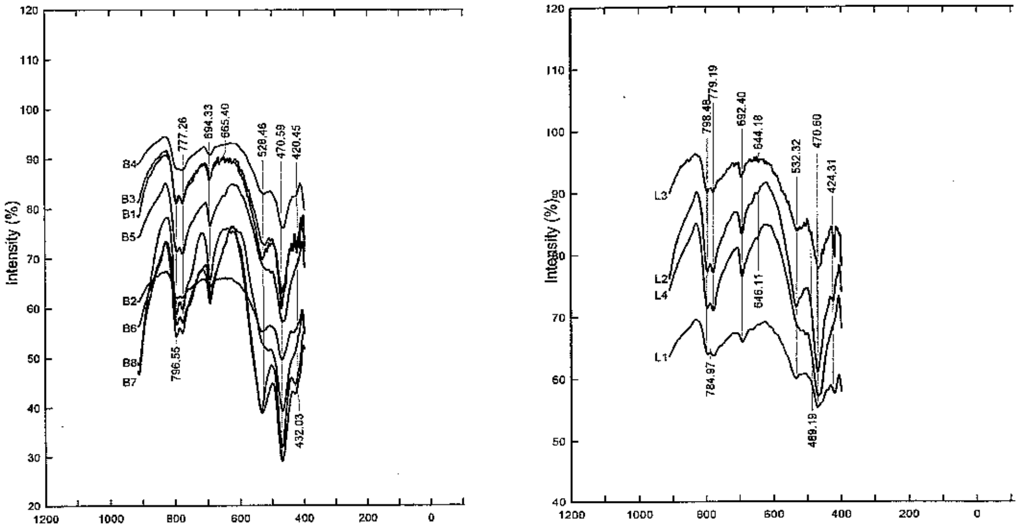


Fig. 4.29 – The FTIR spectra for the 400 – 900cm^{-1} region. **A** – Belait Formation. **B** – Lambir Formation.

Aliphatic C-H paraffin compounds were observed in only sample B1 and B3 at 665.40cm^{-1}. In the Lambir Formation however, similar functional groups were detected at 646.41cm^{-1} for samples L2 and L4 as well as at 644.18cm^{-1} in sample L3. Shared peaks between the C-H / Aryl C-H / Aryl-H compounds were observed in all samples from the Belait Formation except in samples B2 and B4 with peaks occurring at 777.26cm^{-1} and 796.55cm^{-1}. In the Lambir Formation, this group was observed to occur at 779.19 cm^{-1} in samples L2, L3 and L4, at 784.97cm^{-1} in all Lambir Formation samples; and at 798.48 cm^{-1} in sample L1. Shared peaks of C-H / Aryl H meanwhile were presents in all samples of the Belait Formation at 694.33cm^{-1}. In the Lambir Formation, similar molecular group was observed in peak of 692.40cm^{-1}. Aromatic dominance in the Belait Formation suggests presence of heavier hydrocarbon in the formation.

Table 4.10 – The Belait and Lambir Formations functional group, wavelength and transmittance percentage from the 400-900cm^{-1} FTIR region.

Belait Formation FTIR (400 – 900cm^{-1} region)

Functional group	Wavelength (cm^{-1})	Sample and Transmittance (%)							
		B1	B2	B3	B4	B5	B6	B7	B8
Aryl C=C	420.45	73	-	71	-	-	-	-	-
	432.03	-	-	-	-	-	-	45	48
	470.59	60	50	62	75	56	40	31	29
	528.46	71	55	72	82	-	-	39	39
CH	665.40	88	-	88	-	-	-	-	-
CH / Aryl-CH	694.33	85	-	85	-	77	62	61	65
CH / Aryl-CH / Aryl-H	796.55	81	61	81	-	71	54	56	59
	777.26	81	61	81	88	70	55	56.5	60

Lambir Formation FTIR (400 – 900cm^{-1} region)

Functional group	Wavelength (cm^{-1})	Sample and Transmittance (%)			
		L1	L2	L3	L4
Aryl C=C	424.31	68	71	79	-
	470.60	55	61	78	58
	489.19	-	-	83	-
	532.32	60	71	83	-
CH	644.18	-	-	95	-
	646.11	-	90	-	82
CH / Aryl-CH	692.40	65	83	92	77
CH / Aryl-CH / Aryl-H	779.19	-	76	90	70.5
	784.97	64.5	-	-	-
	798.48	-	76	90	71

4.7.5.2 The 1370 – 1680cm^{-1} FTIR region

FTIR peaks in this range are represented by the aliphatic compounds (CH_2 and CH_3) and shared peaks (group) between the aromatic and carbonyl compounds [68, 90-92]. Aliphatic compounds continued to dominate in the Lambir Formation compared to the samples from the Belait Formation (Fig. 4.30). Presence of aliphatic such as the CH_2 and CH_3 compounds especially CH_3 was observed to occupy much of the Lambir

Formation aliphatic spectra in this range. Observations of the transmittance percentages on the aliphatics also revealed lower values in Lambir Formation especially in samples L1, L2 and L4 (Table 4.11). This suggests that the Lambir Formation might be dominated with lighter hydrocarbon compounds.

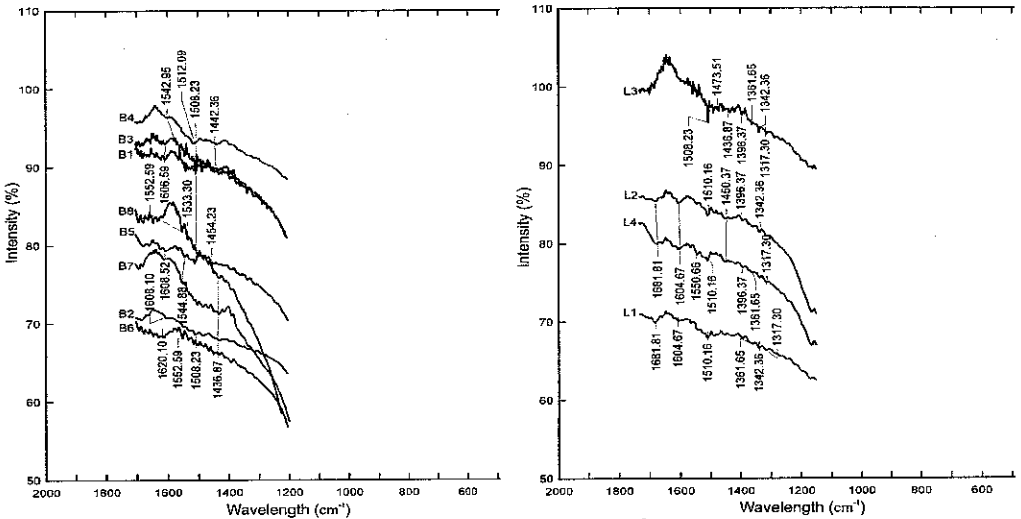


Fig. 4.30 – The FTIR spectra for the 1370 – 1680cm^{-1} region. **A** – Belait Formation. **B** – Lambir Formation.

Aliphatic CH_2 molecular group occurs at 1436.87cm^{-1} in Belait Formation samples B2, B6, B7 and B8, whereas in the Lambir Formation, CH_2 was present in sample L3 only at 1436.87cm^{-1} and 1473.51cm^{-1}. CH_3 molecular group can be observed at peaks measuring 1317.30cm^{-1}, 1342.36cm^{-1}, 1361.65cm^{-1}, 1436.87cm^{-1} and 1450.37cm^{-1} at various proportions in the Lambir Formation samples but not in the Belait Formation. Shared peaks between the CH_2 and CH_3 molecular groups were observed to occur in Belait Formation samples B1, B3, B4 and B5 at peaks recorded at 1442.66cm^{-1} and 1454.23cm^{-1}. Shared peaks between the aromatic olefin (Aryl C=C) and carbonyl compounds (C=O) were also observed in both formations occurring in various samples (Fig. 4.30). This compound is represented by peaks occurring at 1508.23cm^{-1}, 1510.16cm^{-1}, 1512.09cm^{-1}, 1533.30cm^{-1}, 1542.95cm^{-1}, 1544.88cm^{-1}, 1550.66cm-1, 1552.59cm^{-1}, 1604.66cm^{-1}, 1606.59cm^{-1}, 1608.52cm^{-1} and at 1681.61cm^{-1}.

Table 4.11 – The Belait and Lambir Formations functional group, wavelength and transmittance percentage from the FTIR 1370-1680cm^{-1} region.

Belait Formation FTIR (1370–1680cm^{-1} region)

Functional group	Wavelength (cm^{-1})	Sample and Transmittance (%)							
		B1	B2	B3	B4	B5	B6	B7	B8
CH_2	1436.87	-	69	-	-	-	65	72	76
CH_2 / CH_3	1442.66	89.5	-	90.5	93	-	-	-	-
	1454.23	-	-	-	-	78	-	-	-
Aryl C=C / C=O	1508.23	89.5	68	90		78	67	72	79
	1512.09	-	-	-	92.5	-	-	-	-
	1533.30	-	-	-	-	-	-	-	81
	1542.95	91	-	89	-	-	-	-	-
	1544.88	-	-	-	-	79	-	75	-
	1552.59	-	-	-	-	-	68	-	82
	1606.59	93	-	93	-	-	-	-	83
	1608.52	-	-	-	-	-	79.5	78	-
	1620.10	-	-	-	-	-	68	-	-

Lambir Formation FTIR (1370–1680cm^{-1} region)

Functional group	Wavelength (cm^{-1})	Sample and Transmittance (%)			
		L1	L2	L3	L4
CH_3	1317.30	66	81	93	75
	1342.36	66.5	81.5	94	-
	1361.65	67	-	95	75.5
	1396.37	-	83	96	76
	1450.37	-	83	-	76.5
CH_2	1436.87	-	-	97	-
	1473.51	-	-	97	-
Aryl C=C / C=O	1508.23	-	-	95	-
	1510.16	68	85	-	76.5
	1550.66	-	78.5	-	85
	1604.66	70	85	-	79
	1681.81	70	85	-	80

4.7.5.3 The 2700-3000cm^{-1} FTIR region

Similar to the preceeding region, this range of FTIR is useful in interpreting the aliphatic compounds (Fig. 4.31; Table 4.12). It is only attributed to the hydrocarbon compounds [66, 90-92]. In the Belait Formation, aliphatics were only observed by joint peaks between the CH and CH_2 molecular group as well as CH molecular group in sample B2 only. Peaks for the CH and CH_2 joint molecular group was detected at 2854.45cm^{-1} and 2925.81cm^{-1} whereas the aliphatic CH was at 2891.10cm^{-1}.

However, aliphatics were detected in the Lambir Formation with shared peaks of CH and CH_2 in samples L2 and L4. These peaks were observed to occur at $2854.45 cm^{-1}$, $2921.96 cm^{-1}$ and $2927.74 cm^{-1}$. CH_3 molecular group was observed in sample L1 only at $2879.52\ cm^{-1}$. Similarly, CH peak of Lambir Formation at this range was only observed again in sample L1 at $2945.01 cm^{-1}$. Although these peaks were observed in higher transmittance, this again suggests the possible presence of lighter hydrocarbons in the Lambir Formation samples.

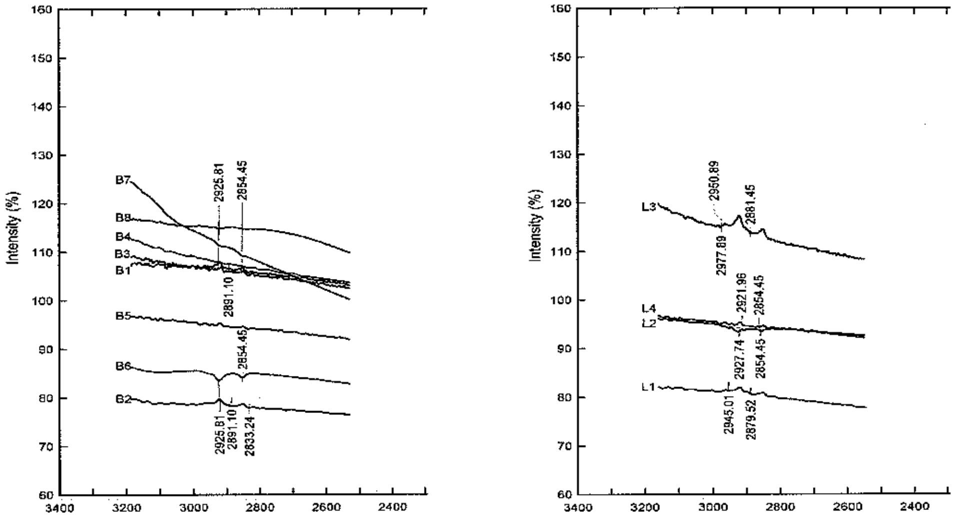


Fig. 4.31 – The FTIR spectra for the $2700\text{-}3000 cm^{-1}$ region. **A** – Belait Formation. **B** – Lambir Formation

Table 4.12 - The Belait and Lambir Formations functional group, wavelength and transmittance percentage at $2700–3000 cm^{-1}$ region.

<table>
<tr><th colspan="10">Belait Formation FTIR (2700–3000cm⁻¹ region)</th></tr>
<tr><th rowspan="2">Functional group</th><th rowspan="2">Wavelength (cm⁻¹)</th><th colspan="8">Sample and Transmittance (%)</th></tr>
<tr><th>B1</th><th>B2</th><th>B3</th><th>B4</th><th>B5</th><th>B6</th><th>B7</th><th>B8</th></tr>
<tr><td>CH</td><td>2891.10</td><td>-</td><td>78</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td rowspan="2">CH / CH₂</td><td>2925.81</td><td>-</td><td>80</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>2854.45</td><td>-</td><td>79</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><th colspan="10">Lambir Formation FTIR (2700–3000cm⁻¹ region)</th></tr>
<tr><th rowspan="2">Functional group</th><th rowspan="2">Wavelength (cm⁻¹)</th><th colspan="8">Sample and Transmittance (%)</th></tr>
<tr><th colspan="2">L1</th><th colspan="2">L2</th><th colspan="2">L3</th><th colspan="2">L4</th></tr>
<tr><td>CH</td><td>2945.01</td><td colspan="2">81</td><td colspan="2">-</td><td colspan="2">-</td><td colspan="2">-</td></tr>
<tr><td>CH₃</td><td>2879.52</td><td colspan="2">81</td><td colspan="2">-</td><td colspan="2">-</td><td colspan="2">-</td></tr>
<tr><td rowspan="3">CH / CH₂</td><td>2854.45</td><td colspan="2">-</td><td colspan="2">92</td><td colspan="2">-</td><td colspan="2">93</td></tr>
<tr><td>2921.96</td><td colspan="2">-</td><td colspan="2">-</td><td colspan="2">-</td><td colspan="2">95</td></tr>
<tr><td>2927.74</td><td colspan="2">-</td><td colspan="2">94</td><td colspan="2">-</td><td colspan="2">-</td></tr>
</table>

4.7.6 Differences in Hydrocarbon Migration between the Fluviatile and Shallow Marine Sedimentary Rocks

The variations between the quantity of organic matter shown by TOC, functional group analysis from FTIR and type of dominated compounds from the UV-Vis analysis suggest that there are differences in the hydrocarbon quality and quantity between the samples. Differences encountered were not only in terms of the compounds variations, but extend to the intensity and transmittance for a given compound within the samples. These variations were not only limited in between formations but also occurred within formation as well. It could be also observed that samples which have higher values of E4/E6 (>1.0) tend to be aromatics dominated whereas samples having lower E4/E6 (<1.0) tend to be aliphatic dominance. Observations between the formations E4/E6 ratio and molecular group from these analyses suggest that the hydrocarbons in the Belait Formation samples are dominated by aromatic compounds while the Lambir Formation samples are dominated by the aliphatic compounds. Comparison in the FTIR transmittance between both Formations also reveals that Lambir Formation samples possess lower amounts of aromatics than the Belait Formation (Table 4.10). This can be observed by higher transmittance of the aromatic compounds detected in Lambir Formation. FTIR analysis in Table 4.11 and Table 4.12 than continued to show dominance of aliphatic compounds in all Lambir Formation samples with varying transmittance percentage.

All these variations suggest possibility of different trend in migration experienced by both formations. Different rates of migration from the source may also occur within the same formation. Differences in the pore sizes and porosity further extend the effect of migration. Samples which have higher pore sizes were observed to prone towards having aromatic dominance compounds. These could suggest the possible presence of geopressure anomalies. In the thicker Belait Formation [26]. These alterations on the pressure and temperature experienced by the Belait Formation might possibly drive the less dense aliphatic compounds out from the formation while retaining the heavy /denser aromatics behind. Based on their hydrocarbons quality, aliphatic dominated Lambir Formation could be possibly comparable to a Type I or Type II class of kerogen while the aromatic dominated Belait Formation is comparable to a Type-III class kerogen.

4.7.7 Summary

It can be concluded that there are differences that could distinguish between the Belait and Lambir Formation. The criteria for these differentiating characteristics were proposed based on differences in the sedimentary features observed during field studies, microfabric analysis conducted from samples of both formations and the hydrocarbon molecular group interpretations from the UV-Vis and E4/E6 ratio studies. Not every criterion from the study is compiled in the list. Selections of these criteria were based upon the common features that should be able to distinguish the two formations from each other. These differentiating characteristics are hoped to provide future researchers interested with both formations some basis for differentiating them. To summarise the findings of this study, we have prepared a flowchart to help differentiate these formations during the field visit, microfabric analysis and lab study (Fig. 4.32).

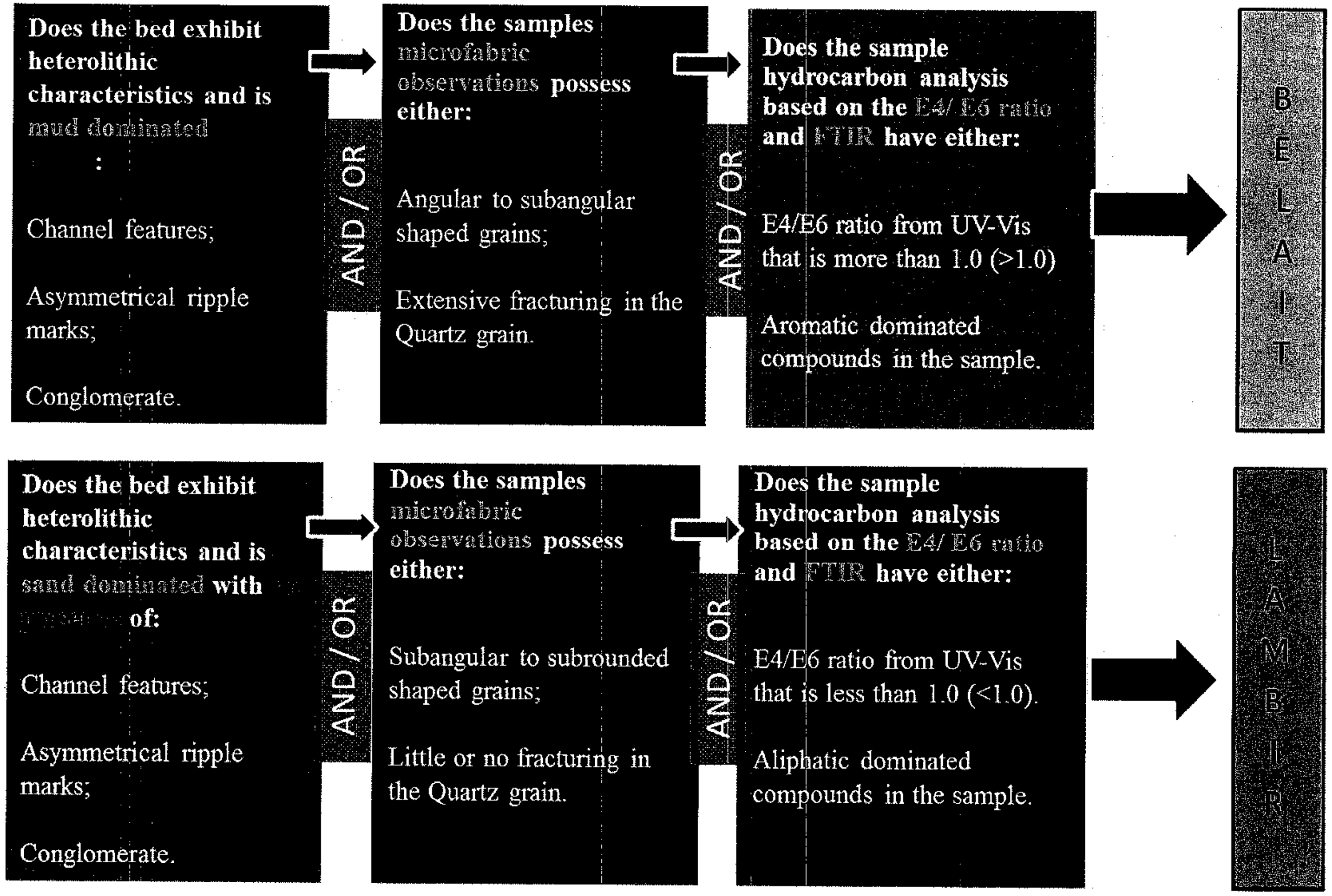


Fig. 4.32 – The differentiating characteristics workflow to distinguish between Belait and Lambir Formations.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Chapter Overview

This chapter provides the conclusions from this study as well as some recommendations for future research work.

5.2 Conclusions

The first objective is achieved based on the field studies conducted with the outcrops from Belait and Lambir Formations. Based on the study, it is concluded that there are a few distinguishing features between the formations that may be seen in all outcrops. In terms of sedimentary structures, it could be observed that Belait Formation possesses asymmetrical ripple marks whereas the Lambir Formation possesses symmetrical ripple marks. Cross-beddings are common features in the Lambir Formation whereas channels and conglomerates are common in the Belait Formation. Ophiomorpha Nodosa burrows are also more common in the Lambir Formation. In terms of facies characteristics, muddier heterolithics dominate the Belait Formation compared to the sandier heterolithics that is common in the Lambir Formation outcrops. Massive sandstones are common in the Lambir Formation whereas carbonaceous shales are commonly present in the Belait Formation outcrops. In terms of coal occurrences, coal laminations were observed frequently in the Lambir Formation and a bit lesser in Belait Formation. Coal fragments are easily observed in the Belait Formation than in the Lambir Formation.

To achieve the second objective, both Formations were evaluated in terms of their petrophysical, microfabrics and geochemical characteristics. In terms of their physical properties, Belait Formation sandstones have higher pore sizes than its Lambir Formation counterpart. Hg-porosity analysis revealed Belait Formation sandstones possess porosity that can be considered as excellent (>25%) while sandstones from Lambir Formation recorded porosity that ranges from fair to excellent. EGME surface area revealed that Belait Formation mudrocks possessed higher values of surface area. Similarities in the surface area observed in both formations sandstones revealed similar presence of phyllosilicates. Thermal conductivity for Belait Formation sandstones has much narrower range of values than the Lambir Formation. Most of the mudrock samples however recorded thermal conductivity values which are higher than the sandstones. Mineralogical analysis revealed that both formations consist mainly of quartz and clay minerals. Belait Formation has angular shaped grains compared to the sub-rounded grains found on Lambir Formation. Fracturing of the quartz grains is more extensive in the Belait Formation. XRD analysis revealed that most peaks of the Belait Formation have 2:1 phyllosilicates. Geochemical analyses showed samples from both formations having TOC ranges that can be interpreted as good. E4/E6 ratio from UV-Vis analysis suggests that Belait Formation consists of aromatic dominated compounds whereas the Lambir Formation is dominated by aliphatic compounds. FTIR revealed that aromatic olefins were found in all the Belait Formations with lower transmittance than in Lambir Formation. Aliphatic compounds such as CH, CH_2 and CH_3 however were found more frequent in the Lambir Formation samples with varying transmittance values.

Combinations of these key features can be detected in a given outcrop. Therefore in addressing the third objective of this study, the development of the keys to differentiate between these formations takes this into consideration. In essence, it is concluded that the keys for differentiation can be used to match a given outcrop to either one of the two formations studied. In cases where this is not possible, similarities to proximal outcrops that can be identified could help in the assignment of formation. We managed to differentiate this two formations based on the proposed key.

5.3 Recommendations for Future Work

Based on this study, there are a few recommendations that can be implemented. As this study only dealt with the Belait and Lambir Formations located in Northern Sarawak, sampling could be extended to samples of the Belait Formation from other areas as well. Occurrences of the Belait Formation extend to Brunei and up to Sabah. The Lambir Formation outcrop used here only covers the Miri part of Sarawak but occurrences of the formation extend to Bakong Valley.

In this study, samples were subjected to KBr micro-disc pellet method. It is however recommended that new technology in FTIR which is the Attenuated Total Reflectance (ATR) type of FTIR is to be used. This technique of FTIR will be a great advantage for new studies that will involve large scale sampling as it involves no preparation and allows samples to be examined directly. ATR-FTIR also allows liquid to be analyzed directly which will hugely benefit the hydrocarbon analysis.

The results of the study, specifically the results of FTIR and UV-Vis, indicate very clearly that migration of hydrocarbon is a complicated process but can be tracked down using these techniques. These techniques can also be used as a possible lead to the source rocks, however this needs to be studied in a petroleum systems in this area. The study also indicates that the petroleum industries can have enhanced information on reservoir quality rocks. Based on the above, it is evidence that this study contributes a methodology which should be of significance in the petroleum exploration phase.

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