STATUS OF THESIS

Title of thesis	SEDIMENTOLOGY, MICROFOSSILS AND DEPOSITIONAL FRAMEWORK OF SANDAKAN FORMATION, SABAH

I, KHOR WEI CHUNG hereby allow my thesis to be placed at the Information Resource Center (IRC) of Universiti Teknologi PETRONAS (UTP) with the following conditions:

1. The thesis becomes the property of UTP
2. The IRC of UTP may make copies of the thesis for academic purposes only.
3. This thesis is classified as

☐ Confidential

☑ Non-confidential

If this thesis is confidential, please state the reason:

____

____

The contents of the thesis will remain confidential for ________ years.

Remarks on disclosure:

____

____

Endorsed by

Signature of Author

Permanent address:

2328-R,

Taman Lumba Kuda, ALOR STAR.

05250. KEDAH. MALAYSIA

Date : 22ND May 2013

Signature of Supervisor

Name of Supervisor

Dr. Chow Weng Sum

Date : 3RD June 2013

UNIVERSITI TEKNOLOGI PETRONAS

SEDIMENTOLOGY, MICROFOSSILS AND DEPOSITIONAL FRAMEWORK OF SANDAKAN FORMATION, SABAH

By

KHOR WEI CHUNG

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

Signature:

Main Supervisor: AP Dr. CHOW WENG SUM

Signature:

Co-Supervisor: AP Dr. ABDUL HADI ABD RAHMAN

Signature:

Head of Department: AP Dr. ABDUL HADI ABD RAHMAN

Date: 3RD JUNE 2013

SEDIMENTOLOGY, MICROFOSSILS AND DEPOSITIONAL FRAMEWORK OF SANDAKAN FORMATION, SABAH

By

KHOR WEI CHUNG

A Thesis

Submitted to the Postgraduate Studies Programme

as a Requirement for the Degree of

MASTER OF SCIENCE

PETROLEUM GEOSCIENCE

UNIVERSITI TEKNOLOGI PETRONAS

BANDAR SERI ISKANDAR

PERAK

MAY 2013

DECLARATION OF THESIS

Title of thesis	SEDIMENTOLOGY, MICROFOSSILS AND DEPOSITONAL FRAMEWORK OF SANDAKAN FORMATION, SABAH

I, KHOR WEI CHUNG hereby declare that the thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UTP or other institutions.

Witnessed by

Signature of Author

Permanent address:
2328-R,
TAMAN LUMBA KUDA
05250. ALOR STAR.
KEDAH. MALAYSIA.

Signature of Supervisor
Dr. CHOW WENG SUM

Date : 22ND MAY 2013

Date : 3RD JUNE 2013

DEDICATION

to my family and friends.

ACKNOWLEDGEMENT

I would like to extend my greatest thanks to my supervisors Assoc. Prof. Dr. Abdul Hadi Abd. Rahman and Assoc. Prof. Dr. Chow Weng Sum for their never ending support, encouragement, advices and critical feedbacks throughout this research.

I am also thankful to University Technology PETRONAS (UTP) and the Ministry of Higher Education Malaysia for giving me the opportunity to complete this Master of Science Degree.

Besides, special thanks to my family for their encouragement that has always been the core motivator.

Lastly, many thanks to my friends for accompanying me throughout my studies in University Technology PETRONAS. Nevertheless, I wish them all the very best and an undertaking future.

ABSTRACT

The Sandakan Formation of the Segama Group is exposed across the Sandakan Peninsula in eastern Sabah. This Upper Miocene part of the Segama Group unconformably overlies the Garinono Formation and is conformably overlain by the Bongaya Formation. This formation was investigated with detailed logging of outcrops and microfossils analysis in order to map the depositional facies and sedimentary environment.

This study reveals the presence of eight lithofacies 1) Thick amalgamated sandstone, 2) Thin, lenticular interbedded HCS sandstones and mudstone, 3) Laminated mudstone with *Rhizophora*, 4) Sandstone with Shell Fragments 5) Laminated Mudstone, 6) Strip mudstone with thin sandstone and siltstone, 7) Interbedded HCS sandstone and mudstone, and 8) Sandstone with Herringbone Structure. Based on the presence of *Rhizophora, Brownlowia, Florchuetia sp., Polypodium, Stenochleana Palustris, Ascidian Spicule,* low angle cross bedding, very fine grained sandstone, thin alternations of very fine sandstone, silt and clay layers showing cyclicity (muddy rhythemites), rocks in the Sandakan Formation are interpreted as a transgressive shoreface succession over the mangal estuary. Three facies associations could be deduced from the eight lithofacies; 1) Gradual coarsening upwards shoreface, 2) abrupt change facies, and 3) estuary facies association.

ABSTRAK

Formasi Sandakan adalah sebahagian daripada Segama Group yang terdedah di seluruh Semenanjung Sandakan yang terletak di timur Sabah. Kumpulan Segama yang berusia Upper Miocene ini, terletak di atas unconformasi Formasi Garinono dan adalah didasari oleh Formasi Bongaya. Formasi ini telah dikaji dengan logging terperinci pada outcrops dan juga analisis microfossils untuk memetakan facies depositional dan persekitaran enapan.

Kajian ini telah mendedahkan kehadiran lapan lithofacies 1) Thick amalgamated sandstone, 2) Thin, lenticular interbedded HCS sandstones dan mudstone, 3) Laminated mudstone with Rhizophora, 4) Sandstone with Shell Fragments 5) Laminated Mudstone, 6) Strip mudstone with thin sandstone dan siltstone, 7) Interbedded HCS sandstone dan mudstone, and 8) Sandstone with Herringbone Structure.

Berdasarkan kehadiran Rhizophora, Brownlowia, Florchuetia sp., Polypodium, Stenochleana palustris, Ascidian Spicule, sudut rendah cross bedding dan juga butiran size pasir yang halus pada Formasi Sandakan ditafsirkan trangrassi shoreface. Tiga facies association boleh disimpulkan daripada tujuh lithofacies; 1) pengasaran secara beransur-ansur ke atas shoreface, 2) facies perubahan yang mendadak, dan 3) muara facies association.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

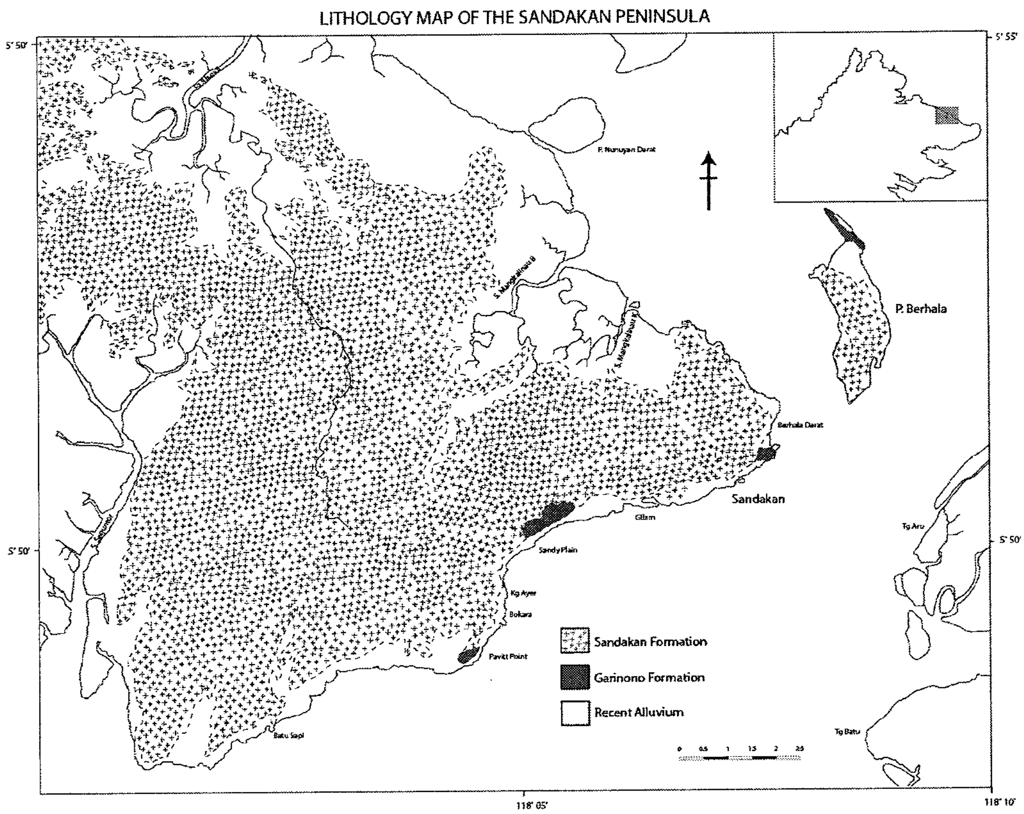


Figure 1.1: Sabah Regional Geological Map (Modified from the Geological Map of Sandakan Peninsula, Geoscience and Mineralogy Department of Malaysia, 1993).

1.1 Chapter Overview

This chapter discusses the objectives of this study, problem statement, project time line and the area of study.

1.2 Introduction

The tertiary silisiclastic sequence of the Borneo Island in East Malaysia has been extensively studied in recent years. Most of the petroleum reserves in the world are found in reservoirs with silisiclastic sequences in passive basins. This is mostly due to a combination of their extensive sizes, and the presence of nearby source rocks, and seals. The thick sequence of sandstone interbedded with organic-rich mudstones in the Borneo Island is a potential reservoir. This research focuses on studying the depositional environment of the Miocene Sandakan Formation in East Sabah.

1.2.1 Location

The Sandakan Formation is named based on locality, after Sandakan City.
SandakanCity is located at the Sandakan Peninsular, East Sabah, Borneo, Malaysia.

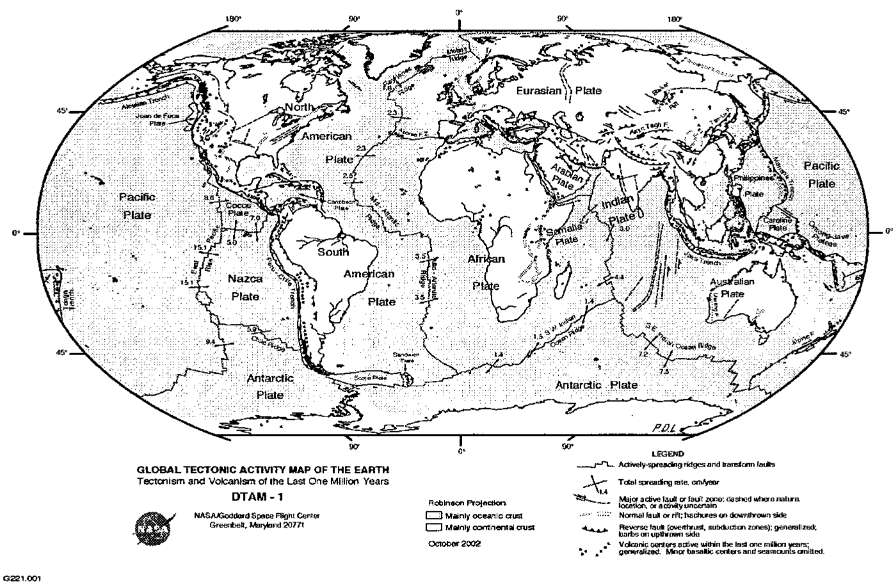


Figure 1.2: Location of Sabah as a passive margin (Modified from NASA, 2003)

It covers approximately 70 square kilometers and is bounded by longitudes 117° 90' E and 118° 10' E and latitudes 5° 75' N and 6° 00' N (Tarek, 2003).

1.2.2 The Geography of Sabah

The northeast of Sabah is covered by the Crocker Range. The Crocker Range is elongated and stretches from Tama Abu Range, Sarawak to Kudat division in Sabah. The Central Sabah division is mostly consisting of ground higher than 200 m. Low and flat latitude ground could only be found the coastal area. The highest peak of this mountain range is Mount Kinabalu with the height of 4,095 m.

1.2.2.1 Political Boundaries and Development

Sabah covers approximately 74,000 kilometer square, bordering with Brunei Darulsalam and Sarawak on the west (Richmond, 2010). It neighbors with Kalimantan, Indonesia on the south and Philippine on the east (Gullick, 1967). The Crocker Range is used as a political boundary to separate east and west Sabah. There are 5 divisions in Sabah which are West Coast, Kudat, Tawau, Sandakan and Central Sabah. Out of these 5 divisions, there are 23 districts in Sabah.

1.2.3 Season, Climate, Flora and Fauna

Sabah is no exception from the equatorial climate, tropical – sunny and hot throughout the year. Average daily temperatures are around 27°C (Pidwirny, 2008). Due to the little differences, it is difficult to distinguish between dry and monsoon seasons. Other countries that share similarities of this tropical climate are those which are located along the equatorial line, namely, Indonesia, Columbia, Peru, Costa Rica and Equador, Central America (Costa Rica Guide, 2005).

Sabah has tropical rainforests that are rich in botanical species. Approximately 2,500 flower species plants could be found in Sabah which is one third of the species found in the world. Sabah also has mountain range, tidal swamp and mangrove forest.

These variety of habitats support varied life forms and plants. Two hundred and ten mammals, 620 birds and 150 reptiles could be found in Malaysia (Richmond & Simon 2010). Sabah, Borneo, is also a habitat to a rare primate species, the Orang Hutan.

1.2.4 General Geology

Based on the diagram below, the whole Sandakan Peninsular is underlain by Late Neogene clastics and is being surrounded by Neogene volcaniclastics. These volcaniclastics units are known as the Segama Group. Segama Group comprises the Libong tuffite, the Tungku and the Tabanak Conglomerate Formations (Wilford, 1967).

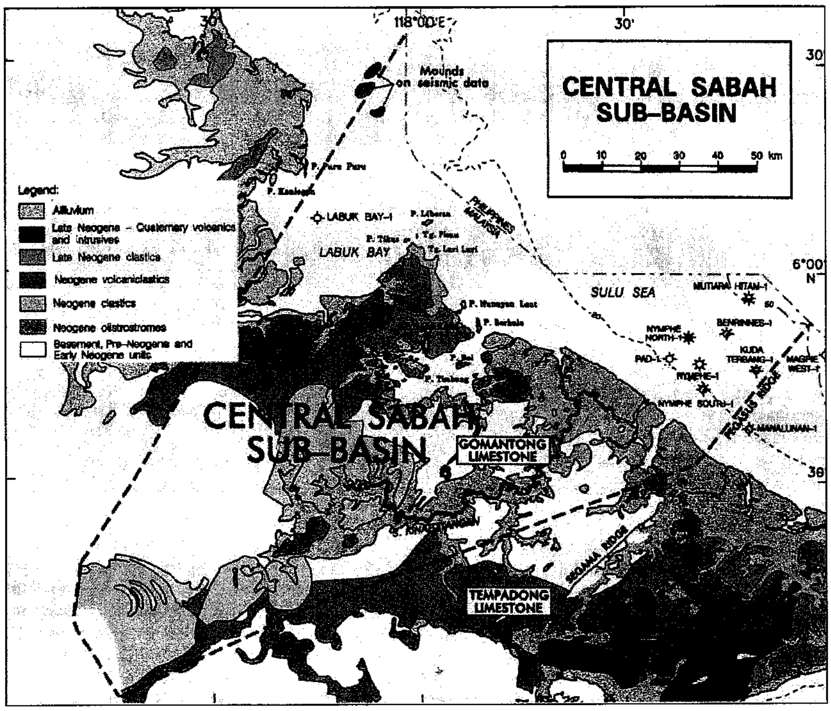


Figure 1.3: Geological map of east Sabah. The orange colour represents Neogene clastics. (Adapted from Leong 1999)

The stratigraphy of Sandakan Peninsular is shown in Figure 3. The Sandakan Formation is adjacent with the Tanjong Formation. Tanjong Formation is located slightly below than Sandakan Formation due to its subsidence into sub circular and circular basins. Despite the little difference in stratigraphy, the Sandakan Formation is suggested to be slightly younger than the Tanjong Formation based on paleontological studies (Lee 1970; Clennell, 1996; Leong, 1999). Both of these formations are described by Leong (1999), to have similar lithology and characteristics as well as depositional environment. Sandakan Formation which is located in Sandakan town suggested to be slightly younger than the Tanjong Formation based on paleontological studies (Lee 1970; Clennell, 1996; Leong, 1999). Both of these formations are described by Leong (1999), to have similar lithology and characteristics as well as depositional environment. Sandakan Formation which is located in Sandakan town and the adjourning area has been mapped and studied by Lee (1970) and Clennell (1996).

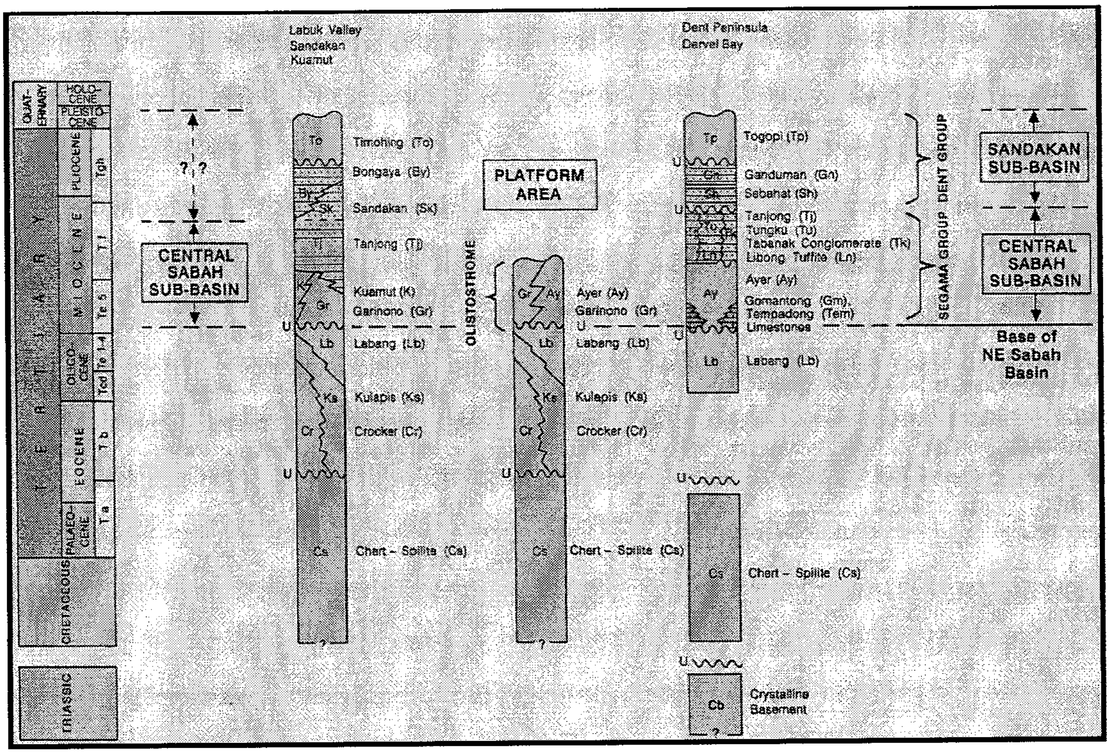


Figure 1.4: Generalized stratigraphy of onshore Sabah (adapted after Lim, 1985a and cited in PETRONAS, 2008)

The Sandakan and Tanjong Formations are overlain by younger Late Tertiary to Early Quaternary clastics, which are the Bongaya Formation and Timohing Formation respectively. Below the Sandakan Formation and the Tanjong Formation is the Garinono Formation and they are separated by an unconformity, a Shallow Regional Unconformity (SRU). The SRU marks the inflection point between two major regional subsidence in early Miocene which took place on the western side. The two major regional subsidence are:-

i) rapid tectonic subsidence (>500 m/ma) between 14.7 and 9 Ma followed by,

ii) a generally slow subsidence.

The SRU stretches from east of the Baram Delta, in the eastern Sarawak to the Tarakan Basin in the southeast of Sabah. The Garinono Formation is defined as a chaotic mixture of mud – matrix olistostromes, broken formations, tuff and tuffaceous layers. It is deposited due to the extension tectonism accompanied by explosive volcanism between Eastern Sabah and Southeast Sabah during Early Miocene (Hutchinson 1992a). This tectonic activity caused 12, 000 sq km of olistostrome to form and it is one of the biggest terrane in the world (Leong, 1976; Clennell 1991). The unconformity that overlies the Garinono Formation indicates the end of the formation of olistostrome and mark the difference between the Garinono sili-volcaniclastic Formation and the Sandakan siliclastic Formation.

1.3 Problem Statement

Depositional environment is one of the prominent elements in reservoir modelling. The demands of the modern petroleum industry on accurate characterization of facies are highly exacting. If the facies are wrongly interpreted, the foundation of most elements in the reservoir characterization process breaks down and higher risks will be taken.

Although the Sandakan Formation represents one of the late tertiary Miocene units of Sabah, no detailed facies analysis has been presented yet and only a few papers have dealt with paleo - environmental and microfossils aspects. Several previous studies, Fitch (1958), Haile & Wong (1965) and Staufer and Lee (1972) covered the initial survey of the Sandakan Formation and concluded that this formation consists of 3 fundamental facies, namely, the mudstone, sandstone and conglomerate facies. In 1998, Noad proposed that the Sandakan Formation is deposited in a shallow marine and mangrove environment whilst Tulot (2002) proposed a shoreface environment. Ahmed Tarek in 2002, evaluated the geochemical elements of this formation.

Detailed paleo - environment is important for biostratigraphic studies, basin analysis, though precise sedimentologic and stratigraphic information was not available.

Some very fundamental questions have so far remained ambiguous and they are as listed as below:-

1) What are the characteristics of the different sedimentology facies and biofacies within Sandakan Formation?

2) What are the bioturbation indices / abundance of microfossils throughout the siliciclastic succession in Sandakan Formation?

3) Does Sandakan Formation have a distinctive microfossil signature to characterize the deposition environment?

4) Is there any application of microfossils to sequence stratigraphy?

5) Where are the ancient shallow marine, transition zone and brackish water zone?

This paper is based on the integration of sedimentologic, microfossils, and sequence stratigraphic data to refine depositional models, which were constructed only on the basis of sedimentological and microfossils evidence. This is because the distribution of microfossils is dependant to the subtle changes in environmental parameters. In the present study, microfossils data have been particularly useful to detect the presence of estuarine deposits accumulated under brackish-water conditions and have provided the high resolution necessary to propose more rigid facies and sequence stratigraphic models.

1.4 Objectives

The main goal of this research is to integrate microfossil and sedimentological data to reconstruct the paleoenvironmental and paleogeographic evolution of the Sandakan Formation during the mid to late Miocene within the sequence-stratigraphic framework. s.

The specific objectives of this research were:-

1) To describe and interpret the sedimentary facies of the Sandakan Formation based on lithology, sedimentology stratigraphy, geometry and fossils identification.

2) To identify the facies associations in terms of sedimentary processes and environments.

3) To propose a depositional model taking into account of the sedimentological and micropaleontological characteristics of the Sandakan Formation and their evolution through time within a sequence-stratigraphic framework.

1.5 Project Timeline

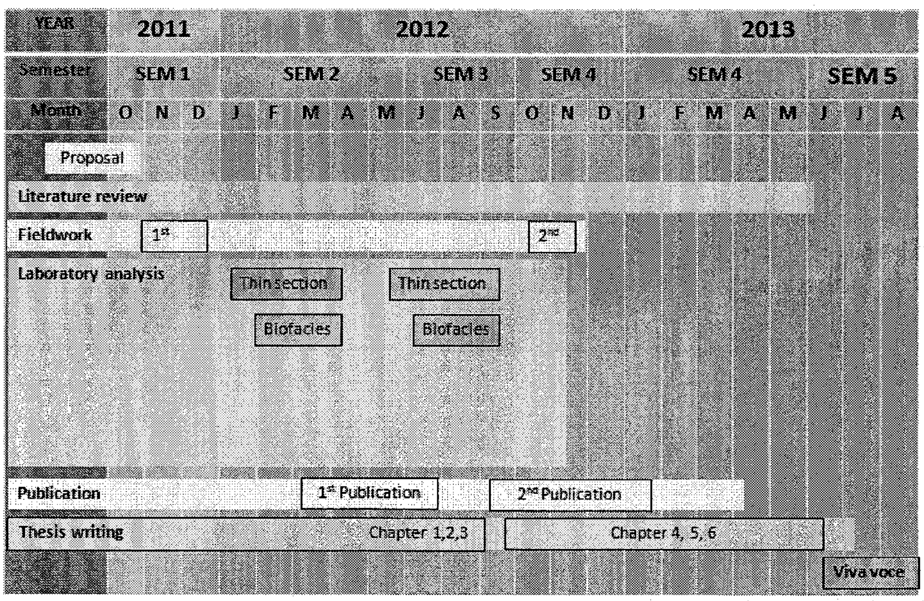


Figure 1.5: Gantt chart showing the composite timeline throughout this research.

This research first started on 23rd May, 2011. The field work for this project were carried out on November, 2011 and November, 2012. Laboratory analyses were carried out twice in early 2013 and mid-2013. A technical paper were written and presented in June, 2012 at the ICIPEG (International Conference on Intergrated Petroleum Engineering and Geoscience) and a paper is send for publication in SAINS MALAYSIAN on January 2013. The research proceed with thesis writing and compilation of the chapters. Finally, it ended with the Viva Voce in mid-2013.

1.6 Study Area

This study is conducted on the onshore sedimentary succession exposed in eastern Sabah from Sungai Garinono to Pulau Berhala. The Sandakan Formation is located in the Sandakan Peninsula in east Sabah. The research area covers approximately 12 kilometer square from longtitude E118° 02.553' to E118° 07.993 and latitude N05° 050.095 to N05°51.286.

1.7 Thesis Outline

This thesis consists of five chapters. Chapter 1 is the introduction including the scientific problems and objectives of the study. Included in this chapter is the overview of the previous works on the stratigraphy of East Sabah, Malaysia. Chapter 2 presents the literature review on the geological setting, general geology, tectonic history and studies covered. Chapter 3 presents the material and methods that were used in this research. Included in this chapter are the laboratory analysis methods and the fundamental concept of geology applicable on this study. Chapter 4 explains the results of field observation. While Chapter 5 includes discussion on the sedimentological and biofacies, stratigraphy, deposition environment and depositional model. Chapter 6 includes the conclusions and recommendations for further study.

CHAPTER 2

LITERATURE REVIEW

2.1 Chapter Review

This chapter discusses the literature review of the study area. It explains the area selected for the study and the previous relevant research done. This chapter also summarizes the work carried out by Fitch (1950), D.T.C. Lee (1970), John James Noad (1998), Suraya Tulot (2002) and Tarek Ahmad (2002).

2.2 Regional Tectonics of Sabah

Tongkul (1999) in his paper proposed a tectonic evolution model of Sabah which had been revised by Leong, 1999. Tongkul focused more on the crystalline basement and the acidic igneous rocks which is argued by Leong to have a different origin and tectonic history.

The tectonic history of Sabah is closely related to the Southeast China Sea and Philippine. Sabah shares the margin with Southeast China Sea on the north, Philippine's Celebes Sea on the East and Sulawesi Sea on the Northeast. The geology of Sabah can be divided into five major tectonic stages throughout the geological time scale, from Cretaceous to Pliocene.

2.2.1 Cretaceous to Eocene

During this period of time, Proto Southeast China Sea Plate collided with the Proto Borneo Plate at the northwest and southeast direction (Tongkul, 1992). This collision resulted an extension of the southern part of the China Plate. The former subduction trench zone is probably located at the central part of Sabah.

Proto Southeast China Sea Plate consists of Rajang, Sapulut, East Crocker and Trusmadi Formations while the Proto Borneo Plate consists of Pre-Cretaceous crystalline basement (Hutchinson, 2005). This collision produced a subduction zone beneath the Rajang Group Fold Thrust Belt (RFTB) after Eocene. This collision is also supported by the oregenic building activities. Besides, the colliding formations deformed and were uplifted in the Eocene tectonic episode (Geological Survey of Malaysia, 1995). This Eocene tectonic episode folded the Palaeogene and older units in Sabah (Leong, 1999).

Xia and Zhou (1993), suggested that this collision caused the opening of Southeast China Sea and deformed an ancient Tethys Ocean on the 'Nansha Block' – a microcontinental block in the Dangerous Ground located north of the existing Sabah Trough.

2.2.2 Oligocene – Early Miocene

The Rajang Group Fold Thrust Belt (RFTB) which is the result from the Eocene tectonic episode created a new deposition center to the west and east. The collision also caused the upliftment of the Temburong and West Crocker Formations (Tongkul,1992).

Towards East Sabah, two significant rifting which are the NE trending Sandakan Rift and SE trending Tarakan Rift. These rifts explained the formation of the Sandakan and Tarakan Basins. However, Sandakan Basin is later on reworked by another tectonic episode at the opposite NW direction. The rifting is also associated with volcanism and the formation of chaotic deposits (olistrostromes)(Leong, 1999). These volcanism activities can be explained from the volcaniclastic formation around the Sandakan Peninsula.

2.2.3 Early Miocene – Middle Miocene

The Sandakan rift continues to rift as new deposition forms, the Tanjong and Kapilit Formation. In the east, Sulu Sea opens, widening the Sandakan Basin which serves as a new and larger depocenter – extensional basin (Tongkul 1991). The eastern part of Sabah is still tectonically active and volcanism activity continues throughout this period of time.

2.2.4 Late Miocene – Early Pliocene

The rifting of the Sulu Sea stopped in Late Miocene and caused the upliftment around the Sandakan Peninsula (Tulot, 2002). This major upliftment comes along with heavy erosion as it could be seen as the Shallow Regional Unconformity (SRU). The volcanic activities at the Sandakan Peninsula and the Dent Group ceased. However, a new phase of volcanic activity and igneous intrusions towards the South, Semporna and Tawau occurred from Late Miocene to Quaternary.

2.2.5 Pliocene – Recent

Most tectonic event ceased and the volcanic arc in the Dent Penisula migrated to Tawau and to Semporna Peninsula (Leong, 1999). From the satellite imagery, the rings of volcanic crater could be seen in a line moving away from Sabah in the southeast direction.

2.2.5.1 Mud Volcanoes, Seepages, Hot Springs and Salt Diapers

Mud volcanoes are seen and noted down by Fitch in 1950 around the Sandakan Peninsula, Pulau Berhala and Pulau Pahlawan. In his report, he interpreted that these mud volcanoes indicate little seismic activities. They are also reported to be in the Tingkayu, Tawau area along with gas seepages and hot springs. The mud volcanoes were at their peak in 1959 (Kirk, 1962).

Also in Kirk's report, two small mud volcanoes were seen in Miocene sandstone and shale around the Mostyn Estate area, near Kunak, emiting non-sulphurous gas. It came along with slightly saline water.

South of the Sandakan Peninsula and the Dent Peninsula, Haile and Wong recorded that there are mud volcanoe activities as well. There are larger mud volcanoes and have been reported in Tabin, Lipad, Segama, Kretam, and Rasang. Rock boulders are ejected along with the mud and in certain areas like Tagai Ulu Tabin and Tabin Mud Volcano, crystals of pyrite and calcite are found in the mud (Haile and Wong, 1965). The formation of these crystals of minerals could be explain by the over saturation of salt in the mud.

Ironically, the boulders are cracked like volcanic bomb and are baked. The mud too, appears to be bluish-grey and some have a purplished-reddish baked colour. Probably it is affected by the iron oxide (III) composition and other possible associated elements like copper (II).

What could be concluded from the mud volcanoes from the different localities is that they have fairly short life and are active again after several years. Thus, periodical layers of mud could be observed and some form thin layers of salt in between the mud layers.

2.3 Description of the study area

The Sandakan Formation is located in the eastern side of Borneo, bounded by the Celebes Sea on the SE side and Sulu Sea on the east. On the offshore of East Sabah, the sea floor decrease exponentially to 3000m towards Philippine side.

The formation is named after Sandakan City. The northern and southern margins of Sandakan district are bounded by Sungai Labuk and Sungai Kinabatangan. These fluvial systems explain the transportation of sediments from Central Borneo oto form the Sandakan Formation, as well as other adjacent formations.

Sandakan Formation is exposed at the northeast margin of Central Sabah Sub – Basin (Leong, 1999). Sandakan Formation is also the source of full material for the (onshore) portion of the Sandakan Basin and Sulu Sea Basin. The Sulu Sea Basin is the Sandakan Basin in Philippines territory (Macvirick, 2010). The Sandakan Formation juxtaposed with the Tanjong Formation. Sandakan Formation is a derivation of Tanjong Formation and they are separated during the segmentation of Sandakan Sub – Circular Basin (Clennell, 1996; Lee 1970). South of Sandakan, a carbonate profile Gua Gumontong could be found.

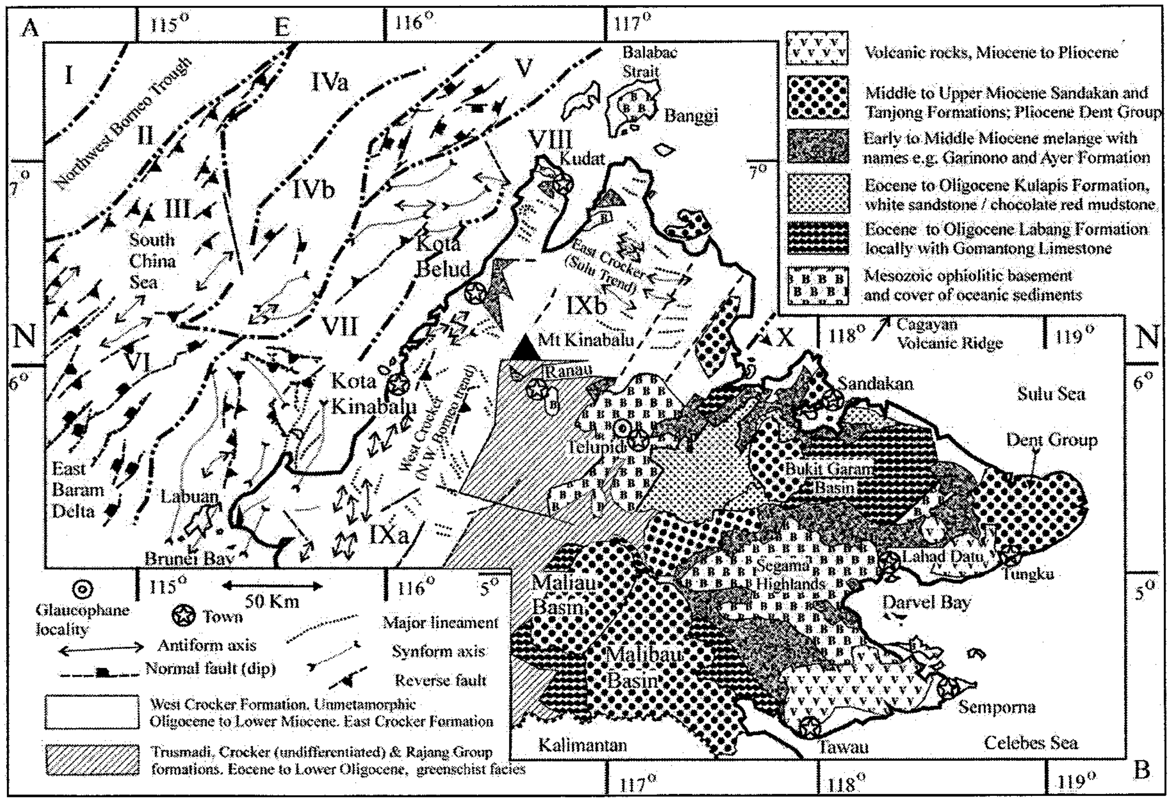


Figure 2.1: Sabah Regional Tectonics Map (Adapted from Journals of the Geological Society, JGS)

2.3.1 Sandakan City

Sandakan City is a fast growing commercial centre which is facing a bay Teluk Sandakan. The logging industry is regarded to be the main cause for Sandakan to flourish in the 1950s. During the timber boom era, Sandakan was said to have the world's greatest concentration of millionaires. However, some claimed that what made Sandakan to thrive was not solely timber industry. Sandakan is also famous for its luxury goods like pearls, sea cucumbers and birds' nests (Rowthron et al, 1999).

Many activities center around the busy docks and wharves that sprawl along the bayside for many kilometers. Sandakan's resources like rattan, timber, rubber, copra, palm oil and even birds' nests are shipped through the docks. Barges, ferries and motorboats of every type and description buzz around Teluk Sandakan, probably back and forth to Zamboanga in the Philippines.

Sandakan is also famous amongst the tourists. Forty kilometers offshore there is the Turtle Islands National Park, one of the world's few turtle sanctuaries (Wijnen, 2001). On the outskirt of Sandakan, there is the Gomantong Caves and super wildlife watching at the Sungai Kinabatangan.

2.3.2 History of Sandakan City

Ever since the rise and fall of human civilization, Sandakan was listed to be a stopping point for traders routing back and forth from Philippines and China.

In the 18^{th} century, Sandakan fell under the rule of the Sultan of Sulu, who ruled the southern islands of Philippines. Later around the 1870s, the foreign community was mainly Germans who settled on Pulau Timbang, in Teluk Sandakan. However, the first foreign settlement was founded by Captain Willian Schuck, a Scott. Schuck was rewarded an island, Pulau Timbang from the Sultan of Sulu. With the authority of the Sultan of Sulu, William Clarke Cowie, a German, then replaced Schuck by trading guns and weapons to the Sulu Kingdom. Since then, the area is named as Sandakan, which in Sulu language means "*the place that was pawned*". But soon, the area was renamed as "Kampung German" and it explains the huge population of Germans in Sandakan.

In 1879, Baron von Overbeck, an Austrian, acquired a lease from the Sultan of Sulu, Sultan Sulu Jamal Ui Alam, for much of eastern Sabah. This was later sold to

Alfred Dent, a Hong Kong-based publisher. Sandakan was established by the Resident named, William Burges Pryer, and it boomed. He introduced the Law of Trading's Taxes as a way to gain income for the city. At that moment, Kampung German made a tremendous development; it actually encountered a fire due to the carelessness of a resident named, Sabtu. In that incident, the whole village including Pryer's house were burnt down. The residents of Kampung German were relocated to Elopura in 1879, which means Beautiful City, where today it is renamed as Buli Sim Sim.

A privileged company, the North Borneo Chartered Company, was assigned to administer North Borneo (Sabah) in 1881. Through this company, North Borneo became a protectorate of the British Empire with internal affairs administered by the company until 1946 when it became the colony of British North Borneo.

In 1884, Sandakan became the capital of British North Borneo and it remained as capital until the Japanese invasion and subsequent Allied bombing in 1945 virtually destroyed the town. The destruction was far greater for the British to rebuild and thus in 1946, the capital was moved to Jesselton or now it is called Kota Kinabalu.

Sandakan City is also well known for its infamous "Sandakan Death Marches" where it was the site of a Japanese prisoner of war camp during World War II. In the marches, disease and starvation took a high toll mainly due to insufficient ration. Only 6 man survived out of 2400 prisoners.

Sandakan is currently the second biggest city after Kota Kinabalu (Jesselton). The population of Sandakan City is approximately more than 350,000 people, a far cry from the early days where it increased from 28,000 in 1970, 222,819 in 1999 and 243,126 in 2002 (Lee, 1970; Yearbook of Statistics Sabah, 1999; Hamsan, 2002;). The population increases about 6% a year.

2.4 Sandakan Formation Background

2.4.1 Sandakan Formation Background based on D.C.T. Lee (1970)

The term Sandakan Formation was introduced by Lee in 1969 and recited in his report in 1970. Lee described Sandakan Formation to be moderately dipping and consists of mudstone, sandstone and siltstone, with coal seams and conglomerate. The age of this formation is Upper Miocene (Tf $_{1\text{-}3}$) and overlies an unconformity and Garinono Formation. The paleo - deposition environment for Sandakan Formation is shallow marine and deltaic environments.

Lee had conuctedoutcrop surveys on a few localities:-

I. Sibuga area
II. Batu Sapi Road
III. Labuk Road
IV. Sungai Gum Gum Kechil
V. Pulau Timbang and Pulau Berhala (in the Sandakan Harbour)
VI. Sungai Segalid Valley

Based on Lee, Sandakan Formation is a repeating sequence of mudstone, sandstone, siltstone and minor coal seams. The facies changes based on localities. Conglomerate could only be found at the bottom of the Sandakan Formation and it is exposed in the southeastern part of Sandakan Peninsula near Sim Sim area. In this locality, sandstone, siltstone and mudstone interbeds could be seen, with siltstone and mudstone occurring less than 5 feet thick. Kampong Baharu, which is located towards the northwest direction has an increasing proportion of mudstone up to 200 feet thick. In Sungai Manila, it is dominated by mudstone and it occurs up to 500 feet thick.

There are 3 lithology facies as explained by Lee:-

I. Mudstone Facies
II. Siltstone / Sandstone Facies, and
III. Conglomerate Facies

2.4.1.1 Mudstone Facies

Mudstone constitute more than 50% of Sandakan Formation. It is interbedded with siltstone and sandstone. The thickest mudstone bed is 500 feet. The mudstones are dark grey and greenish in color. The carbonaceous matter differentiates the lithology where dark grey mudstone contains high carbonaceous matter. In the southern part of Sandakan Peninsula, coal seams are associated with thick mudstone beds. The coal seams are less than 2 feet and are only thicker than 2 feet at Tanah Merah.

2.4.1.2 Sandstone / Siltstone Facies

In Lee's report, siltstone and sandstone are categorized as one facies. Siltstone occurs together in sandstone as interbedds. Siltstone beds are commonly found and ranges from 2 feet to rarely exceeding 10 feet thick. In this facies, thinly laminated black carbonaceous layer could be found and are common in siltstone layers. The siltstone is greenish to grayish and some parts are weathered to yellowish. Siltstone contains less quartz and is finer compared to the sandstone. Heavy minerals are commonly found in siltstone and fine sandstone, but are rare in coarse sandstone.

2.4.1.3 Conglomerate Facies

This facies is exposed at certain localities such as at Tanjong Papat. Conglomerate beds are averagely 3 feet thick and they prograde upward into pebbly sandstone. The pebbles are rounded and comprise fine grained: tuffite and mudstone measuring one to two inches in diameter.

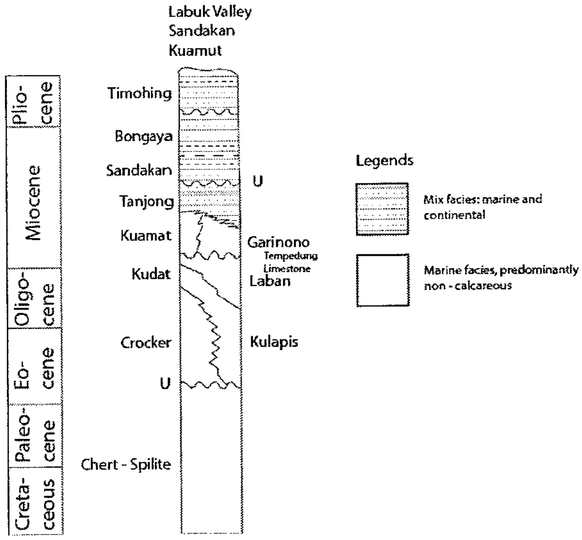


Figure 2.2: Generalized Stratigraphy of the Labuk Bay, Sandakan and Kuamat (modified after Lim, 1985a).

2.4.2 Sandakan Formation Background based on F. H. Fitch (1950)

This research was carried out as requested by the Geological Survey Department of British Territories in Borneo. It was to comply with the increasing demand of construction materials as well as economic purposes. This research also emphasized greatly on geochemical prospecting for mineralogy such as copper, coal, tin, copper, nickel and chromite deposits.

In 1950, the term Sandakan Formation was not yet being used. Fitch classified the lithology based on location and age. Sandakan Formation was categorized to be aged from Miocene to Quaternary and at a better extend, Aquaitanian ($Te_{1\text{-}4}$). Previous aging study was also carried out by Reinhard and Wenk (1951).

The lithology under Aquaitanian, ($Te_{1\text{-}4}$), consists of thick – bedded or massive greyish sandstone, grey shale and mudstone. Grey shale and mudstone appear to be interbedded with sandstone and fossil plant remains (coal seams). The grey mudstone and sandstone interbeds contain *Ophiomorpha*.

Based on Fitch's field observation, there are loose blocks and boulders of sandstone, dolerite and rocks identified in the field as greywacke and serpentine breccias. It is suggested that they are somehow derived from the Crocker Formation and could be seen at the banks of Kinabatangan near the tributary stream of Belat and close to the exposed sandstone conglomerate. These boulders had been transported down the river in recent time due to erosion and weathering.

Fitch also stated that there is a correlation between the shale in Lokan River and Tangkulap River with the Aquitanian Setap Group of Sarawak in terms of age from Foraminifera dating. The dating of limestone at Kuamut and Deramakot still remain ambiguous. The fossils in these limestones failed to show whether the rocks are Aquitanian or Upper Miocene (Reinhard and Wenk, 1951).

The lithology in the Sandakan Peninsula is different from the Kinabatangan and Kuala Labuk areas. The pyroclastic rocks (Garinono Formation) are overlain by Upper Miocene interbedded sandstone, shale and carbonaceous shale with seams of coal (Sandakan Formation). Overlying them is the yellow, argillaceous sandstone (which is described more to siltstone) that builds the cliffs on Berhala Island (Upper Sandakan Formation) and on the coast of Teluk Sandakan (Sandakan Town). The sandstone beds behind these cliffs are younger and are massive. They are slightly interbedded with less than 5 feet shale.

The gravel beds near to the Sandakan Airport and several parts of Sandakan City area are said to compose largely of quartz pebbles. The gravel beds are 10 feet thick around Sandakan Airport control tower and lie low at the foothill. These alluvial coarse alluvial deposits consist of vein quartz and grey sandstone clasts with clay matrix. They are Pliocene and are younger than the massive sandstone.

Through these field observations, Fitch suggested that the sea level was once higher than the present day which explains the deposition of massive sandstone alone Teluk Sandakan, as seen at the cliffs. In terms of provenance, transportation and processes, Fitch suggested a few possibilities:-

1) They were derived from a nearby source that yielded little input.
2) They were transported for long distances with consequent destruction of pebbles of other rocks that might have accompanied them.

However, Fitch disagreed of the opinion that there was no nearby source and the only known source was the Trusmadi Formation of the interior of North Borneo.

There is also no similar occurrence in modern deposits in Sabah. Lastly, he suggested that there is a relation between the pebbles and the occurrence of the quartz rich sandstone.

2.4.3 Sandakan Formation Background based on John James Noad (1998)

This research was carried out to serve the purpose as a PhD thesis report. This report included logs at a scale of 1:100, study of stratigraphy, facies and macrofossils (fossil cast, ichnology and plan fossils) over Sabah and Sarawak.

The Sandakan Formation is defined to be the fill of Sandakan Basin (Yin 1985) and covers most part of Sandakan Peninsula (together with Garinono Formation). Some parts of the Sandakan Formation are exposed on the neighbouring islands. Previously, Sandakan Formation was described as Tanjong Formation and there was some confusion as both Formations have similarities and a small age gap. However, in 1970, Lee redefined and separate Sandakan Formation from Tanjong Formation. Sandakan Formation is 2500m thick and comprises sandstone, siltstone, mudstone and thin coal seams. Citing from Stauffer and Lee, 1972, in John Noad's thesis, it forms a faulted synclinal in the central basin and southern part of Sandakan Peninsula.

Sandakan formation consists of two main rock types which are sandstone and mudstone. Some parts appear to be massive sandstone, thinly and thickly interbedded. A series of more resistive sandstone slopes could be seen due to long term weathering. At Labuk Road, interbedded fine mudstone and sandstone could be seen. Further north, the composition change to be more carbonaceous and mudstone dominated rocks. Towards the south, the sandstone and mudstone seem to be interfingering.

A few sediment structures could be found in Sandakan Formation, they are:-

1) Fine lamination
2) Small to medium scale cross-bedding
3) Current and wave ripples
4) Channeling

5) Ball and pillow

Based on the structures and fossil content, it is suggested that the depositional environment is shallow marine and deltaic environment. The sediment is transported through fluvial means from the west (Lee, 1970; Stauffer and Lee, 1972).

John Noad described Sandakan Formation with 9 lithofacies:-

i. Lithofacies 1: Mudstone and Rooted Trees (Mrt)
ii. Lithofacies 2: Sandstone beds, Channelized, Trough Cross-Bedded (Sct)
iii. Lithofacies 3: Thin Silty Sandstone, Bioturbated Mudstone (StM)
iv. Lithofacies 4: Sandstone, stacked packets of Trough Cross-Bedded (St)
v. Lithofacies 5: Sandstone beds, thick Tabular Planar Cross-Bedded(Sp)
vi. Lithofacies 6: Sandstone beds with abundant *Skolithos* (Ssk)
vii. Lithofacies 7: Thin an Intermediate Interbedded Channelized Sandstone and Mudstone (SMin)
viii. Lithofacies 8: Thick Mudstone beds with abundant ironstone cemented casts of crabs (Mcr)
ix. Lithofacies 9: Futureless or laminated Mudstone beds (Mlm)

2.3.4.1 Lithofacies 1: Mudstone and Rooted Trees (Mrt)

This lithofacies comprises dark grey mudstone with abundant logs, rooted trees and carbonaceous detritus, and a brackish to marine macrofauna. It is also made up of thick, cohesive, dark grey mudstone, with abundant fauna.

Carbonized and petrified wood up to 2.5m in length could be found in these mudstone beds. These are either carbonized or diagenetically cemented with siliceous cement. There are some persevered trunks up to 200cm in diameter and probably they were buried when they are still living. The coal seams, mudstone also contains a variety of leaves. In most localities of this facies, amber clasts could be found and the clasts could reach up to 15 cm in diameter. The amber clasts are well rounded and contain insect fauna including spiders, ants, thrips, gall midges and a parasitic hornet. Some of the amber had been bored, probably by small brackish worms.

Through the interpretation of macro fossils, the deposition environment was terrestrial and paralic, with very shallow or intertidal water depths. Brackish water mangrove was also present as it is indicated by the presence of abundant *Teredinids* (shipworms) (Gale 1995). Mollusks and crustacean seems to be present in a wide range of environment, from low energy to high energy, low-lying swampland and lagoonal deposits in fresh water. The term 'mangal' is introduced to explain a mangrove condition.

A few types of mangrove pollens had been recorded in the Sandakan Formation including *Rhizophora, Sonneratia* and *Avicennia.* However, they are not described in the lithofacies. Besides, the mangroves are buttressed and contain carbonized seasonal ring. Similar features could be observed at Kuala Selangor, in the Klang Estuary, Peninsula Malaysia.

This mangrove environment is strongly supported by the presence of mangrove lobster, such as *Cerithium sp* and *Batillaria sp.* These species live in muddy condition and also marine condition. It is also related to marine organisms such as these reef building corals (Karasawa, 1991) form the Miocene of Japan. Bivalves are found in this lithofacies and are concentrated at a certain horizon as they are periodical. This could be due to the relocation of these bivalves during storm events (Reading and Collinson, 1996).

The mineralization of this lithofacies indicates the process of diagenesis through the presence of sideritic nodules, pyrite and the mineralization of many logs (petrified and carbonized woods). Iron oxide leaching is also present signifying that the water that runs through the pore waters is rich with iron oxide. With the presence of sulfur and iron oxide, precipitation of pyrite could take place. However, the relatively low pyrite concentrations suggest that its formation was limited by the supply of organic matter in some mudstones (Huggett and Gale, 1995; Huggett and Gale 1998).

Low supply of organic matter explains the relatively low pyrite concentration as sulfur is a product of decomposition along with the organic matter. With this, only certain amount of iron oxide reacted. The left over iron oxide precipitates as a leaching mark (reddish orange stain).

This lithofacies (Mrt) is somehow has some similarities with Sct, StM and St lithofacies.

2.4.3.2 Lithofacies 2: Sandstone beds, Channelized, Trough Cross-Bedded (Sct)

This lithofacies comprises channelized trough cross-bedded sandstone interbedded with Lithofacies Mrt. It is also made up of fine grained to very fine grained sandstone beds, generally with channelized bases with a relief of up to 2 m. This lithosfacies interfinger with the grey mudstone in Mrt lithofacies. The thickness of this sandstone ranges from 1 m to more than 14 m thick and it is fining upwards. The trough cross-bedding structures reduce in size along with the grain size. At the base of the sandstone, the trough cross-bedding is approximately 1 m and above, it occurs up to a thickness of 30 – 50 cm. These rocks may appear massive due to weathering.

This lithofacies includes channeled sandstone beds with planar cross-beds dipping at right angles to the channel margin and at the base of channel, thin heterolithic inter-laminated siltstone of StM lithofacies occur.

The top of the sandstone channel progrades into thinly laminated siltstone and overlying mudstone. Generally the channel orientates N – S or NW – SE. Many of the sandstone beds show liesegang banding with the top and bottom have leaching stain. The several centimeter thick crusts could be the evidence for the running ground water to be iron rich.

It is also interbedded with Mrt lithofacies which is rich with macro fossils. The macrofossils in the sandstone are devoid mainly due to the effects of diagenetic dissolution. The dissolution is high in sandstone compared to the mudstone in Mrt as pore water movement tends to concentrate on highly porous beds, in this case is this lithofacies' sandstone. Gastropod casts are rare.

Several traces of trunk fossil, *Ophiomorpha* (Ekdale et al. 1984), *Planolites* leaf casts, tracks of arthropod – *Thalassina* and feeding traces are present on the finer upper part of this lithofacies or in the upper channel. *Thalassina* is interpreted to be claw marks to more blurred traces (Goldring and Seilacher, 1971). The sediment is observed to be poorly lithified suggesting that the sediment deposited at a very slow phase and indicated a low energy environment, probably a dying channel.

There is also another obvious type of trace fossil which is the bird footprints. These bird footprints are found at the border between the lower contact of this sandstone with the mudstone layer or at the bottom of the channel overlying the thinly laminated mudstone layer. It is preserved by the cementation of iron through leaching and formation of iron curst. The footprints are thought to be imprints of the green plover which is a type of shorebird that has straight bill and large pointed wings (CP & BMNH, 1996). These bird footprint structures at the base of the channel suggest that the flow in the channel and the sedimentation rate were slow. The water level was extremely shallow too or the footprints would have been quickly eroded away. Based on this, the channel may start off with a slow flow or merely a pool that later on became a part of a larger channel system.

This lithofacies is closely related with Mrt Lithofacies where this sandy channel cuts through the carbonaceous grey mudstone. The channels are not stacked and are isolated within the mudstone beds. The question is, are these channels amalgamated? Based on Smith, 1983, there is hardly any evidence showing anastomosis, branching of the channels or two channels crossing each other. The fine grains reflect on the source of the sediment, rather than its process and transportation (Noad, 1993).

Small sized trough cross-bedding shows approximately 1 meter depth of water flow (Allen, 1982) and this sediment structure is present in three dimensions along the channel. Noad suggested that the depth of the channel should reach 14m because the well sorted sand in the channel was compacted readily.

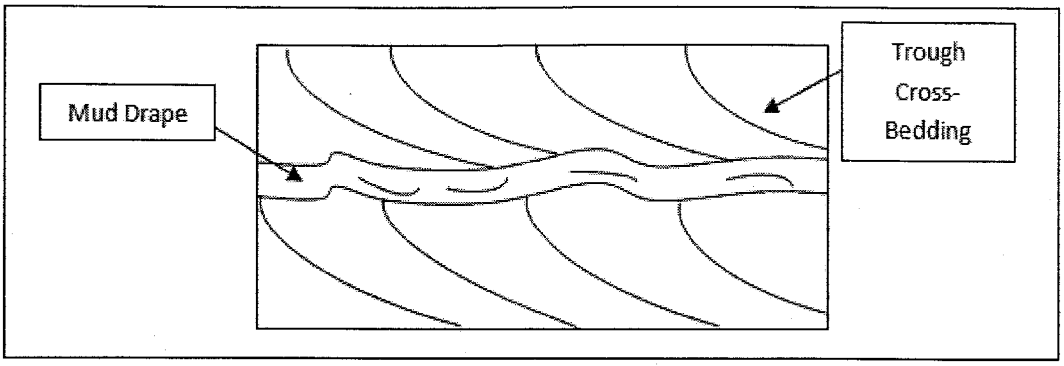


Figure 2.3: Mud drapes in between trough cross bedding (Modified from Noad, 1998)

Certain localities of this lithofacies contain mud drapes but it is towards the top of the channel. This sudden change of lithology shows that there was a temporal change in water flow and depth of the water. It also suggests a change in the rate of deposition, from rapid deposition to slow and back to rapid. The trough cross-beds and current ripples show unidirectional flow. These channels are more laterally extensive, suggesting wide channel morphology. Besides, the presence of *Ophiomorpha* in these sediments signifies brackish to marine conditions (Pollard et al., 1993). To be more specific, it could be tidally dominated estuarine conditions.

There is a lack of evidence indicating channel stacking and this suggests that the channels do not meander. It was also not a major distributary area, but rather a quiet backwater with a few shallow channels flowing seaward from a probably low-lying hinterland.

2.4.3.3 Lithofacies 3: Thin Silty Sandstone, Bioturbated Mudstone (StM)

This lithofacies contains thin interbeds of silty sandstone and highly bioturbated mudstone, with abundant muddy drapes and rare rootlets (rarely). The thickness of this lithofacies of mudstone is between 0.5 to 5 cm. The mudstone is well bioturbated and contains thin sandy or silty rippled drapes. This lithofacies (StM) could be observed to be associated with lithofacies Mrt and St.

At certain localities, this lithofacies pass into very fine grained sandstone with lamination less than 1 cm thickness. It also contains bands of thin, approximately less than 2 cm thick ironstone nodules with an internal spacing between the nodules of 10 cm to 15 cm between the nodules. Molluscs casts could be found in these ironstone, but they are rare.

There are some but rare amber clasts and some wood fragments towards the top of this lithofacies indicating that the environment had temporarily changed to a brackish condition. The sea level must have fallen over a short period of time, enabling mangroves to grow.

The mixture of lithofacies Mrt and Sct indicates a low energy to marginal marine environment. The interbeds of sandstone and mudstone show a temporal change in water depth, energy and velocity; process and transportation. The channel retrograde, so the sand shifted towards the head as well as salinity. Lower salinity reduces bioturbation so that the inter-laminae mud beds are preserved.

The sediments in this lithofacies are thought to have been deposited on a mixed to muddy tidal flat. As a proof, sedimentary structures like lenticular bedding and finely interbedded sands and thicker mudstones could be seen (Reineck and Wunderlich, 1968)

2.4.3.4 Lithofacies 4: Sandstone, stacked packets of Trough Cross-Bedded (St)

This lithofacies contains trough cross-bedded sandstone beds. The trough cross-bedding vary from 30 cm – 50 cm to approximately 100 cm in size. This St lithofacies generally appears to overlie Mrt lithofacies with a flat base contact.

This trough cross-bedded sandstone at some localities is interbedded with thin grey mudstone beds and separated by thin horizontal rippled sandstone bed in between sets of trough cross-bedded sandstone beds.

This lithofacies graded from medium or fine grained sand to very fine grained sand and commonly with climbing ripples structures. Due to iron leaching, the rippled layers are capped by ironstone, probably a post deposition forming crust, reddish orange in colour.

A few fossils could be found in the sandstone beds. Moulds of bivalve and gastropod fragments were observed, probably this is due to dissolution after deposition. Trace fossils are abundant, and the ichnofossil is dominated by *Ophiomorpha* burrows. Sub-horizontal and horizontal tabular burrows are also present, but they are less compared to *Ophiomorpha*, like *Planolites* and *Rhizocorallium*. The track trace fossils could be observed and they run along the ripple troughs.

This thick sandstone is suggested to have been deposited in the shoreface zone. Shoreface zone contains abundant ripple marks (Johnson, 1977).

2.4.3.5 Lithofacies 5: Sandstone Beds, thick Tabular Planar Cross-Bedded (Sp)

This is a less common lithofacies that contains planar cross-bedded sandstone beds. This lithofacies sandstone beds are a meter thick and they are dipping at 30° NW. It is exposed at few places and at the triple junction between Cecily Road and North Cecily Road, where it appears as a series of stacked cross-bedded sandstone beds up to 60m. The thickest cross-bedded single set is measured to be 502 cm thick and almost all of the beds are dipping steeply toward the east direction. On averagely, the beds are 1 m to 2 m thick and are interbedded with much thicker trough cross-bedded sandstone layers (St lithofacies).

The planar cross-bedded sandstone of this lithofacies (Sp) is also similar to the trough cross-bedded sandstone in the St lithofacies in terms of grading. This lithofacies grades from medium or fine grained sand to very fine grained sand and commonly with climbing ripples structures. Due to iron leaching, the rippled layers are capped by ironstone, probably a post deposition forming crust, reddish orange in colour. The wave propagating from WNW, and the longshore current produced the three dimensional dunes – trough cross-bedding. While, the thin ripple layers represent the reworking of sediment surface into ripples mark. The high rate of sediment supply will help to maintain the shallow environment of the shore.

The St and Sp lithofacies represent subtidal to upper shoreface deposits. The water depth ranges between 5 m to 10 m or in some case, less than 5 m. It is very clear that the sandstone beds are deposited in a sand dominated environment and affected by longshore currents or rip-currents.

2.4.3.6 Lithofacies 6: Sandstone beds with abundant Skolithos (Ssk)

This facies contains thin to medium bedded sandstone beds with abundant *Skolithos*. The sandstone beds are stacked and thin mudstone beds (up to a few cm) are not common. The beds are 15 cm to 70 cm in thickness. The sandstone beds are not completely massive and sediment structures like planar cross-bedding (at the base) and hummocky (at some locality) could be observed.

The sand is fine to very fine and the bed has horizontal laminations near its base where it is overlain by low angle trough cross-bedding. The thin, finely laminated mudstone layers are less than 1 cm thick and a set of sandstone bed is approximately 20 cm in thickness. The paleocurrent is towards the northeast direction. Each set of sandstone bed is rippled on the top, mostly dominated by wave ripples.

Dissolution diagenesis is the major cause that explains why most fauna fossils are common. However, some rare casts of bivalves have been collected from the sandstone. Horizontal burrows are seen on the base of the sandstone. Vertical *Skolithos* are small and look like small pillars between the sands. The depositional environment is deeper toward the base of the sandstone where horizontal burrows are used mostly to trap nutrients for food grows by the worms. *Ophiomorpha* burrows are also present but they are not common and could only be seen occasionally.

Skolithos ichnofacies represents intertidal settings (Hantzschel, 1975 cited in Noad, 1998) and the ideal environment includes the foreshore and shoreface zones of beaches, bars, and spits. This environment is also associated with the rapid fluctuation of sea level phenomena where alternating thin (mudstone) and thick layers (sandstone) will be produced. This inchofacies normally is found in a high energy environment with abundant suspended food. The organisms will borrow to hide from the high energy smashing waves and vertical burrows are common.

2.4.3.7 Lithofacies 7: Thin and Intermediate Interbedded Channelized Sandstone and Mudstone (SMin)

This lithofacies is a series of stacked interbedded sandstone and mudstone and consist of 2 end members:-

I. Laterally persistent sandstone beds with extremely flat bases interbedded with mudstone. It is less than 50 cm in thickness.

II. Thick channelized sandstone measuring 2 m to 50 m in width. It is exposed up to 2 m into the underlying beds.

Heterolithic sets of interbedded sandstone, mudstone, siltstone interbedded is the prominent and most common lithology in the Sandakan Formation. The sandstone beds measure less than 150 cm in thickness and averagely are in between 10 cm to 50 cm. This lithofacies thins towards the northwest and eventually give way to Lithofacies Mcr. Some parts are interbedded with associated sandstone beds (St) and this type of interbedding is more common in the eastern part of the Sandakan Peninsula.

Sedimentary structures that could be found in this lithofacies are:-

I. Hummocky cross-laminae
II. Trough cross-bedding
III. Lags at the base of trough cross-beds
IV. Flat erosive bases (on thin tabular sandbodies)
V. Climbing ripples (on more silty beds)
VI. Asymmetrical ripples marks (that produces small scale cross-laminae)
VII. Symmetrical ripples (reworked from VI)
VIII. Dewatering and loading structures
IX. Small scale convolute bedding (top of thinner sandbodies)
X. Ball and pillow horizons.

As with the case in previous lithofacies, the microfossils are barren due to dissolution. Casts of marine bivalves and gastropods have been found. Leaves incluing some stem are preserved in thinly laminated mudstone. The mudstone samples did not contain foraminifera. Trace fossils are abundant showing high life activities. The trace fossil assemblage shows well-oxygenated bottom with rich food source.

The depositional environments interpreted as fairly shallow and a high energy environment where the mudstone beds do not contain foraminifera. Foraminifera could be found only in marine and deep marine condition. In such environment, pollens and spores should be present.

2.4.3.8 *Lithofacies 8: Thick Mudstone Beds with abundant ironstone cemented casts of crabs (Mcr)*

This lithofacies is interpreted to have fairly shallow marine inner shelfal mudstone beds. It is made up of thick grey mudstone, with occasional very thin but laterally persistent silty sandstone beds. It is generally less than 10 cm in thickness and may extend up to 300 m.

This lithofacies contains some sedimentary structures. They are:-

I. Cross bedding (low angle at the base)
II. Ripples marks (top of the beds)
III. Thin carbonaceous laminae

There are also internal structures like ironstone cementation during diagenesis, and they are called ironstones. This lithofacies shows flat bases and contains low angle hummocky cross-bedding. At some localities there are small winged channels, with an average of 50 cm and rarely exceeding 3m in thickness. These are composed of sandy siltstone, and show trough, or occasionally hummocky cross-bedding, with ripples over the top few centimeters.

In this lithofacies, some macrofossils could be found. Noad described that there are crab casts in between the ironstone beds as well as some shell materials are preserved. There are up to 25 species of crabs including *Raninids, Portunids, Calappids* and *Xanthids* (Davie, 1993). Different localities show different types of crabs. This could be due to the variation of deposition environment or probably changes in water depth. Crabs inhabited either in an intertidal or sublittoral environment, and that most modern crabs prefer a muddy-sandy substrate. There are also more than 15 types of bivalve including *Glycimeris Nucula, oysters* and *Veneroids*. Only one burrow dwelling bivalve is found which is *Penicillus*.

Trace fossils this lithofacies mostly resulted from crabs. They are generally preserved as horizontal tabular structures around 2 cm in diameter. Some of the mudstone beds have been sampled and processed for microfossils purposes. It is found that the foraminifera have been pyritised which could indicate the presence of a slightly reducing condition, although this is belied by macrofauna, or probably this could be a diagenetic feature.

The thick mudstone beds are deposited in a low energy condition from suspension and the thin silty sandstone layer are laid down as a sheet-like deposit in a higher energy condition. This interpretation could be well supported if the contact between beds is observed. With the understanding from crab groups, it could be deduced that the water depth for this deposit is less than 200 m, and probably less than 100 m.

There are 2 assemblages of foraminifera. Calcareous foraminifera is predominant in Assemblage A which could suggest that the environment contains oxygen, low energy and low sedimentation. A second group, Assemblage B contains a limited range of agglutinated foraminifera species which indicate a typical low oxygen environment.

2.4.3.9 Lithofacies 9: Futureless or laminated Mudstone beds (Mlm)

This lithofacies contains finely laminated mudstone. The lithology is grey mudstone and silty beds. The mudstone is finely laminated, with some impersistent silty beds, 1 cm to 5 cm in thickness. The silty beds show slightly eroded bases, low angle cross-lamination and have finely comminuted carbonaceous material on the bedding planes.

In this lithofacies, the macrofossils also undergo dissolution diagenesis, similar to most of other lithofacies. Ichnofossils could be found but they are mostly subvertical and horizontal burrows, which show that the depositional environment was not of high energy environment.

This lithofacies was deposited in a low energy condition where mudstone and siltstone formed. This lithofacies is thought to be more distal, similar to Mcr lithofacies. As it is very fine grained and tightly packed, formation of iron oxide (ironstone or leaching) hardly happen which prevented the development of ironstone around the casts of the macrofossils.

This mudstone and siltstone beds are also structureless which also supports the idea of a low energy condition. This lithofacies are deposited in a deeper condition where horizontal burrows are used to capture nutrient for food growth. Probably this was below the Storm Wave Base Line.

2.4.4 Sandakan Formation based on Suraya Tulot (2002)

A research on sedimentology and reservoir properties of the Sandakan Formation shoreface succession was conducted as a partial fulfillment by Suraya Tulot for her Degree of Master in Science at University Brunei Darussalam. Generally, there are 4 sedimentary facies identified and they are as stated below:-

1. Facies 1: Massive Sandstone
2. Facies 2: Interbedded clean Sandstone with Mudstone
3. Facies 3: Carbonaceous Sandstone
4. Facies 4: Thick Mudstone

a) Facies 1: Massive Sandstone Facies

This massive sandstone facies is interbedded by thin mudstone. The massive sandstone extends laterally and it is about 10 m to 30 m in thickness. It is also featureless. However, trough cross bedding structures and parallel to low angle cross lamination are commonly seen within this facies. The sandstone is light yellow to whitish in color and it is soft and friable, as it was probably weathered. The grain size ranges from fine to medium and it is coarsening upwards. Higher energy structures like cross bedding contains coarser grains compared to lower energy structures like lamination. The massive sandstones contain flat horizontal *Ophiomorpha* and this index fossil is rated one (Highest rate is "6" which is most commonly found and "1" is the lowest which is rarely found). The trace fossils are random in the massive sandstone. Leaching of iron oxide does occur, encrusting the burrows. Tulot also suggested that the ichno-footprints were made by birds.

Overlying this massive sandstone is interbedded sandstone and mudstone where the sandstone bed is 0.3 m to 1 m in thickness and the mudstone is 5 cm to 10 cm in thickness. Ripple marks can be found at the top of the sandstone beds. The mudstone bed is not continuous and disappears as the sandstone beds thicken. There are also formation of concretions (grape like) ironstone at the top layer of the sandstone where leaching of iron oxide could be found.

Shallow water condition and shoreface setting has been suggested. This argument is well supported by the low energy structures found like symmetrical ripple marks and fine grains. There are also indications of two-ways current moving in and out (Nicholas, 1999). All in all, it is a foreshore environment where little mud is found in the sandstone. Parallel lamination, low angle cross beds and the grading of coarser sand shows that the massive sandstone was formed in high wave energy.

b) Facies 2: Interbedded clean Sandstone with Mudstone Facies

In this facies, the sandstone is thicker than the mudstone. The sandstone bed is 70 cm to 150 cm in thickness while the mudstone is 30 cm to 50 cm. The sandstone is soft and friable with ripple marks on the surface and is coated with iron oxide. Bed contacts are sharp with erosional bases.

There are a few sedimentology structures found in this facies:-

a) Parallel lamination

b) Symmetrical ripple marks

c) Hummocky cross stratification (HCS)

d) Trough cross bedding

e) Planar cross bedding

The HCS signifies high energy environment and it forms in sandstone deposits (Klein & Marsaglia, 1987). There is also *Ophiomorpha* observed suggesting a shallow marine environment. A vertical and low distribution of tracefossils indicate a low energy condition. The mud layers were rich in carbonaceous material for the organisms. Thus, the organisms would crawl out and grazed for food during fair days and would burrow during the storms for shelter.

The contact between sandstone and mudstone was sharp with scour marks. It indicates that the mudstone is deposited in a storm condition. This storm event is periodic and thin mudstone layers could be observed. It also indicates an offshore transition environment where storm layers form.

c) Facies 3: Carbonaceous Sandstone Facies

This facies has a high content of carbonaceous material and fine to very fine grained sandstone. This facies is also exposed at the Istana Road located near Sandakan Town. The outcrop is 200 m wide and the sandstone beds are 8 m to 10 m thick.

This facies consists of stacked sandstone interbedded with thin carbonaceous mudstone layers. The carbonaceous mudstone beds are thin ranging from 2 cm –to a few mm. They are also patchy and discontinuous. The sandstone in this facies has fine lamination at the base and is overlain by high energy sedimentary structures such as HCS and trough cross bedding.

The most common trace fossil found here is the *Ophiomorpha* and burrows. The burrows are vertical and oblique. No fossil body was found.

The HCS, troughs, high angle planar cross beds and the biogenic signature suggest that this facies is deposited in high energy conditions. The carbonaceous material was deposited as suspended sediment during fair weather.

d) Facies 4: Thick Mudstone Facies

This facies is composed of thick mudstone with alternation of thin sand layer and lenticular sandstone units. The average thickness of this facies is 6 m to 8 m. Parallel laminations, flaser beddings and symmetrical wave ripples could be seen at the thin sandstone beds. Coals lens could be found in between the thick mudstone beds. The isolated lenticular sandstone units are suggested to be tidal channels. The length of this lenticular sandstone differs from other localities. In Batu Sapi, the length is less than 5m and the relief is 0.3 m thick, whilst at Cecily Outcrop, up to 8 m wide lenticular sandstone with a 0.5 m incision could be found. The top of the sandstones are capped by ripple marks. Burrows are caused by found in this facies and are 2 cm to 30 cm in length. The burrows are *Ophiomorphal,Chondrites, Thalassinoides* and *Planolites.*

The occurrence of *Ophiomorpha* and *Skolithos* inchnofacrics indicate that this facies was deposited under intertidal settings with shifting sand substrate and fluctuating water condition. Result from the foram and pollen analysis shows that the shale sample is barren of foraminifera but has of abundant mangrove pollen. This mudstone is therefore a mangrove swamp related to coaly mudstone.

2.4.5 Sandakan Formation based on Tarek (2003)

Tarek had conducted sedimentology logging on 6 different outcrops with the resolution of 1:50 around Sandakan Town and there are 12 facies identified. They are:-

- **a)** Facies SDS1 (Rippled topped sandstone)
- **b)** Facies SDS2 (Interbedded thick sandstone-shale)
- **c)** Facies SDS3 (Interbedded thin sandstone-shale)
- **d)** Facies SDS4 (Hummocky cross-stratified sandstone)
- **e)** Facies SDS5 (Channelized/ gutter cast sandstone)
- **f)** Facies SDS6 (Thick clean, cross-bedded sandstone)
- **g)** Facies SDS7 (Sandstone lenses/ layers within Facies SDM1)
- **h)** Facies SDM1 (Grey laminated-mudstone with carbonaceous materials, coal fragments)
- **i)** Facies SDM2 (Lenticular-bedded mudstone)
- **j)** Facies SDM3 (Laminated-mudstone)
- **k)** Facies SDM4 (Laminated-mudstone with interbbedded laminated siltstone and sandstone)
- **l)** Facies SDC1 (Coal layers)

2.5 Paleontology of East Sabah

The suggested age for this formation is Upper Miocene. It correlates closely with the Bongaya Formation which is exposed at the Bongaya River. The formation contains foraminifera such as *Ammobaculites sp, Ammonia spp,Bolivina sp, Globogeronoides spp, Globorotalia sp, Trochammina sp and Uvigerina sp.* Macrofossils could also be found in this formation such as Gastropod, *Turritella sp* and *Cerithidea sp* (Lee et al, 2004).

CHAPTER 3

METHODOLOGY

3.1 Chapter Overview

This chapter will discuss the methodology that would be used in carrying out this research. This workflow starts with literature study, fieldwork planning, fieldwork, laboratory analyses, facies analysis and lastly depositional modeling.

3.2 Methodology Flow Chart

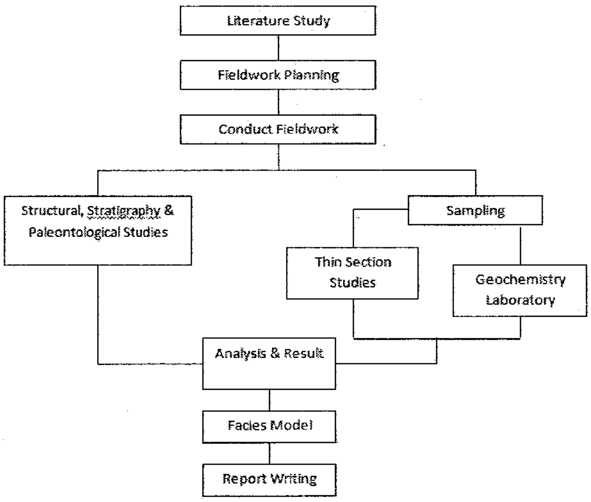


Figure 3.1: Methodology Flow Chart of this research

3.3 Rock Description

From the study of outcrops, hand specimens, and thin sections, detailed observation can be obtained. Consolidated sandstone samples are used to make thin sections for a higher level of description, petrography study (Middleton and Kraus, 1980).

3.4 Outcrop Observation

Outcrops offer vertical profiles of the sedimentary strata. This is important to construct the continuous bedding sequence perpendicular to the strike and dip. However, there may be limitations where exposures are bias towards certain lithology, for example sandstones tend to be more exposed compared with mudstone. Besides, the underlying lithological control must be well accounted.

3.5 Data Collection and Utilizations

Sedimentology structure, grain size, bed contacts, texture and fabric, and occurrence of fossils in outcrops were studied during the fieldwork. The types of ichnofossils and geometry of the traces were also observed in the field. The description on ichnofossils is done based on McIlroy, 2004. Description of the sedimentary rocks could be divided into: -

I. Lithology
II. Texture of beds
III. Sedimentology Structures
IV. Fossil Content
V. Paleocurrent Data

3.5.1 Lithology

Lithology is mainly about mineralogy or composition and colour of the rock. Lithological observation was made and noted in the field.

3.5.2 Texture of Beds

The texture of the beds include grain size, grain shape, sorting and fabric, designation of beds and bedding planes, bed thickness, bed geometry and contacts between beds.

3.5.3 Sedimentary Structures

The internal structures of beds, structures on bedding surfaces or any large-scale structures involving several beds could be categorized as sedimentary structures. Symbols for the sedimentary structure symbols are important and were prepared pre-fieldtrip. Wrong usage of symbols could lead to misguided interpretation.

Identification of sedimentary structures is crucial for data recording. It is used mainly to reconstruct the deposition environment (Pettijohn, 1975). Sedimentary structures are three dimensional but on paper, it could only be seen as two dimensional. The important sedimentary structures that are recognized are:-

1) Cross Stratification
2) Lamination
3) Grading
4) Soft Sediment Deformation
5) Bioturbation and Trace Fossils
6) Pedogenic horizons
7) Concretions
8) Flute Marks
9) Tool Marks
10) Load Casts
11) Bedforms
12) Primary Current Lineation
13) Shrinkage Cracks
14) Trace Fossils
15) Sand and Mud Volcanoes
16) Raindrop Impressions

3.5.4 Fossil Content

Fossil content includes trace fossils, preservation mode and types of fossil. Fossils like gastropods, bivalves and ichnofossils could be found.

3.5.5 Paleocurrent Data

Paleocurrent data is the orientation of paleocurrent indicators and other essential structural information such as dipping direction of the cross beds and ripple marks. The direction of the sediment transported in the past could be determined with paleocurrent data. Each individual bedform has its own direction(s). Paleocurrent data indicate the direction of the paleo-slope and the patterns of sediment dispersal. In the Sandakan Formation, ripples could be seen within some particular beds. Noad (1998) digitized the paleocurrent data which were collected.

3.6 Fossils

Fossils are also another important element besides sedimentary structures. Even though some lithofacies do not contain ichnofossils, they can still provide critical information and indicate the deposition conditions (Tucker, 1960). A list of questions that act as a guide line during on field investigation was prepared. These questions bonded the fieldwork to the objectives of the research and are as listed below:-

1) Are the fossils in growth position?
2) Are the fossils encrusting substrate – iron oxide crust?
3) Do epifaunal fossils have a preferred orientation?
4) Do fossils occur only in certain lithofacies, or different lithofacies contain different fossils?
5) Are the delicate skeletal fossils structures preserved and in what sense if they are preserved - cast?
6) Have the fossils been bored or encrusted?
7) What is the degree of bioturbation - ichnofabric?
8) What is the composition of the fossil assemblage?

9) Is it dominated by a few species? If yes, are they equally distributed or is there any dominating species?

10) Do the fossils occur peferentially in nodules?

3.7 Sampling

Mudstone and sandstone samples were collected for petrographic and paleontological analysis. Approximately, 10 samples were collected from each outcrop depending on the size and exposure of the outcrop. Micropaleontological analysis requires mudstone samples while making of thin section for petrographic analysis requires sandstone samples. The blue thin sections impregnated with blue epoxy were made in Shell Sarawak Berhad.

Thirty samples of mudstones and 31 samples of sandstones were taken during the first field trip in Sandakan. The mudstone samples are used for micropaleontological studies whereas the sandstones samples are used for petrographic and heavy mineral studies.

The micropaleontological analyses include palynology and study for foraminifera and nannofossils, were conducted at Orogenic-Panterra Laboratory Services Sdn. Bhd.

3.8 Stratigraphic Sections and Logging

Stratigraphic logging in the field will determine the physical nature of the outcrop and exposures. There are a few elements measured on-site, namely:-

1) Thickness of the beds
2) Rock type (shale, sandstone, mudstone, etc)
3) Geological structures
4) Current Directions (paleocurrent data)
5) Strike and Dip
6) Texture (coarse, medium to fine-grained)
7) Percentage of carbonaceous material (organic materials)
8) Fossils (as described above)

9) Colour

3.9 Micropaleontological Analyses

This research includes palynological, foraminifera and nannofossils analyses. These analyses were carried out in Orogenic Sdn. Bhd.

3.9.1 Palynogical Analyses

The laboratory procedure for the making of palynological thin sections is as below:-

1. Samples are cleaned and crushed.
2. 30 grams of the samples are weighed and transferred into the glass beakers.
3. Water and detergent are added into the glass beaker until the samples are covered over. Then the mixtures are stirred thoroughly.
4. The glass beakers are stirred and heated on the hotplate for 1 minute at a temperature around 50° C to 60°C.
5. A separated oil layer could be seen floating on top of the water layer.
6. The stirring and heating process could be extended longer, depending on the quantity of the separated oil.
7. Repeat Steps 4 to 6 for 2 – 3 times until the oil is completely removed.
   ** Sample with watersbased mud would skip Steps 3 – 7 and continue with Step 8.*
8. Add 10% HCl to the sample until it totally submerges the sample. Then stir thoroughly and leave the mixture for 1 hour.
   Note: The HCl is to dissolve the carbonate component present in the mud sample. Tiny bubbles of CO_2 (Carbon Dioxide) could be seen as a result of the HCl and Carbonate reaction.
9. After 1 hour, if the reaction still takes place, wait for another 1 hour.
10. Decant the HCl and then transfer the sample from the glass beaker to 50ml centrifuge tube. The sample is then rinsed twice with tap water.
11. Then transfer the sample into a plastic container.

Figure 3.2: Pouring in the Hydroflouric Acid into the samples to remove the silica content.

12. Add 55% - 65% HF till it submerges the sample. Then stir and leave the sample overnight for a complete reaction.

    Note: This procedure is to remove the siliclastic component.
13. Decant the HF and rinse the sample twice with tap water.
14. Then add 10% HCl again until it covers the sample and stir thoroughly. Leave the mixture for 10 minutes.

    Note: This procedure is to CLEAN the sample from Colloidal Silicates and Silicofluorides which may form during HF treatment.
15. Transfer the sample from the Plastic Container to the 50ml centrifuge tube.

    Note: This method skip Acetolysis.
16. Add $ZnBr_2$ (Zinc Bromide) (Specific Gravity 2.2) until it fills approximately 3 / 4 of the plastic tube and stir thoroughly.
17. Then centrifuge it for 30 minutes at 3000 rpm.
18. Particles denser than 2.2 S.G. will sink to the bottom of the centrifuge tube.
19. Remove the floating top layer with a pipette into a small test tube.

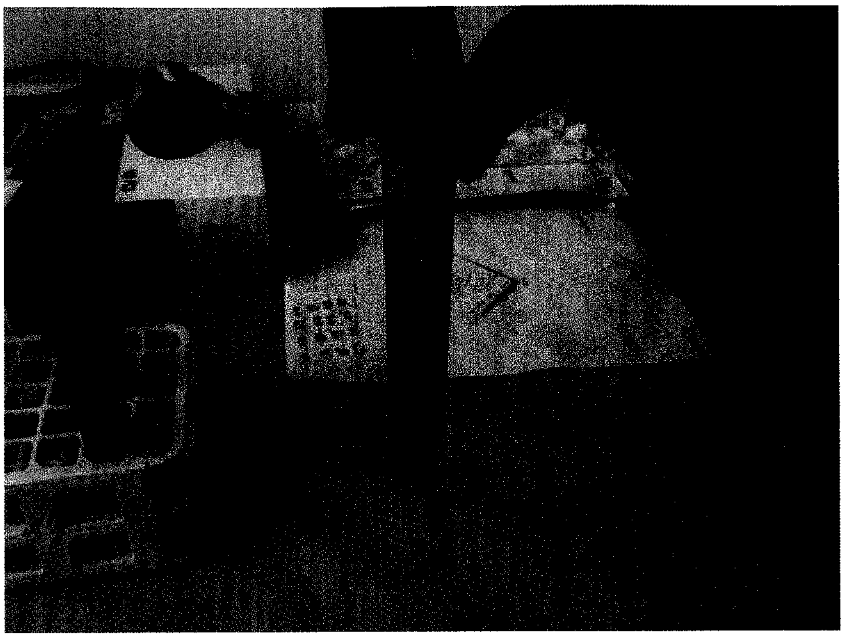


Figure 3.3: The residual in Zinc Bromide solution. The organic material floats while the denser materials sink to the bottom.

20. Add concentrated HNO_3. Let the oxidation reaction take place for 2 minutes and shake occasionally.
    Note: The oxidation time depends on the sample. It could be longer if the sample is older in age.
21. Add a little yet significant amount of KOH (Potassium Hydroxide) to neutralize the humid acid and lignin.
22. Rinse and decant the mixture before transferring it onto a slide.

3.9.2 Foraminifera Analysis

The mudstone samples were used for foraminifera analysis. The procedure for the foraminifera sample preparation is as below: -

1. Fifteen grams of mudstone samples are weighed and separated in different containers.
2. Then the samples are soaked with water to soften the mudstone.
3. The samples are left over night.
4. Then the samples are crushed and stirred with a spatula.

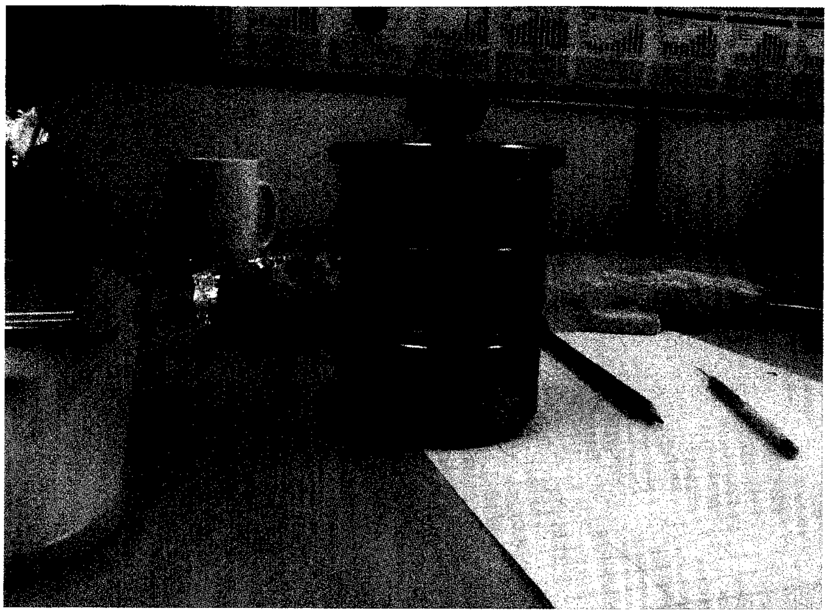


Figure 3.4: Sieves with sizes of 125μm and 250 μm.

5. The samples are then washed through 50 micrometer sieve and the residual are then dried in the oven at 60°C for 1 hour.
6. The dried samples are then sieved with 125 and 250 micrometer sieves.
7. The residual for each sieve size are separated and labeled.

3.9.3 Nannofossils Analysis

Nannofossils analysis was carried out on the mudstone samples. The procedure is as follows:-

1. Twenty grams of the mudstone samples are soaked over the night to loosen up the sediments.

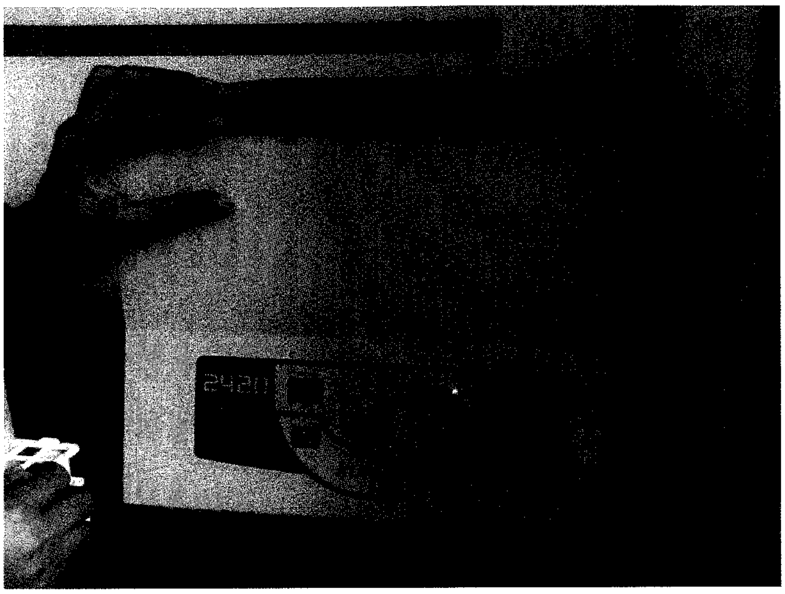


Figure 3.5: A centrifuge machine at Panterra-Orogenic Laboratory

2. The samples are then stirred and 20 ml of the samples are poured into the centrifuge tubes.
3. The centrifuge tubes are then bathed in a Sonic Water Bath at a low rate of 20 000 Hz for 30 minutes. Bathing the samples for more than 30 minutes or bathing them at a higher rate will cause the nannofossils to break and fracture.

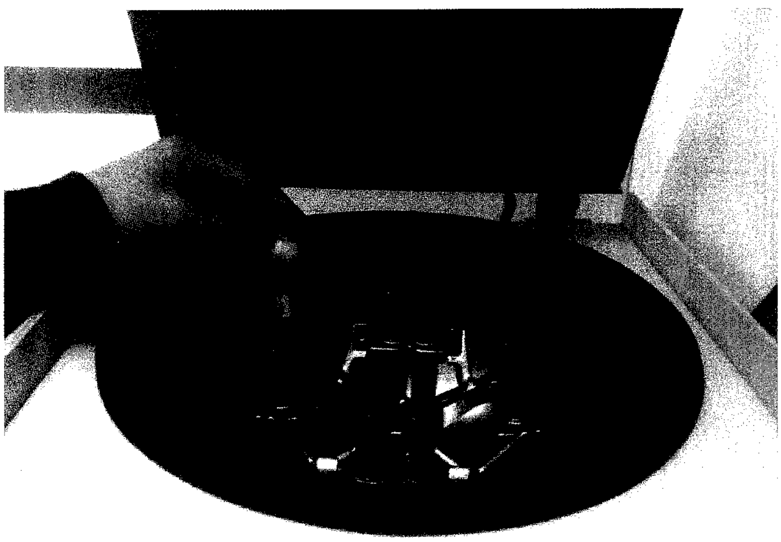


Figure 3.6: The centrifuge tubes in the centrifuge machine.

4. The centrifuge tubes are then centrifuged at 2000 rmp (rotation per minute) to separate the very fine sediments from the coarser grains.
5. The centrifuge tubes are decanted.

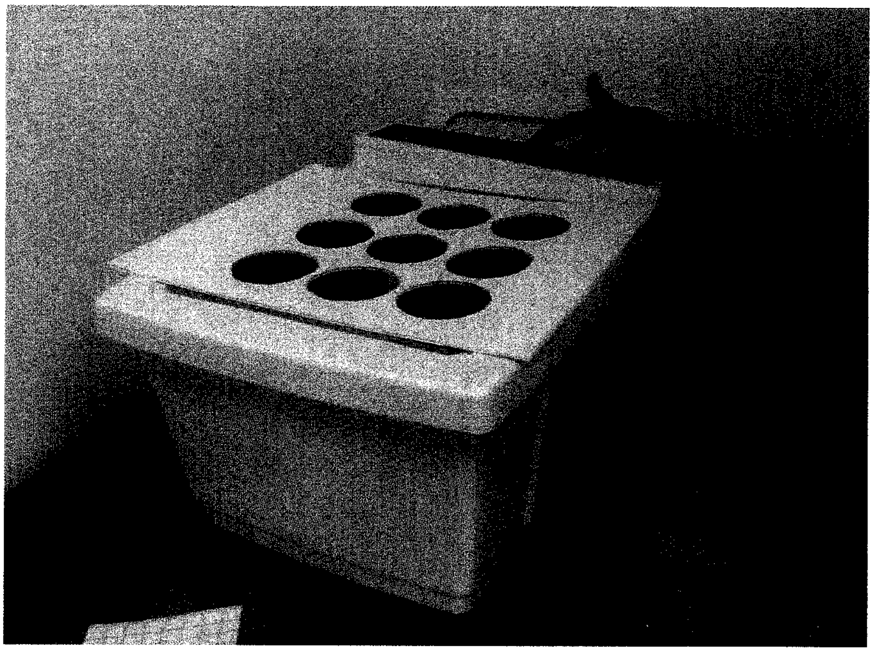


Figure 3.7: Sonic Water Bath Machine set at 20000 Hz.

6. The tubes are then centrifuged again at a slower rate of 200 rpm, to separate the nannofossils, from the organic materials and coarser particles.
7. After that, the centrifuge tubes are decanted and the remnants are then used for the making of thin section.

3.10 Making of Blue Epoxy Impregnated Thin Sections

1. The samples are chipped to a cubicle size of 2 cm x 2 cm.
2. Then the chipped samples are baked at 75 °C for 1 hour, or until it is completely dry.
3. The samples are then degassed in a Logitech 1U30 Impregnation Chamber.
4. While the samples are being degassed, the dye is prepared.
    a. 100 ml of blue epoxy dye is prepared with a ratio of 4 : 1 (resin:hardener) by weight and 3 : 1, by volume (Refer to Table 1).

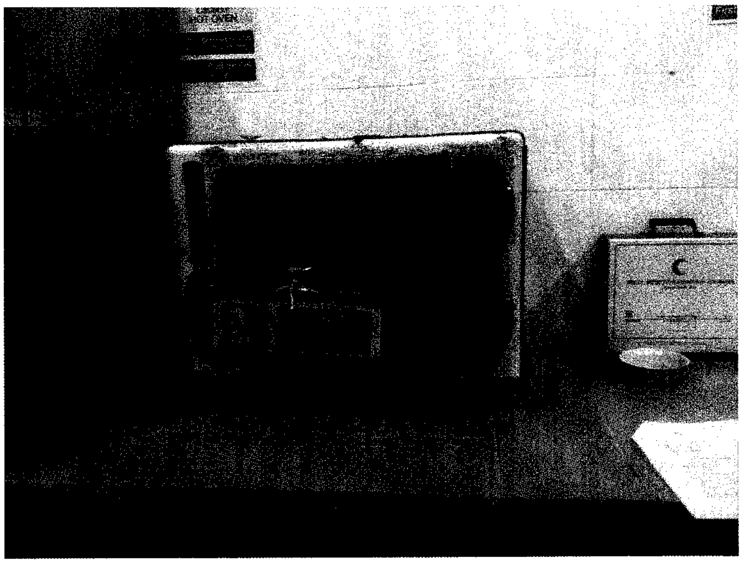


Figure 3.8: The oven is used to dry the sandstone samples.

Component	Mixing Ratio	
	Parts by Weight	Parts by Volume
Part A (Resin)	4	3
Part B (Harderner)	1	1

Table 3.1: The mixing ratio between the resin and harderner.

Notes: Mixing ratios are critical for proper curing and it is recommended that the component parts of Logitech EpoxyPack 301 are measured using burettes. Add the relavant quantity of hardener to the resin and only make up enough resin to cover immediate usage due to its relatively short shelf life.

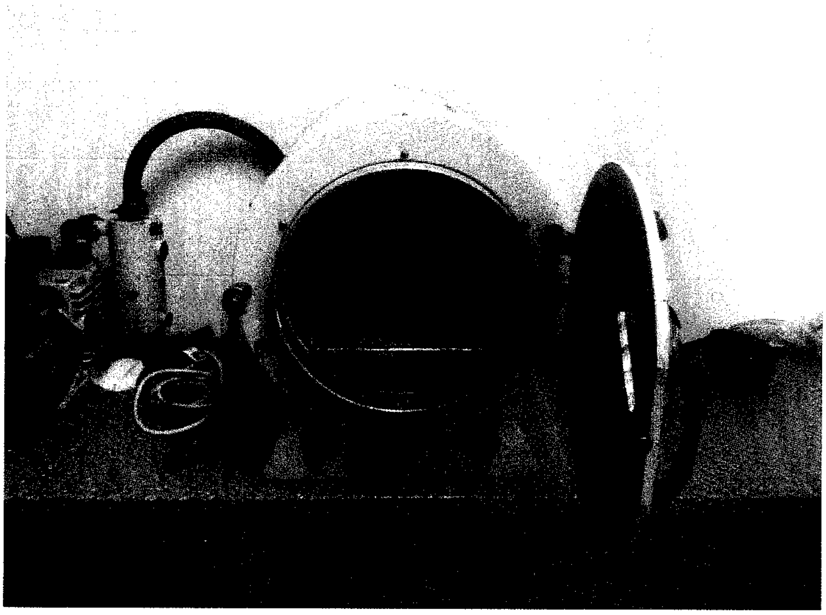


Figure 3.9: The German Vacuum Chamber, Herapus. It is used to vacuum the dye.

5. The prepared dye is then vacuumed in the vacuum chamber before being transferred into the samples in the Logitech 1U30 Impregnation Chamber.

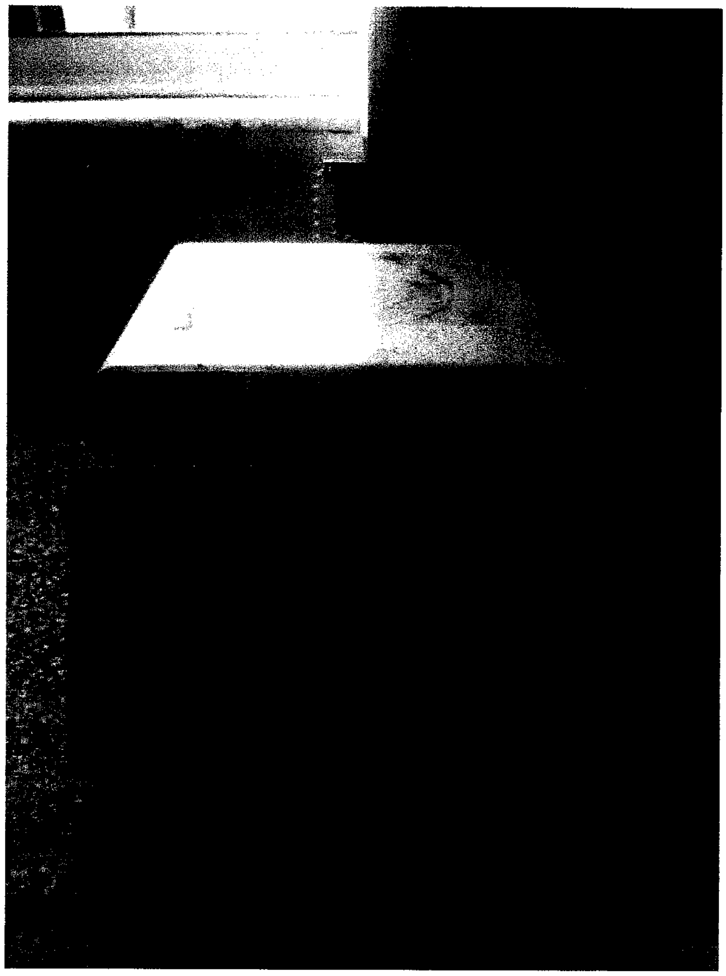


Figure 3.10: The hot plate and mixer is used to mix the part A (resin) and part B resin (harderner) of the epoxy dye.

6. Then the samples are left for 15 minutes for degassing and they are left overnight for the blue epoxy dye to harden completely.
7. Separately, the thin section glasses are polished with Silica Carborumdum Powder a LP50 Auto Precision Lapping & Polishing Machine until it is 1200 micrometer thick.

Figure 3.11: The LP50 Auto Precision Lapping & Polishing Machine in Shell Sarawak Bhd.

8. After leaving the samples to harden overnight, then the samples are removed from the containers.
9. The samples are then cut into half horizontally (depending on the position of the rock samples in the resin) and then trimmed to fit the glass slide.
10. The samples are then hand polished with Silica Carborumdum Powder till they are flat.

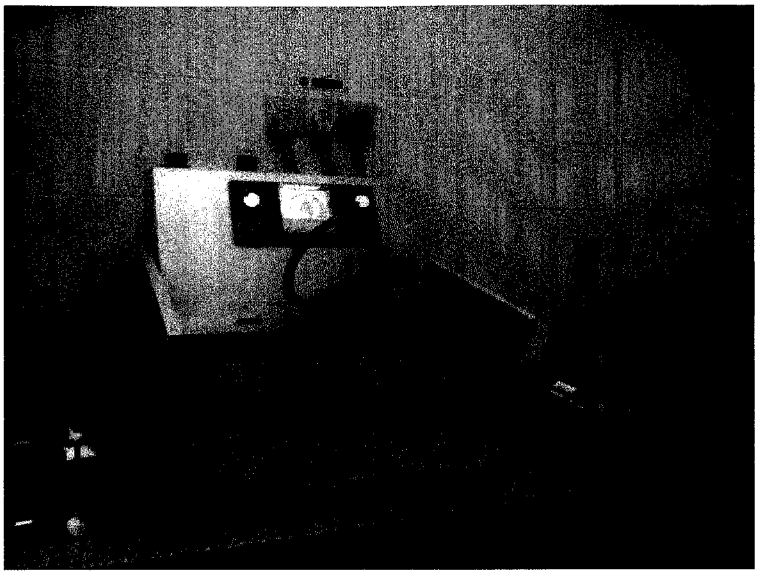


Figure 3.12: A Vacuum Impregnation Unit is used to inject the dye in a closed vacuum system.

11. The samples are pasted onto the thin section glass with the UV Resin.
12. After that, the samples are polished again with the LP50 Auto Precision Lapping & Polishing Machine, with a calibration of 1235 micrometer.

Note: The thickness of the rock slab on the thin section glass will be 35 micrometer.

13. The samples are polished for the last time with diamond powder using a Compact 40 Lapping / Polishing Machine.
14. Finally, the samples are washed, cleaned and dried.

CHAPTER 4

RESULT AND INTERPRETATION

4.1 Introduction

This chapter presents the data collected in the field and results from laboratory analyses. Detailed logging and facies description were carried out on ten different outcrops within and in the vicinity area of Sandakan Town. The outcrops are as lited below in table 4.1:-

No	Locality	Outcrops
1	Buli Sim-Sim Road N5 51.286 E118 07.993	1
2	Tshun Ngen Road N5 51.139 E118 03.771	2
3	Road between Batu Sapi and Sibuga N5 50.095 E118 02.554	3 4
4	Batu Sapi Road N5 51.286 E118 07.993	5.1 5.2 5.3
5	Pintas Sibuga Road N5 51.286 E118 07.993	6
6	Cecily Road N5 50.072 E118 04.771	7
7	Bokuro Road N5 51.286E118 03.771	8

Table 4.1: Locality of the outcrops covered in the Sandakan Peninsula, East Borneo. Locality 4 has 3 outcrops each, namely, 4.1, 4.2 and 4.3.

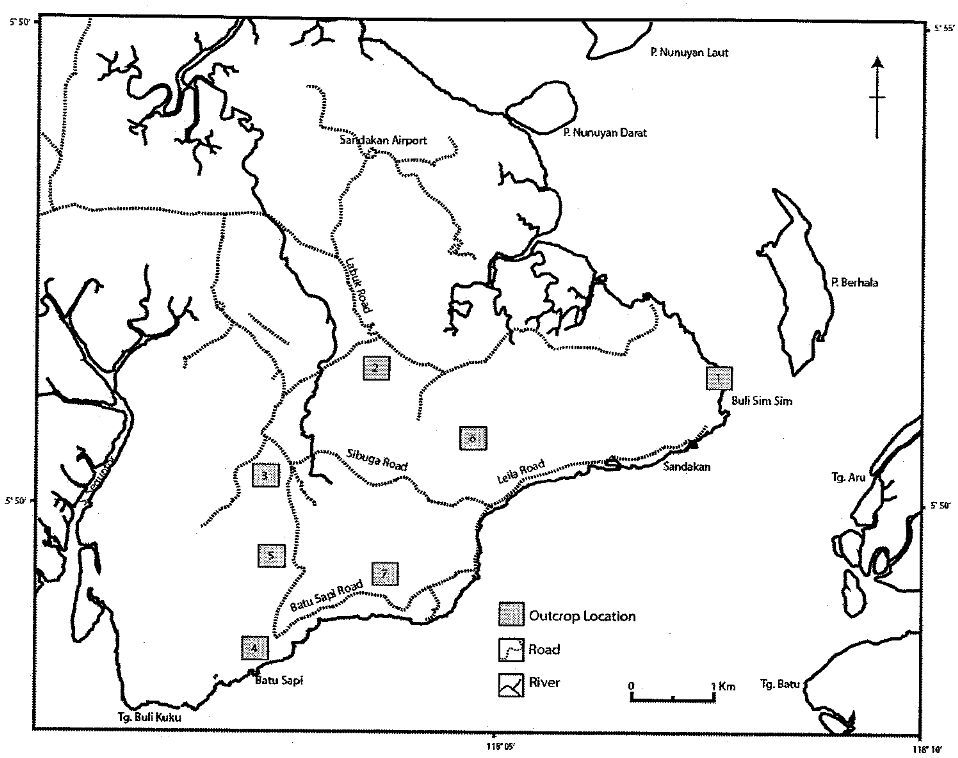


Figure 4.1: Locality of outcrops studied across the Sandakan Peninsular. (Modified from the Geological Map of Sandakan Peninsula, Geoscience and Mineralogy Department of Malaysia, 1969)

4.2.1 Lithofacies Analysis

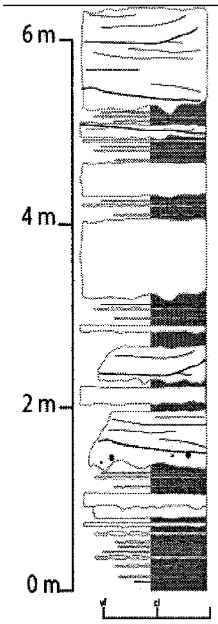
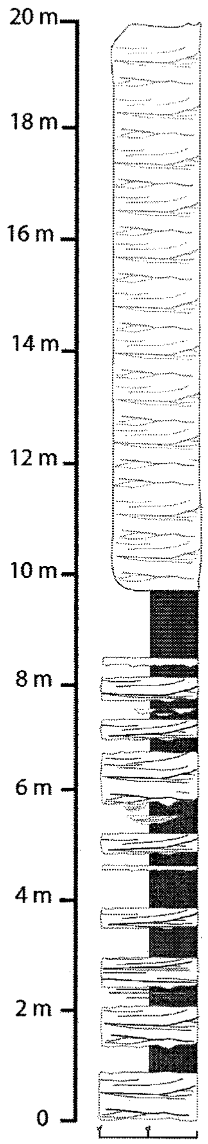
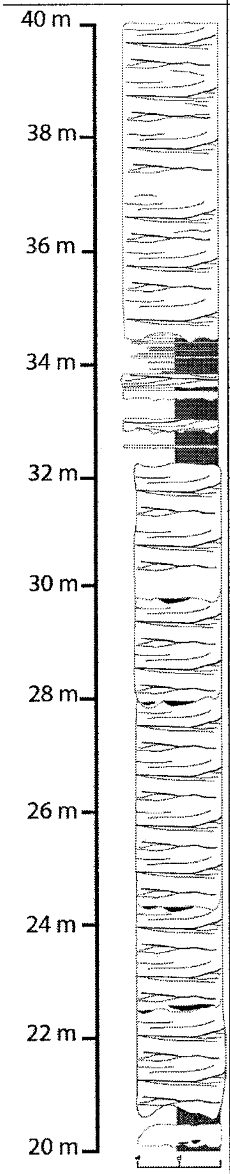
Outcrop 1	Facies	Description	Processes
	F1	Light brownish fine to very fine grained sandstone with low angle HCS	Storm and wave currents
	F6	Interbedded of thin sandstone slivers and laminated mudstone.	Waning currents
	F2	Faintly laminated sandstone	Distal storm C.
	F6	Thin sandstone beds and musdtone	Waning flow
	F2	Brown sandstone with faint lamination. Contains elongated mudballs, 1-2 cm	Storm and wave currents
	F6	Thin sandstone slivers and musdtone	Waning flow
	F2	Fining upwards sandstone with low angle HCS – Concave upwards. No bioturbation. Contains mudballs, 1 – 2 cm in diameter.	Suspension deposits & storm wave current
	F6	Thin bedded sandstone with mudstone	Waning flow
	F2	Sandstone beds with scouring contacts.	Storm
	F6	Thin fine to very fine grained sandstone beds and mudstone. Sandstone beds are less than 1 cm to 5 cm in thickness	Waning currents

Figure 4.2: Stratigraphic section of Outcrop 1 - Buli Sim Sim Road, summaring the organization of facies and their characteristics.



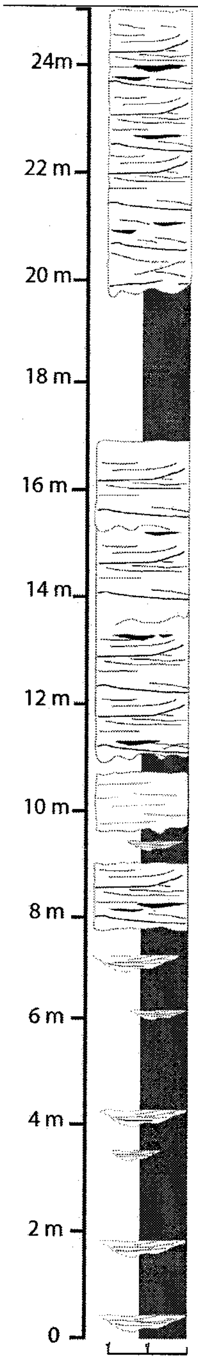
Outcrop 2.1	Facies	Description	Processes
	F1	Thick light brownish sandstone with very faint low angle HCS. Fine to very fine grained. It has irregular top contact. The basal is relatively sharp. It is also subangular to subrounded and well sorted. Thin section analysis: it has approximately 25% of estimated porosity.	Storm and wave currents
	F2	Interbedded light grey Sandstone and dark grey mudstone. Sandstone beds are fine to very fine grained. The sandstone beds show low angle HCS. Most of the beds have a irregular / ripple surface and a scoured basal contact. The sandstone beds range from 10 cm to 78 cm in thickness. No bioturbation in the muddstone. Thickness of the mudstone beds: 20 cm – 58 cm.	Suspension deposits and a more proximal storm wave current
	F6	Striped mudstone with thin laminated sandstone.	Waning currents
	F2	Light grey sandstone and mudstone beds. Low angle HCS is observed at the sandstone beds. The sandstone beds are fine to very fine grained.	Suspension deposits and a more proximal storm wave current

Figure 4.3: Stratigraphic section of Outcrop 2 - Tshun Ngen Road, part 1, summaring the organization of facies and their characteristics.



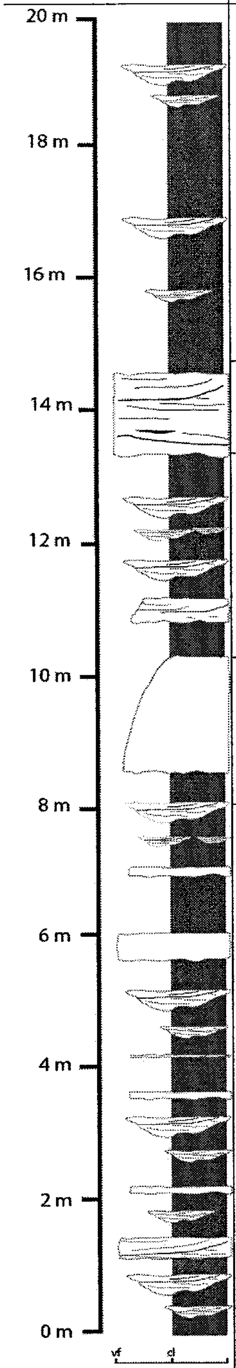
Outcrop 2.2	Facies	Description	Processes
	F1	Thick light brownish sandstone with very faint low angle HCS lamination. Sandstone bed is fine to very fine grained. Top contact looks irregular. Scoured bottom contact.	Storm and wave currents
	F6	Thin sandstone slivers and mudstone.	Waning flow
	F2	Sandstone beds and grey mudstone. The sandstone beds are fine to very fine grained. Faint lamination in sst.	Suspension and storm current
	F1	Thick light brown sandstone Low angle HCS. Fine to very fine grained. The top contact is irregular. Scoured bottom contact. The sandstone grains subangular to subrounded. This sandstone is well sorted. Mudstone lenses are present. The mudstone lenses are approximately 20 cm in length. Thin section analysis: ~ porosity is 16.84%.	Storm and wave currents
	F2	Interbedded sandstone and mudstone beds. Mudstone beds are 13 cm to 26 cm. Mudclasts are present in the sandstone.	Suspension and storm current

Figure 4.4: Stratigraphic section of Outcrop 2 - Tshun Ngen Road, part 2, summaring the organization of facies and their characteristics.



Outcrop 3	Facies	Description	Processes
	F1	Brownish orange sandstone. This sandstone contains HCS and it is fine to very fine grained. Mudstone lenses are present. Mudstone lenses are more than 5cm thick and approximately 10 cm length. Top contact is not observed. Scoured bottom contact.	Storm and wave currents
	F4	Dark grey mudstone. Rare horizontal burrows. Scoured top and irregular bottom contact. Slightly silty bottom.	Suspension deposits
	F1	Brownish orange sandstone. HCS is observed. Fine to very fine grained. Mudstone lenses are seen and averagely 3 cm in thickness and 5 cm in length. Scoured bottom contact. Irregular to flat top contact. Moderately well sorted. Subangular to subrounded grained.	Storm and wave currents
	F2	Sandstone and mudstone beds. The sandstone beds contain HCS. Fine to very fine grained. Dark grey mudstone beds. Irregular top and scouring basal contact with low relief.	Suspension deposits and a more proximal storm wave current
	F3	A mudstone dominated, thin lenticular interbedded HCS sandstone and mudstone. The sandstone lens are 2 cm to 50 cm in thickness. Fine to very fine grained. Burrows are rare. Bioturbation grade 0 – 1. Bottom contact of this section is not observed.	Suspension and distal storm wave currents

Figure 4.5: Stratigraphic section of Outcrop 3 - Road between Batu Sapi and Sibuga, summaring the organization of facies and their characteristics.



Outcrop 4.1	Facies	Description	Processes
	F3	This section is mudstone dominated. Light greyish brown sandstone lenses. The lenses are averagely 1 cm – 22 cm thick, with irregular top contact and erosional basal contact. Thin and faint lamination is present in the sandstone lenses. Dark grey mudstone.	Suspension and distal storm wave currents
	F1	Light brown sandstone. Low angle HCS. Fine to very fine grained. Irregular top. Scoured bottom.	Wave currents
	F2	Sandstone lenses in mudstone. The sandstone lenses are 1 cm – 17 cm in thickness. Fine and very fine grained. Dark grey mudddstone. No bioturbation.	Suspension and distal storm wave currents
	F1	The sandstone beds are fining upwards with faint HCS. Bioturbation is rare. The burrows are 0.5 0 1.5 cm in diameter. Low relief scoured bottom contact.	Storm and wave currents
	F3	Light Brown sandstone lenses and mudstone. The sandstone lenses have HCS. Fine to very fine grained. Rippled surface. The sandstone lenses range from 1.5 cm to 5 cm in thickness. Occasionally, sandstone beds are found. Fine to very fine grained. These beds are 2.5 cm – 30 cm in thickness. With rippled top contact and a low relief erosional surface. Dark grey mudstone. Bioturbation in these mustone beds are rare. The top of the mustone beds are scoured. Bioturbation is rare andd only oblique burrows are found, approximately 1 cm in diameter.	Suspension and storm currents

Figure 4.6: Stratigraphic section of Outcrop 4 - Road between Batu Sapi and Sibuga, part 1, summaring the organization of facies and their characteristics.

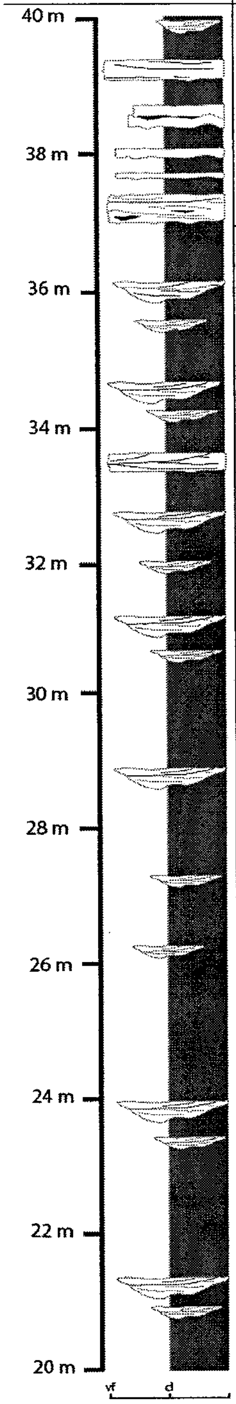
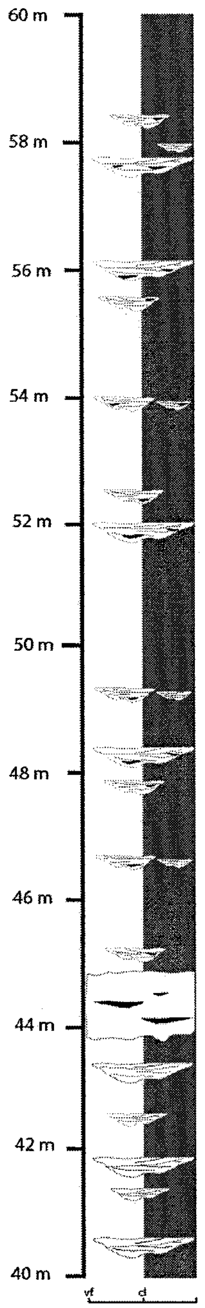
Outcrop 4.2	Facies	Description	Processes
	F2	Brown Sandstone. With low angel HCS. Fine to very fine grained. Bioturbation is rare. The sandstone beds are 12 cm to 35 cm thick. Irregular top contact and erosional basal contact.	Suspension and proximal storm wave currents
	F3	This section is mudstone dominated. Light greyish brown sandstone beds. Horizontally extensive. The sandstone beds range from 1 cm – 22 cm thick. The sandstone beds averagely have a 16 cm relief. HCS presents. The top contact is irregular and a scoured bottom contact. Fine to very fine grained. Bioturbation is rare, probably 0 – 1 rate. Sandstone lenses. The sandstone lenses are averagely more than 2 m wide and 55 cm in thickness. Lenses are thinner towards the top. They are approximately 1.5 cm – 5 cm thick. The sandstoen lenses contain low angle HCS. Fine to very fine grained. Thin lamination could be observed. Dark grey mudstone. Bioturbation is rare. The mudstone beds range from 30 cm to 100 cm in thickness. The top of the mudstone beds are scoured. The bottom of the mudstone beds are irregular. This section consist approximately 70% of mudstone. Bioturbation is rare in the mudstone. Only horizontal and oblique burrows are found with approximately 1 cm diameter. Shell casts are incommon.	Suspension and storm currents

Figure 4.7: Stratigraphic section of Outcrop 4 - Road between Batu Sapi and Sibuga, summaring the organization of facies and their characteristics.



Outcrop 4.3	Facies	Description	Processes
	F3	Sandstone lenses. The sandstone lenses are averagely 7 cm in thickness. The lenses are 37 cm to 7 cm wide with low angle HCS. Fine to very fine grained. Thin lamination is also present in the sandstone lenses. This section is mud dominated and consist approximately 30% of sandstone. Dark grey mudstone. Bioturabation is rare. The mudstone beds range from 30 cm to 100 cm thick. The top of the mudstone beds are scoured and have irregular bottom contact. Mudclasts are present in the sandstone lenses. The mudclasts are averagely 2.7 cm thick and 4.5 cm wide.	Suspension and distal storm currents
	F7	Light greyish brown sandstone. Scoured bottom and irregular top. Fine to very fine grained. Very faint HCS.	Storm and wave currents
	F3	Sandstone lenses. Averagely 70 cm to 6 m wide and 5cm to 42 cm thick. Contain low angle HCS. Fine to very fine grained. Dark grey mudstone. The mustone beds range from 30 cm to 100 cm in thickness.	Suspension and distal storm wave currents

Figure 4.8: Stratigraphic section of Outcrop 4 - Road between Batu Sapi and Sibuga, part 3, summaring the organization of facies and their characteristics.

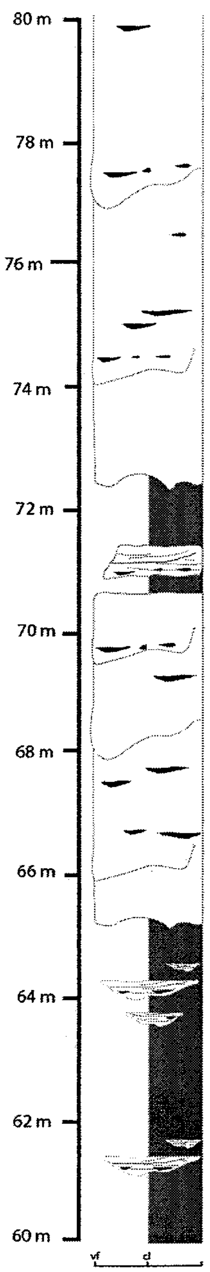
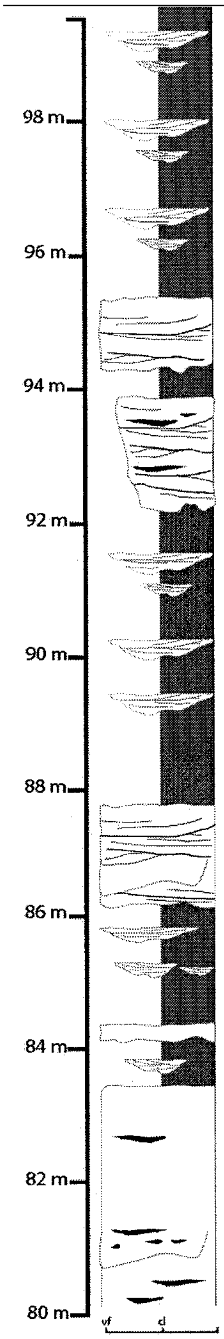
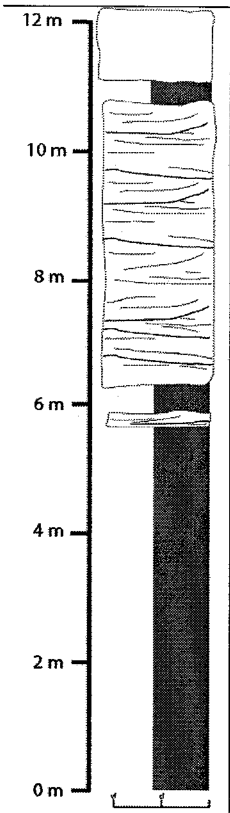
Outcrop 4.4	Facies	Description	Processes
	F1	Light brownish orange sandstone. This sandstone bed is approximately 10m thick. Fine to very fine grained. Top contact is irregular. Bottom contact is scoured. Bioturbation is rare, 0 – 1 rate. The sandstone is amalgamated. Encrustation layers are seen at almost every 4 meters. Contains mudclasts. Muddrapes are found but not horizontally extensive. They are averagely 15 cm thick and 1 m wide.	Storm and wave currents
	F2	Light brown greyish sandstone. HCS. Grading top contact. No bioturbation. Dark grey mudstone, top scoured and bottom irregular.	Suspension and storm currents
	F1	Light orangish brown sandstone. This sandstone bed is approximately 10m thick. Very faint HCS. Fine to very fine grained. Top contact is irregular. Bottom contact is scoured. Bioturbation is rare, 0 – 1 rate. The sandstone is amalgamated. Mudclasts are commonly 1.5 cm thick and 7.5 cm wide.	Storm and wave currents
	F3	Sandstone lenses. Low angle HCS. Fine to very fine grained. Thin lamination is also present in the sandstone lenses. Dark grey mudstone. Bioturabation is rare. The mudstone beds range from 30 cm to 100 cm thick. The top of the mudstone beds are scoured and have irregular bottom contact.	Suspension and storm currents

Figure 4.9: Stratigraphic section of Outcrop 4 - part 4, summaring the organization of facies and their characteristics.



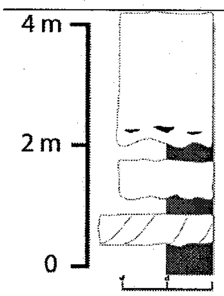
Outcrop 4.5	Facies	Description	Processes
	F3	Sandstone lenses. Low angle HCS. Fine to very fine grained. Thin lamination is also present in the sandstone lenses. Dark grey mudstone. Bioturabation is rare.	Suspension and distal storm wave currents
	F1	Light greyish sandstone. Low angle HCS. Fine to very fine grained. Top irregular. Scoured bottom contact with low relief. No bioturbation. Mudballs present. Mud lenses present.	Storm and wave currents / Suspension for mudstone
	F3	Sandstone lenses. Low angle HCS. Fine to very fine grained. Thin lamination is also present in the sandstone lenses. Dark grey mudstone. Bioturabation is rare. Dark grey mudstone.	Suspension and distal storm wave currents
	F1	Moderately thick sandstone. Scoured bottom. Irregular top. Muddrapes up to 15 cm. Fine to very fine. HCS.	Storm and wave currents
	F3	Sandstone lenses. The lenses contain low angle HCS. Some are faint. Fine to very fine grained. Dark grey mudstone. No bioturbation.	Suspension and distal storm wave currents
	F1	Light orangish brown sandstone. This sandstone bed is approximately 10m thick. Fine to very fine grained. Top contact is irregular. Bottom contact is scoured. Bioturbation is rare, 0 – 1 rate. The sandstone is amalgamated.	Storm and wave currents

Figure 4.10: Stratigraphic section of Outcrop 4 - Road between Batu Sapi and Sibuga, part 5, summaring the organization of facies and their characteristics.



Outcrop 5.1	Facies	Description	Processes
	F1	Whitish brown sandstone Irregular bottom contact. Fine to very fine grained. Very faint low angle HCS lamination. Top irregular contact. Low relief scoured basal contact.	Storm and wave currents
	F7	A thin sandstone bed with thick dark grey mudstone. The sandstone bed features faint HCS lamination. It it fine to very fine grained. The dark grey mudstone contains carbonaceous material.	Suspension deposits

Figure 4.11: Stratigraphic section of Outcrop 5.1: Batu Sapi Road, summaring the organization of facies and their characteristics.



Outcrop 5.2	Facies	Description	Processes
	F1	Whitish Massive Sandstone Mudclasts at the bottom of the sandstone bed. Very faint lamination. Top contact could not be observed. Fine to very fine grained.	Storm and wave currents
	F2	Whitish sandstone beds. 44 cm to 48 cm in thickness. Fine to very fine grained. Dark grey mudstone 28 cm to 40 cm in thickness.	Suspension and proximal storm current

Figure 4.12: Stratigraphic section of Outcrop 5.2 - Batu Sapi Road, summaring the organization of facies and their characteristics.

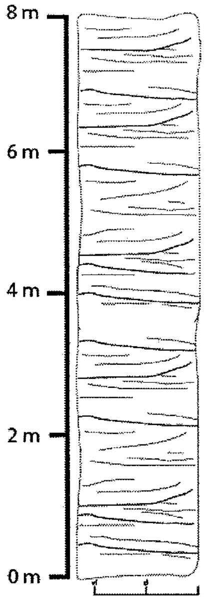
Outcrop 5.3	Facies	Description	Processes
	F1	This section mainly comprises thick faintly & laminated low angle HCS. It is fine to very fine grained. Top and bottom contact not observed. No bioturbation.	Storm and wave currents

Figure 4.13: Stratigraphic section of Outcrop 5.3 - Batu Sapi Road, summaring the organization of facies and their characteristics.

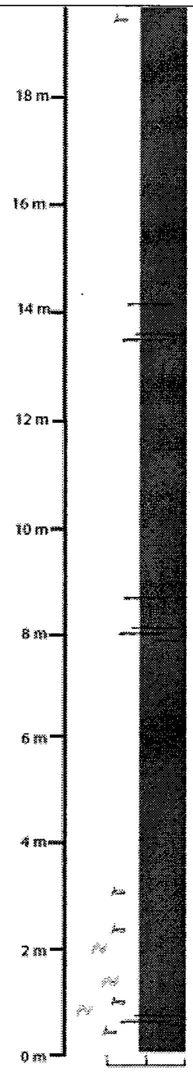
Outcrop 6.1	Facies	Description	Processes
	F7	The thick dark grey mudstone. Carbonaceous. Thin coal lenses present, ranging from 0.9 cm to 1.5 cm in thickness and 8 cm – 15 cm in length. 2 – 3 bioturbation rate. *Thalassinoides* are present. Bivalve casts are present. Petrified woods. Coal lenses are averagely 18 cm wide and 0.8cm thick.	Suspension / wood debris

Figure 4.14: Stratigraphic section of Outcrop 6: Sibuga Road, part 1 summaring the organization of facies and their characteristics.

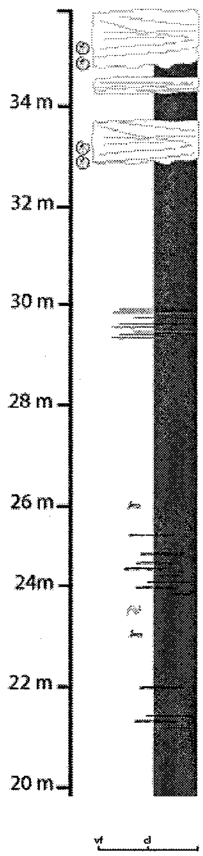
Outcrop 6.2	Facies	Description	Processes
	F5	Brown Sandstone Mudclasts are rare and only found close to the bottom of the beds. Medium to fine grained. Low relief. Shell fragments.	Tidal currents
	F7	The thick dark grey mudstone. Carbonaceous.	Suspension deposits / wood debris
	F6	Thin sandstone slivers and mudstone.	Waning flow
	F7	The thick dark grey mudstone. Carbonaceous. Thin coal lenses present, ranging from 0.9 cm to 1.5 cm in thickness and 8 cm – 15 cm in length. 2 – 3 bioturbation rate. *Thalassinoides* are present. Bivalve cast are present. Petrified woods.	Suspension deposits / wood debris

Figure 4.15: Stratigraphic section of Outcrop 6 - Sibuga Road, part 2, summaring the organization of facies and their characteristics.

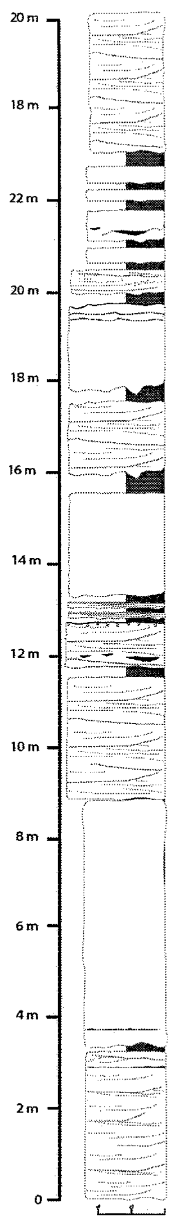
Outcrop 7	Facies	Description	Processes
	F1	Thick massive light brown sandstone. Top contact is not observed. Fine to very fine grained.	Wave Currents
	F2	Thin sandstone beds with faint low angle HCS. Fine to very fine grained. Mud lenses are present. The last bottomost bed is medium to fine grained.	Storm currents and suspension deposits
	F1	Moderately thick brownish sandstone. Medium to fine grained with faint low angle HCS. The mudstone is white in colour. Thin whitish mudstone, generally less than 10 cm in thickness with reddish dots. Some beds feature faint HCS.	Storm and wave currents / suspension deposits
	F2	Thin sandstone beds and mudstone.	Waning flow
	F1	Thick light brown sandstone with faint low angle HCS. The bottom contact of the sandstone beds are erosional. Whilst the top contact is irregular and almost sharp. Mud lenses and mudclasts are found occasionally within the sandstone beds. Some sandstone beds are amalgamated / encrusted with motling surface. Burrows could be traced from the motling surface. The sandstone beds within 0m – 8m interval are fine to very grained. The sandstone beds within 8m – 12m interval are medium to fine graiend.	Storm and wave currents

Figure 4.16: Stratigraphic section of Outcrop 7 - Cecily Road, summaring the organization of facies and their characteristics.

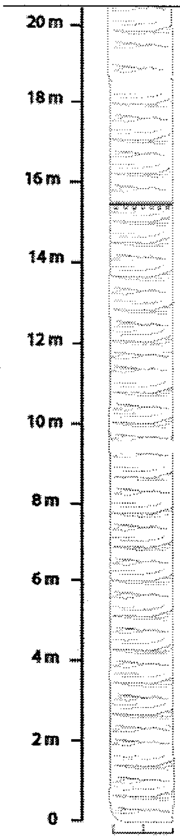
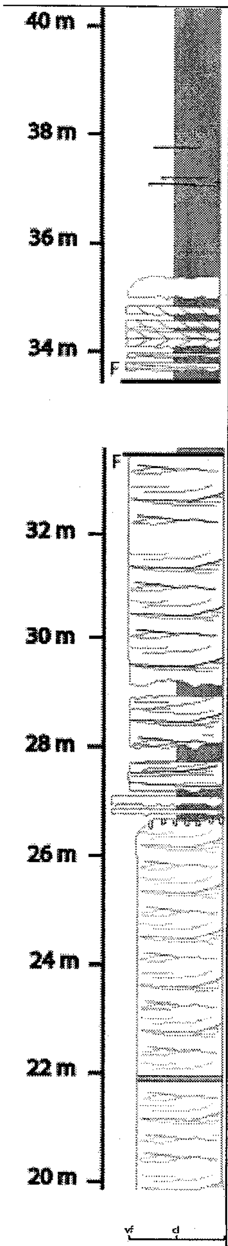
Outcrop 8.1	Facies	Description	Processes
	F1	Light brownish sandstone. Fine to very fine grained. Very faint lamination. Low angle HCS. Encrustation surface / heavily burrowed surface / motling surface. Bioturbation is rare and is mainly found at the encrustation surface. Occasionally mudclasts are found and averagely they are 1 cm in diameter.	Storm and wave currents

Figure 4.17: Stratigraphic section of Outcrop 8 - Bokuro Road, part 1, summaring the organization of facies and their characteristics.



Outcrop 8.2	Facies	Description	Processes
	F7	Carbonaceous mudstone with thin coal lenses.	Suspension deposits / plant debris
	F8	Sandstone beds feature herring bone structure. But flow is dominant to the left, northeast direction.	Tidal Currents
	Fault	Fault	Fault
	F1	The top of this sandstone is bounded by a fault. Light brown sandstone with faint low angle HCS lamination.	Storm and wave currents
	F3	Thin fine to very fine sandstone beds. These beds feature faint HCS. This section contains medium to fine sandstone beds.	Suspension deposits / storm and wave currents
	F1	Light brownish sandstone. Fine to very fine grained. Very faint lamination. Low angle HCS. Encrustation surface / heavily burrowed surface / motling surface. Bioturbation is rare and is mainly found at the encrustation surface. Occasionally mudclasts are found and averagely they are 1 cm in diameter.	Storm and wave currents

Figure 4.18: Stratigraphic section of Outcrop 8 - Bokuro Road, part 2, summaring the organization of facies and their characteristics.

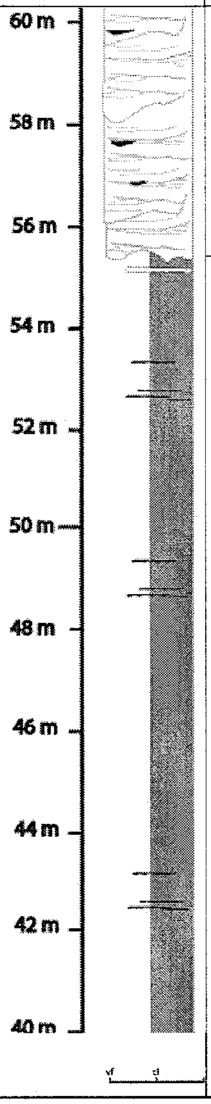
Outcrop 8.3	Facies	Description	Processes
	F1	HCS is observed. This sandstone is fine to very fine grained.Scoured bottom contact. Irregular to flat top contact. The sandstone is also moderately well sorted. Subangular to subrounded grained.	Storm and wave currents
	F7	Carbonaceous mudstone with thin coal lenses.	Suspension deposits / plant debris

Figure 4.19: Stratigraphic section of Outcrop 8 - Bokuro Road, part 3, summaring the organization of facies and their characteristics.

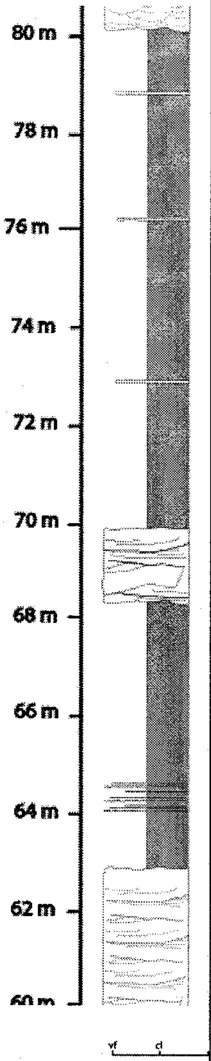
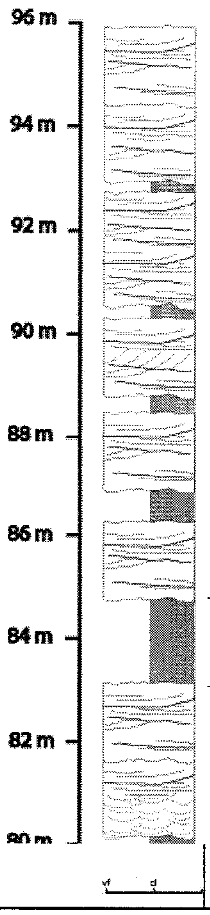
Outcrop 8.4	Facies	Description	Processes
	F4	The sandstone beds are 2 – 3 cm thick and fine to very fine grained. Horizontally extensive Dark grey mudstone.	Suspension deposits / Shelfal deposits / Storm flows distributed the thin sand.
	F1	Fine to very fine grained.	Storm and wave currents
	F4	Dark grey mudstone	Suspension
	F6	Thin sandstone slivers and grey mudstone.	Waning flow
	F4	Darkgrey mudstone	Suspension
	F1	HCS is observed. This sandstone is fine to very fine grained.Scoured bottom contact. Irregular to flat top contact. The sandstone is also moderately well sorted. Subangular to subrounded.	Storm and wave currents

Figure 4.20: Stratigraphic section of Outcrop 8 - Bokuro Road, part 4, summaring the organization of facies and their characteristics.



Outcrop 8.5	Facies	Description	Processes
	E3F1	Brownish orange sandstone. This section contains medium to thick sandstone with thin whitish mudstone. With faint HCS. These sandstone beds have irregular top contact and erosional basal contact.	Storm and wave currents
	F4	Dark grey mudstone	Suspension deposits
	F1	Thick light brownish Sandstone with very faint low angle HCS. Fine to very fine grained. It has irregular top contact. The basal contact could not be observed.	Storm and wave currents

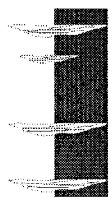
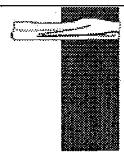
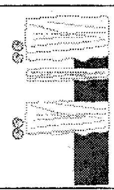
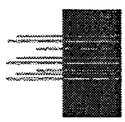
Figure 4.21: Stratigraphic section of Outcrop 8 - Bokuro Road, part 5, summaring the organization of facies and their characteristics.

4.2.1.1 Facies 1 (F1): Thick Amalgamated HCS/SCS Sandstone

Sedimentological Description: This facies comprises light brown, fine to very fine grained sandstone. These amalgamated sandstones are well sorted. Based on the thin section analysis, the sandstone has approximately 25% of porosity. The grains are also subrounded and subangular. Individual sandstone beds generally pinch out, but the bedsets are laterally persistent. The sandstone beds are stacked (amalgamated) especially at the channel structures. The sandstone units can vary from 10 cm – 11 meters in thickness, but commonly 15 cm to 4 meters thick. Load casts, mud balls and thin lenticular mudstructures could be seen near to the base of the sandstone units.Sandstone beds that are thicker than 2 m show Swaley Cross Stratification (SCS) (refer to Figure 4.26, 4.27, 4.29, 4.30, 4.32, 4.33, 4.35, 4.36, 4.38 and 4.39).

Ichnofossils: Trace fossils are very rare though oblique burrows may occur. Bivalve and gastropod casts are rarely seen.

Interpretation: Thick amalgamated beds displaying hummocky cross-stratification represents proximal storm beds and record high-energy oscillatory and combined flows during storms (Buatois & Mangano 2003). This thick bedded, amalgamated hummocky sandstone were formed by repeated storm events. Wave erosion removed mud layers between sandstone beds. This facies took place higher than Fair Weather Wave Base (FWWB) where it is affected by the periodical storm event current (Tulot 2002). The high energy storm current is strongly erosive and is able to remove the top mud layers before the sandstone grains settle down. The deep scours indicate strong erosive flows whereas large load casts suggest rapid influx of sand (Selley 2000). Amalgamated fine to very fine grained sandstones are typical of the lower middle shoreface and have been reported in the literature (Buatois & Mangano 2003; Tulot 2002).

Facies Name / Code	Description	Stratigraphic Section	Location (Outcrop)
F1 Thick Amalgamated Sandstone (Shoreface)	• Faint SCS • Fine to very fine grained • Erosive scouring basal contact • Irregular to flat top contact • Mudstone clasts and lenses are present		3 7 8
F2 Interbedded HCS Sandstone and Mudstone (Offshore Transition)	• Averagely 30cm in thickness • HCS and streaks • Sandstones fine to very finely graded • Sandstone has erosan basal contact • Low microfossils recovery Microfossils: *Rhizophora, Brownlowia, Acrostichum aureum, Stenochleana palustris*		7 8
F3 Thin , Lenticular Interbedded HCS Sandstones and Mudstone (Upper Offshore)	• Sandstone appears as lenses • The thin HCS sandstones are fine – very fine grained • Lenses with erosive base • Mudstone dominated • Low microfossils recovery • Microfossils: *Rhizophora, Brownlowia, Stenochleana palustris, Ammobaculites, Sphenulitus Abies, Reticulofenestra spp, Coronocyclus nitescens*		3 7
F4 Laminated Mudstone (Shelf)	• Sharp top contact • Irregular basal contact • Low bioturbation rate • Very low microfossils recovery		3 8
F5 Sandstone with Shell Fragments (Upper Transition – Lower Shoreface)	• Low angle cross bedding • 0.7 m – 1m in thickness • Commonly fining upwards • Medium – fine grained • Shells are found- gastropods.		2
F6 Striped Mudstone with Thin Laminated Sandstone and Siltstone (Back Shore)	• Beds approximately 1cm or less than 1 cm in thickness • Sandstones are fine to very fine		2 8
F7 Laminated Mudstone with *Rhizophora* (Estuary, Tide dominated?)	• Sharp top contact • Dark grey • Low bioturbation • Microfossils: *Rhizophora, Brownlowia, Shorea, Stenochleana laurifolia*		2 8

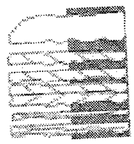
F8 Sandstone with Herringbone Crossbedding (Intertidal Zone)	• Bidirectional • Alternating with thin mudstone • Fine grained.		8

Table 4.2: Summary of Stratigraphic Sections of Sandakan Formation

4.2.1.2 Facies 2 (F2): Interbedded HCS Sandstone and Mudstone

Sedimentological Description: This facies comprises laterally extensive units. Hummocky Cross Stratification, fine to very fine grained, well sorted to moderately well sorted and scouring basal contact are present in the sandstone beds. The sandstone units are 10 cm –140 cm in thickness, commonly 40 cm – 70 cm. The mudstone units are approximately 60 cm thick. The sandstones are also grain-supported with point contacts and comprise more than 95% of quartz, arenites. The shape of the grains is subangular and subrounded.Occasionally, the coal trunk could be found in the sandstone beds (refer to Figure 4.31).

Ichonofossils: Bioturbation is rare.

Biofacies: Micropaleontological studies show barren result in foraminifera, spores, pollens and nannofossils.

Interpretation: This facies suggest an offshore transition environment. It represents a quiet-water sediment fall-out and repetitively. The various thickness of beds suggest that it formed at a moderately strong, intermediate cycles of flow (Pettijohn & Siever 1972). Offshore transition deposits are commonly explained by a regular alternation of sandstones and mudstones (Buatois & Mangano 2003).

4.2.1.3 Facies 3 (F3): Thin Interbedded HCS and Mudstone

Sedimentological Description: Facies 3 is mudstone dominated with regularly interbedded thin sandstone. The sandstone units occur from 5 – 40 cm in lenticular structure. The sandstone units are not laterally extensive. It is brownish with erosive-based, fine to very fine grained sandstone and some units contain hummocky cross stratification (HCS).

Biofacies: Micropaleontologic analysis at the mudstone samples shows sparse distribution of pollen, foraminifera and nannofossil. Landward direction pollens, *Rhizophora* and *Shorea* could be found but are uncommon in this facies. Similarilly the nannofossil, *Sphenulitus abies* and *Reticulofenestra spp*, could rarely be found in this facies.

Interpretation: The thin lenticular sandstones are the drains that scour through the mudstone (Pettijohn & Seiver 1972) .The depauperating distribution of pollens and nannofossils may suggest that they are transported from adjacent environment. Both *Rhizophora* and *Shorea* could be dominantly found in a fluvio- estuary environment (Jenkins 1993). The small counts could explain that the pollens had been transported down from a more terrestrial direction. This facies is interpreted to have been deposited at the upper offshore environment.

4.2.1.4 Facies 4 (F4): Laminated Mudstone

Sedimentological Description: This facies comprises black grey mudstone. The mudstone unit displays sharp top contact. The mudstone consists of subangular to angular claystone, pyrite and quart.

Ichnology: Bioturbation is absent.

Interpretation: Facies 4 records low energy, suspension fallout deposition in the absence of waves and currents (Buatois & Mangano 2002). The absence of bioturbation, dark colour and massive structure suggest an oxygen-depleted conditions (Potter et al. 2005). The absence of oscillatory structures indicates that the deposition occurs below storm wave base. Facies 4 is interpreted to be deposited in a shelf environment. The mudstone laminaes are commonly silt rich. This facies is present at Outcrop 2.

4.2.1.5 Facies 5 (F5): Sandstone with Shell Fragments

Sedimentological Description: This facies consist of light brown and medium to fine grained sandstone. The beds range from 70 cm to 100 cm in thickness. The sandstone beds are composed of isolated mudstone lenses and mudclasts. The mudstone lenses are averagely 6 cm in length and 1 cm in thickness. Fining and thinning upward in the sandstone are common. Based on the thin section, the sandstone grains are well sorted to moderately sorted with few fractured grains and minor intragrains cementation. The porosity is estimated to be approximately 11%. The grains are also subangular and subrounded. It is also categorized as arenite as it contains more than 95% of quartz grains. Shell fragments are found (refer to Figure 4.37).

Ichnofossils: The distribution of fossils in this facies is very uneven. The brachiopods and gastropods appear to be fractured and have thin shells. Occasionally, the casts of these fossils are present. The fragments are infilled with sandstone.

Biofacies: Facies 5 is present in Outcrop 6 and is associated with Facies 5, thick mudstone with abundant *Rhizophora.*

Interpretation: This facies is most likely to form in a high energy environment and yet periodical. The shells are disarticulated and they are exsitu deposit. The upward decrease in grain size and vertical changes in bedforms suggest a decrease in flow velocity and sand supply (Buatois & Mangano 2003). This could also be linked to winnowing of shells in a transgressive lag (Sixmith et al, 2008). This suggests a lower shoreface to a transition zone environment.

4.2.1.6 Facies 6 (F6): Striped Mudstone with Thin Laminated Sandstone and Siltstone

Sedimentological Description: This facies contains thinly laminated greyish mudstone and sandstone. The sandstones are fine to very fine grained and appears to be brownish –orange in colour. This facies ranges around 2 cm in thickness.This facies can be divided into two subfacies which are, a) parallel laminated sandstone and mudstone, and b) ripple laminated sandstone and mudstone. Mud drapes are common within the wrinkles (ripple cross – lamination).

Ichnofossils: Trace fossils are relatively rare in this facies. Occasionally, vertical burrows are found cutting through the laminae.

Interpretation: The alternating laminated sandstone and mudstone and the muddrapes suggest a tidal influenced environment (Yoshida 2004). The variations of tidal currents can be indicated through the thinning and thickening trends (Kvale & Archer 1990; Kvale et al. 1989). Based on Buatois, 2003, this facies can be interpreted as tidal rhythmite. This facies indicates a low energy intertidal flat depositional setting.

4.2.1.7 Facies 7 (F7): Laminated Mudstone with Rhizophora

Sedimentological Description: Approximately 17 meters of this facies is exposed at locality 3, Outcrop SDK-2. This facies is grey to dark grey in color with a large amount of mud, abundant lignite and amber. Occasionally, accumulation of thin coal lenses, leaves cast and petrified wood could be found. Thin-shelled bivalve fragments are rare within the mudstone.

Ichnofossils: *Thalassinoides* are present in the mudstone beds.

Biofacies: These bivalve fragments are present in all the beds and are occasionally associated with petrified wood. *Rhizophora* pollen type is abundant in this facies. Other types of pollens found such as *Stenocleana palustri* and *Shorea* are rarely found.

Interpretation: This facies is interpreted as deposits of low energy, estuary environment (with tidal influence?). The thick mudstone deposits, rich with well-preserved pieces of trunks and leaves cast, suggest that these beds were deposited in a reducing/ anoxic condition (Tulot 2002; Noad 1998). The absence of burrows in this facies suggests that either the rate of sedimentation was too rapid or the salinity was too low to support burrowing organisms (Buatois & Mangano 2002). The dominance of *Rhizophora* pollens, depauperate distribution of foraminifera and nannofossils, and abundant lignite/ coal suggest that the area was formerly a low coastal plain, with a low tide dominated and low energy depositional environment (Avatar cited in Devesh 2007).

4.2.1.8 Facies 8 (F8): Sandstone with Herringbone Crossbedding

Sedimentological Description: This facies is mainly found at Outcrop8. These sandstone beds are fine grained. The thickness of these beds is averagely 20 cm to 30 cm in thickness. The sandstone layers feature Herringbone Cross Stratification. The direction of the Herringbone structure is more dominant to the left, northeast direction. Ocassionally thin mudstone layers could be found in between the sandstone beds.

Ichnofossils: No bioturbation is observed.

Interpretation: The alternating layers of these cross beds dipping in the opposite directions reflect the alternating paleocurrent. This bidirectional feature of herringbone structure suggest a tidal-influenced-environment, intertidal zone (Selley, 2000).

4.3 Petrographic Analysis

This section consists of the petrographic observation and porosity analyses of the thin sections. The preparation for these thin sections was written in Chapter 3.

4.3.1 Thin Section Analysis of Locality 1, Outcrop 1 Sandstones

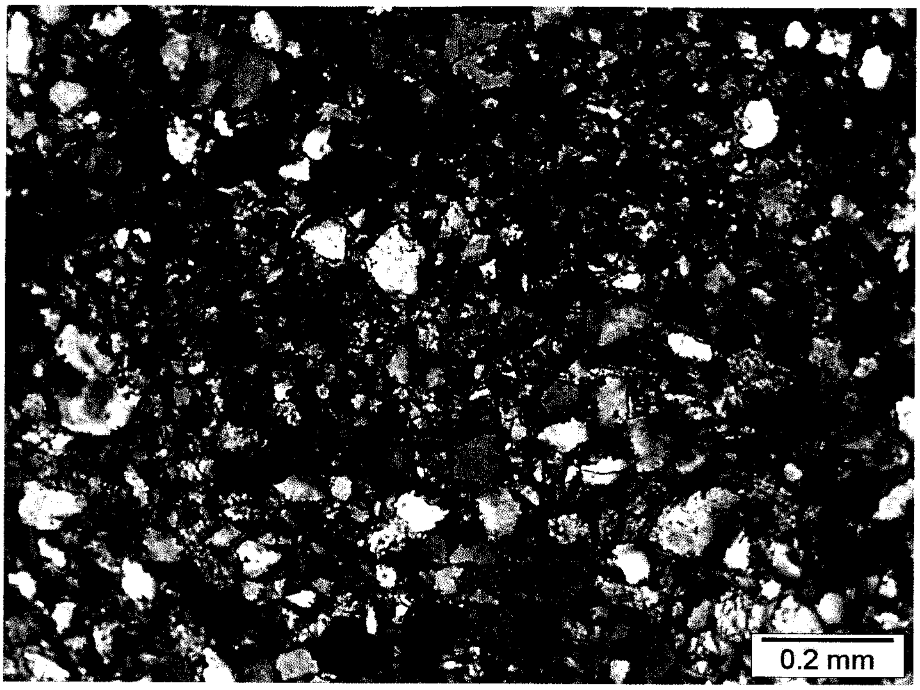


Figure 4.22: Sample TA of Outcrop 1 under x10 magnification and cross polarize light.

Sample Code:	TA
Grains Size:	Fine to very fine
Sorting:	Moderately well sorted
Roundness:	3 to 4
Angularity:	3 to 4
Others:	This sandstone has 6.83% of estimated porosity with minor linear cementation. It is also slightly muddy. The grains are not fractured.

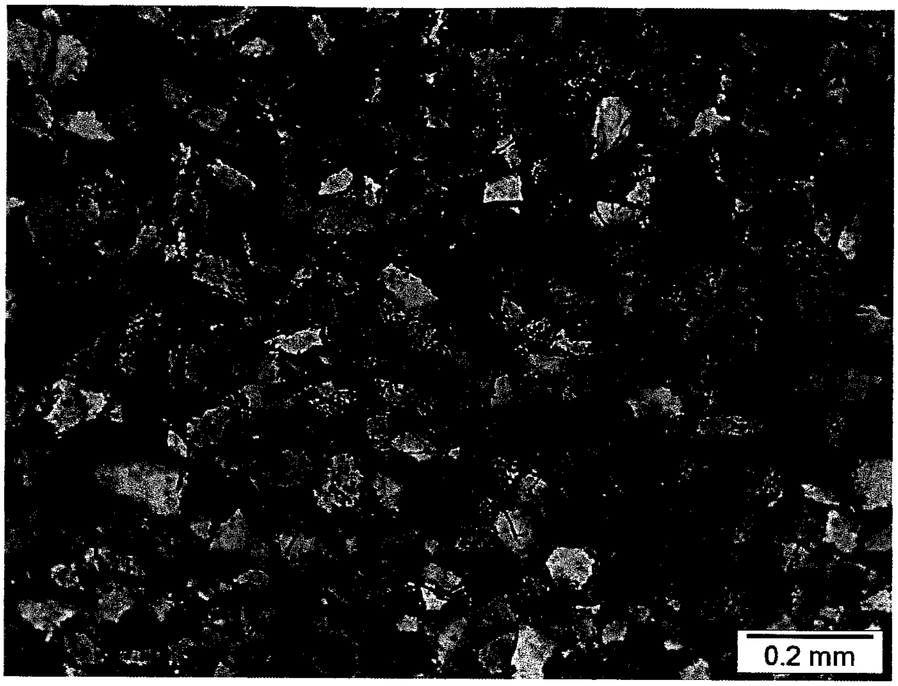


Figure 4.23: Sample TE of Outcrop 1 under x10 magnification and cross polarize light.

Sample Code: TE

Grains Size: Fine to very fine

Sorting: Well sorted

Roundness: 3 to 4

Angularity: 3 to 4

Others: The estimated porosity is 22.37%. The grains have point contacts and it is also grains supported. Linear cementation is rarely seen.

4.3.2 Thin Section Result of Locality 2, Outcrop 2 Sandstones

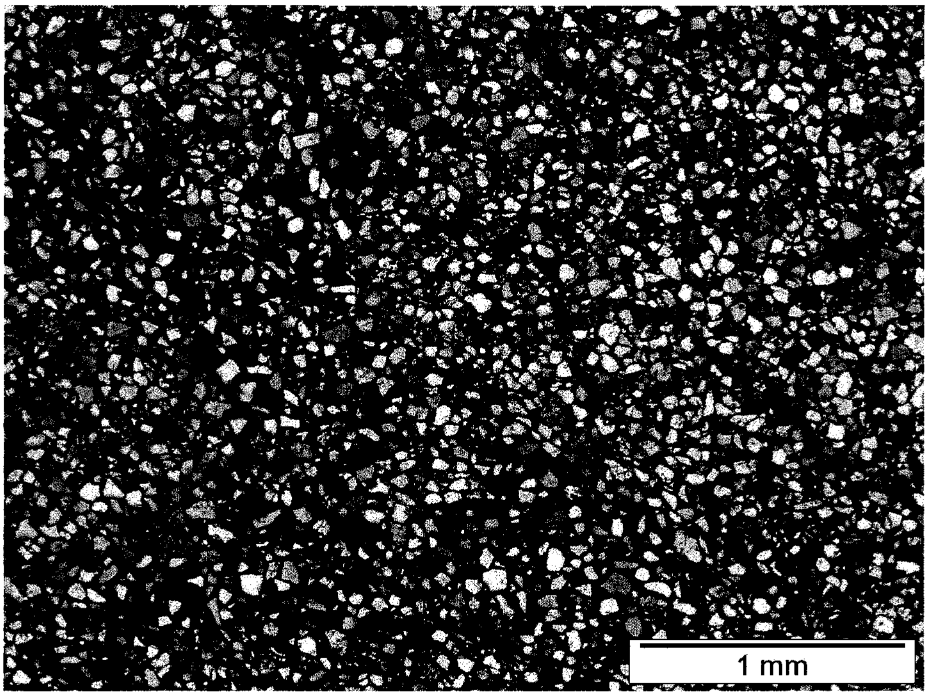


Figure 4.24: Sample NJ of Outcrop 2 under x4 magnification and plain polarize light.

Sample Code:	NJ
Grains Size:	Fine to very fine
Sorting:	Moderately well sorted
Roundness:	3 to 4
Angularity:	3 to 4
Others:	The estimated porosity is 7%. The grains are cemented. The porosity could only be clearly seen along the fractured path.

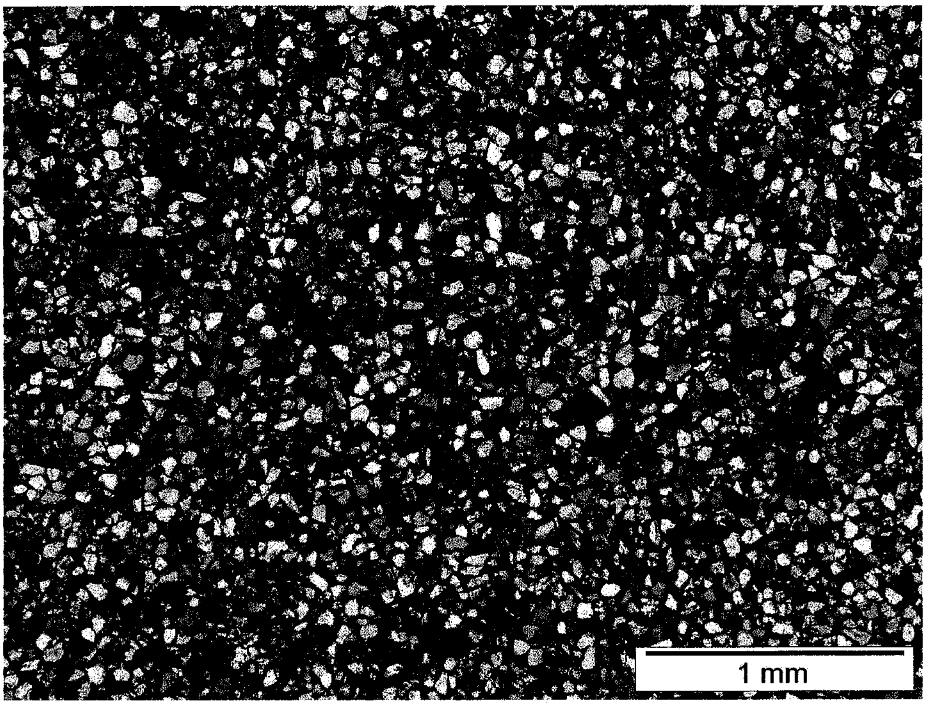


Figure 4.25: Sample NE of Outcrop 2 under x4 magnification and cross polarize light.

Sample Code: NE

Grains Size: Fine to very fine

Sorting: Very well sorted

Roundness: 3 to 4

Angularity: 3 to 4

Others: The estimated porosity is 21.63%. It has minor cementation. Grains contact could be seen.

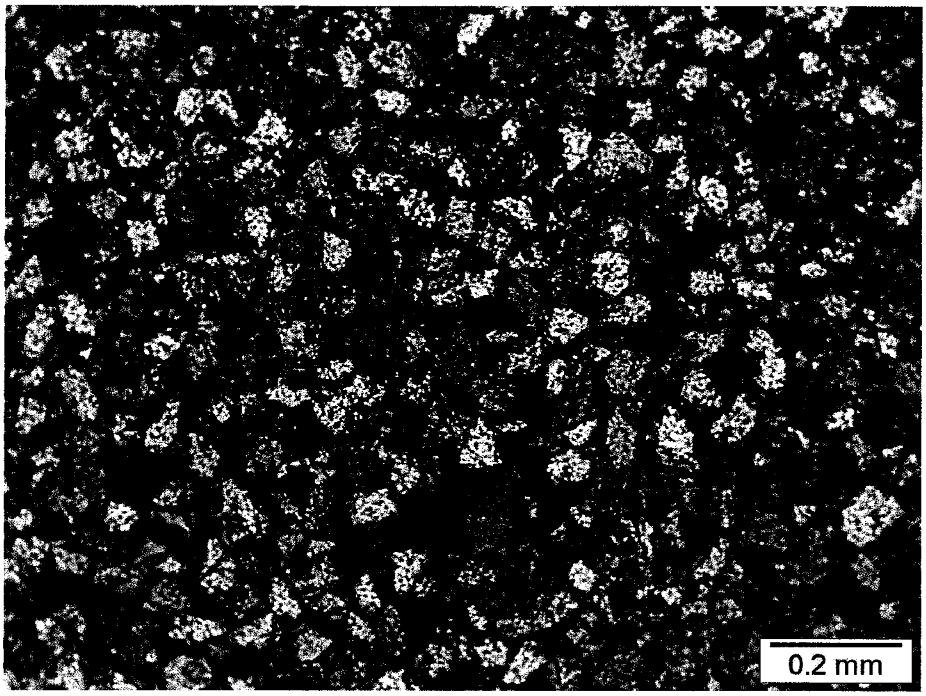


Figure 4.26: Sample NF of Outcrop 2 under x10 magnification and cross polarize light.

Sample Code: NF

Grains Size: Fine to very fine

Sorting: Very well sorted

Roundness: 3 to 4

Angularity: 3 to 4

Others: The estimated porosity is 9.64%. It has minor cementation. Grains contact could be seen. A few grains are fractured.

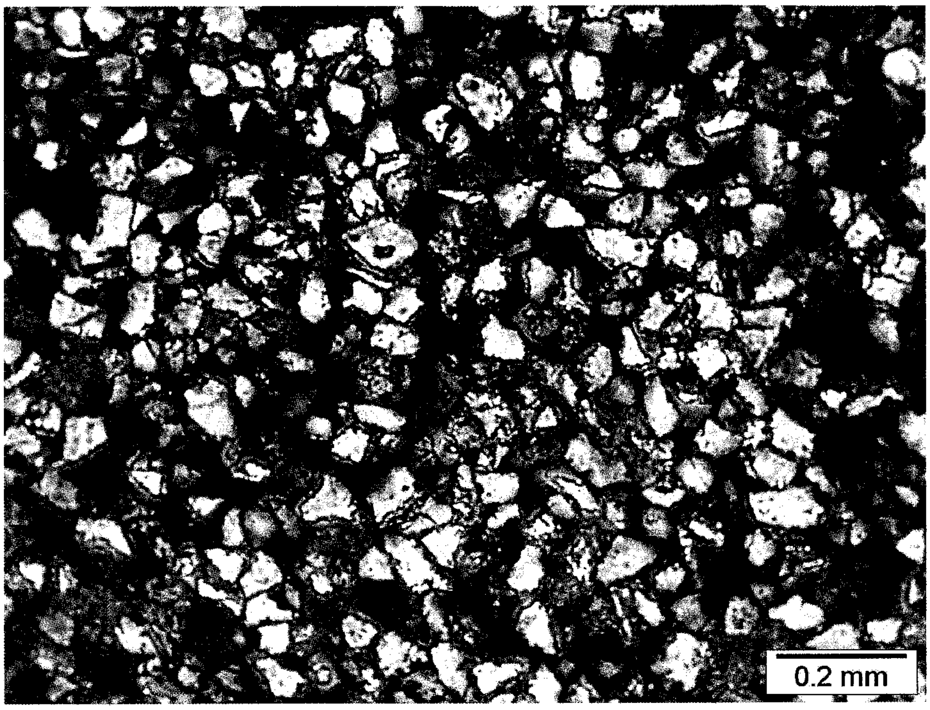


Figure 4.27: Sample NG1 of Outcrop 2 under x10 magnification and plain polarize light.

Sample Code:	NG1
Grains Size:	Fine to very fine
Sorting:	Well sorted
Roundness:	3 to 4
Angularity:	3 to 4
Others:	The estimated porosity is 31.73%. Grains contact could be seen. Some grains are fractured. It has intergrains and minor intragrains type porosity.

4.3.3 Thin Section Result of Locality 3, Outcrop 3 and Outcrop 4 Sandstones

4.3.3.1 Outcrop 3

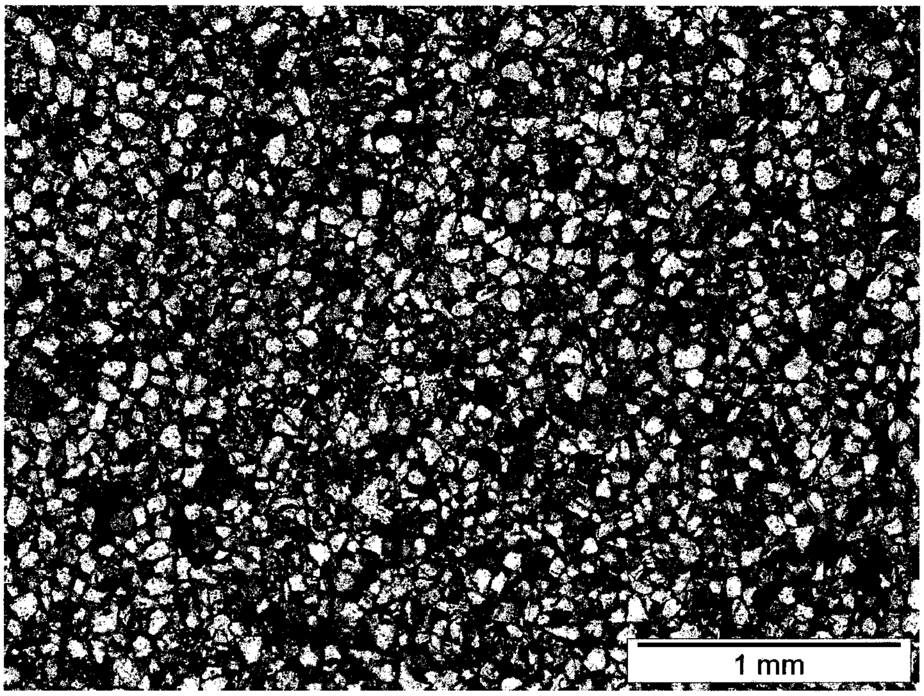


Figure 4.28: Sample OC4 of Outcrop 3 under x4 magnification and plain polarize light.

Sample Code: OC4

Grains Size: Fine to very fine

Sorting: Very well sorted

Roundness: 3 to 4

Angularity: 3 to 4

Others: The estimated porosity is 9.85%. The grains are compacted and it is grains supported.

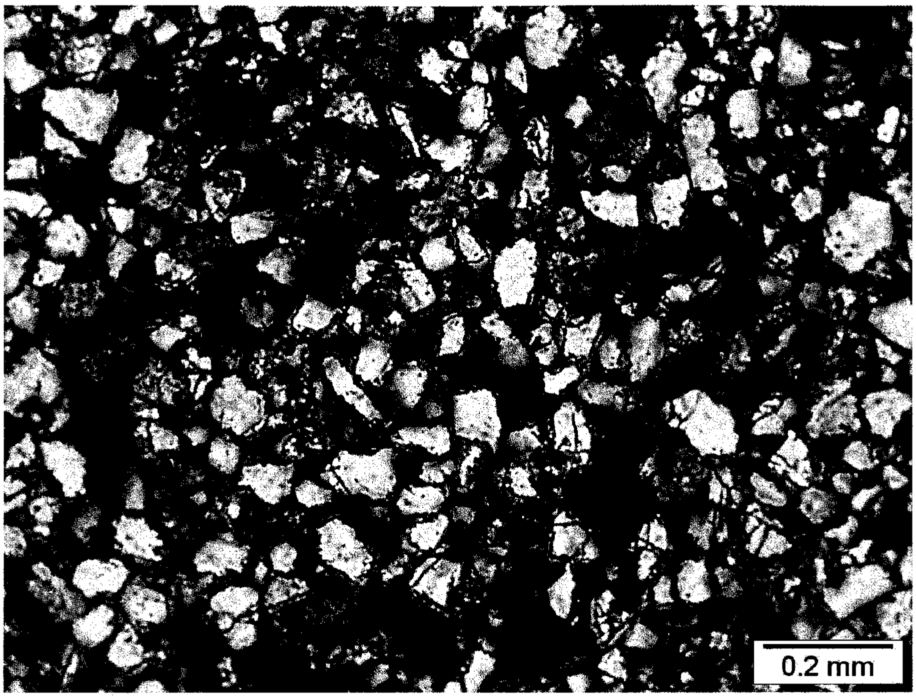


Figure 4.29: Sample OC7 of Outcrop 3 under x10 magnification and plain polarize light.

Sample Code:	OC7
Grains Size:	Fine to very fine
Sorting:	Well sorted
Roundness:	3 to 4
Angularity:	3 to 4
Others:	The estimated porosity is 20.86%. It has no cementation and very few fractured grains.

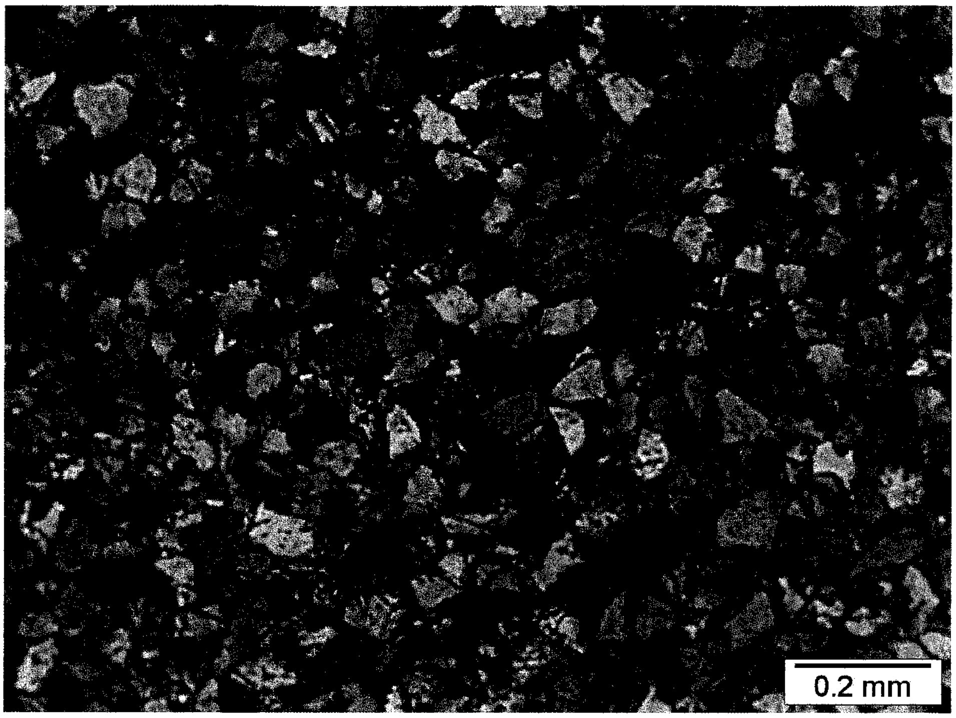


Figure 4.30: Sample OC10 of Outcrop 3 under x10 magnification and cross polarize light.

Sample Code:	OC10
Grains Size:	Fine to very fine
Sorting:	Very well sorted
Roundness:	3 to 4
Angularity:	3 to 4
Others:	The estimated porosity is 26.91%. Grains contact could be seen.

4.3.3.2 Outcrop 4

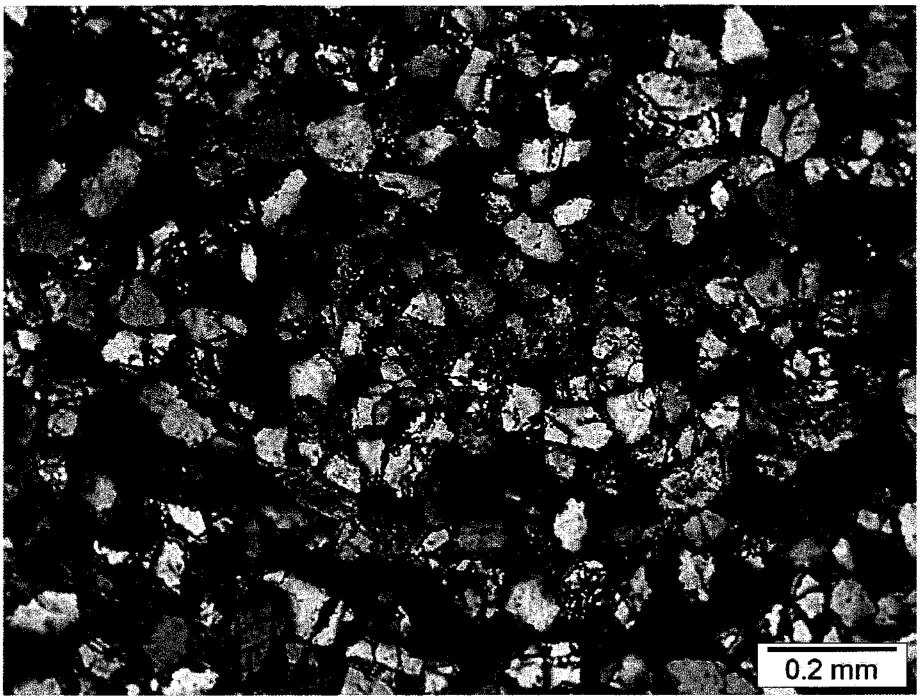


Figure 4.31: Sample JOC1 of Outcrop 4 under x10 magnification and cross polarize light.

Sample Code:	JOC1
Grains Size:	Fine to very fine
Sorting:	Moderately well sorted
Roundness:	3 to 4
Angularity:	3 to 4
Others:	The estimated porosity is 12.67%. It has minor linear cementation. Grains contact could be seen. Fractured grains are common.

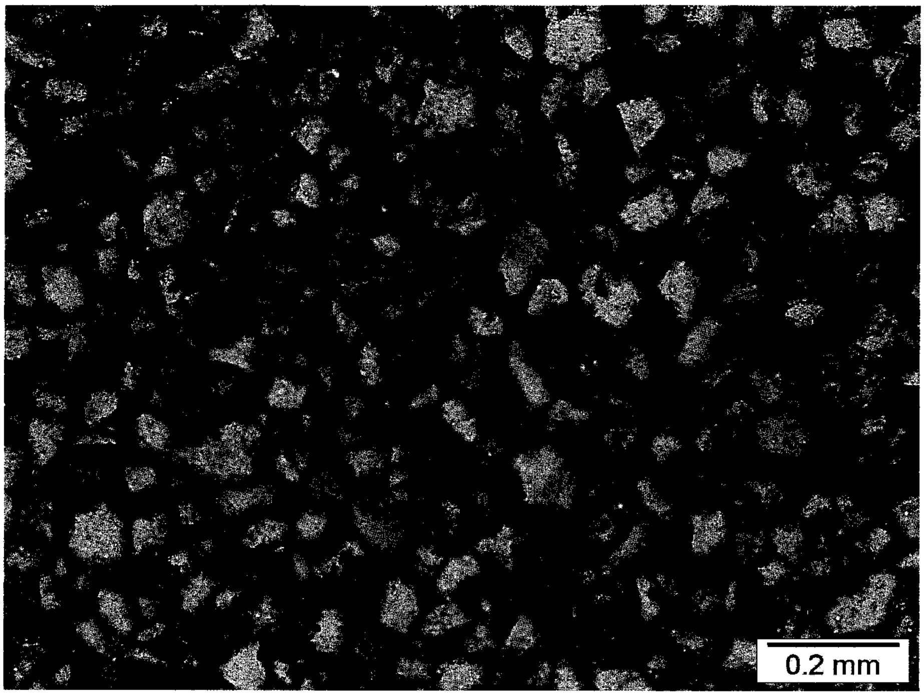


Figure 4.32: Sample JOC4 of Outcrop 4 under x10 magnification and plain polarize light.

Sample Code:	JOC4
Grains Size:	Fine to very fine
Sorting:	Moderately well sorted
Roundness:	3 to 4
Angularity:	3 to 4
Others:	The estimated porosity is 37.04%. It has minor linear cementation. Grains contact could be seen.

4.3.4 Thin Section Analysis of Locality 4, Outcrop 5 Sandstones

4.3.4.1 Outcrop 5.1

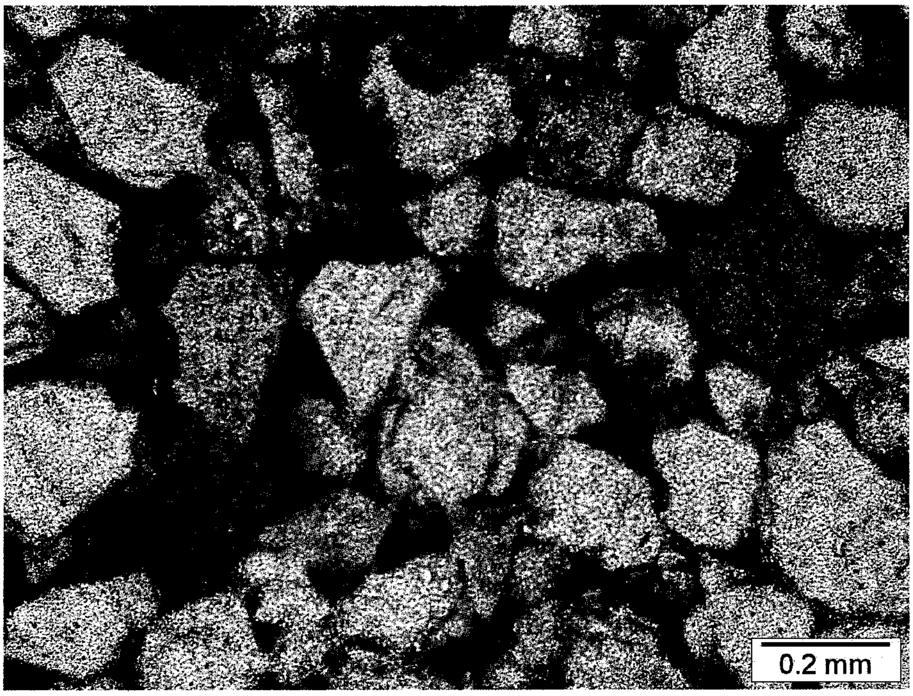


Figure 4.33: Sample AA of Outcrop 5.1 under x10 magnification and plain polarize light.

Sample Code:	AA
Grains Size:	Fine to very fine
Sorting:	Well sorted
Roundness:	3 to 4
Angularity:	3 to 4
Others:	The estimated porosity is 28.73%. It has no cementation and no fractured grains. Grains contact could be seen.

4.3.4.2 Outcrop 5.2

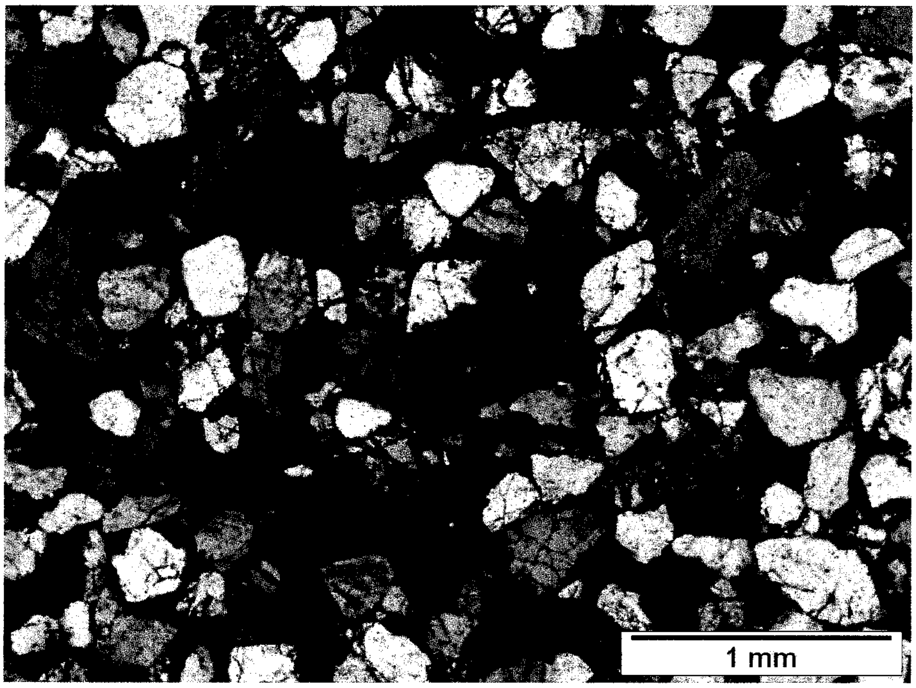


Figure 4.34: Sample BC of Outcrop 5.2 under x4 magnification and cross polarize light.

Sample Code: BC

Grains Size: Fine to very fine

Sorting: Well sorted

Roundness: 3 to 4

Angularity: 3 to 4

Others: The estimated porosity is 32.42%. It has minor linear cementation and a few fractured grains. Grains contact could be seen.

4.3.4.3 Outcrop 5.3

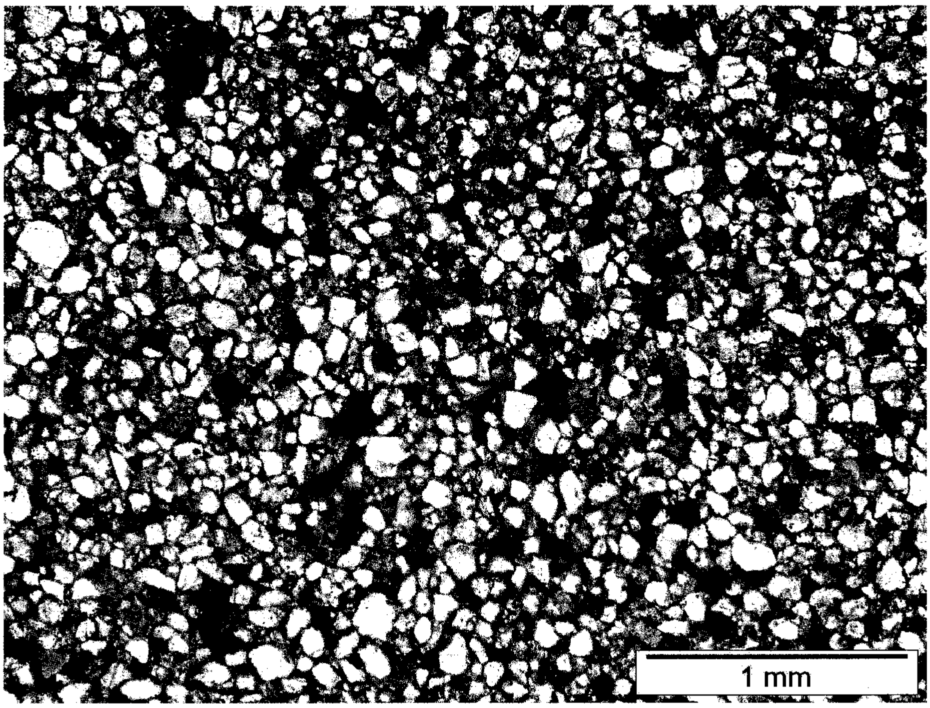


Figure 4.35: Sample CA of Outcrop 5.3 under x10 magnification and cross polarize light.

Sample Code: CA

Grains Size: Fine to very fine

Sorting: Moderately well sorted

Roundness: 3 to 4

Angularity: 3 to 4

Others: The estimated porosity is 19.56%. It has no linear cementation and no fractured grains. It is grains supported.

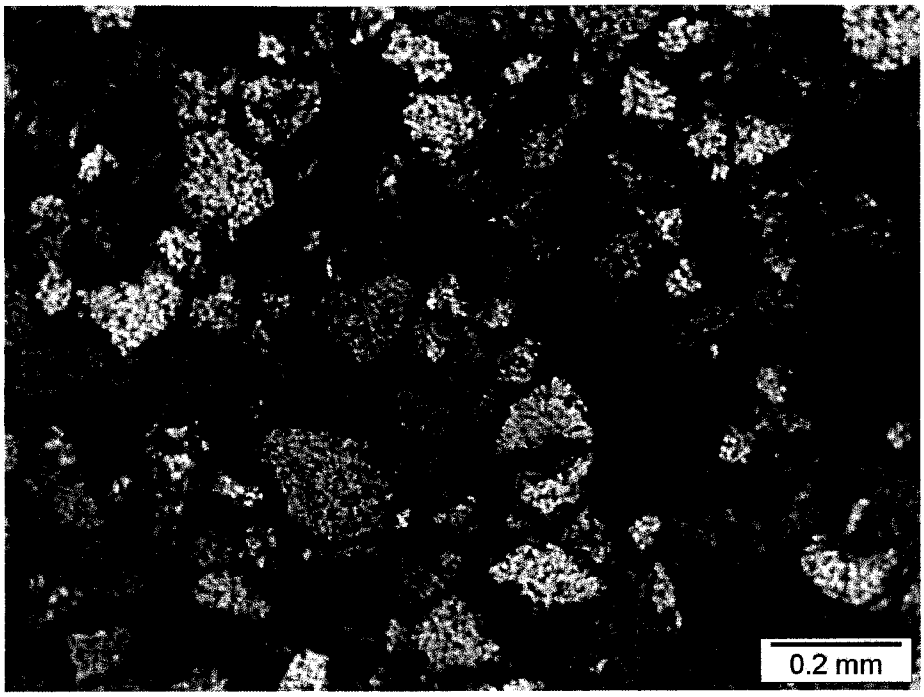


Figure 4.36: Sample CB of Outcrop 5.3 under x10 magnification and cross polarize light.

Sample Code: CB

Grains Size: Fine to very fine

Sorting: Moderately well sorted

Roundness: 3 to 4

Angularity: 3 to 4

Others: The estimated porosity is 21.83%. Grains contact could be seen.

4.3.5 Thin Section Analysis of Locality 5, Outcrop 6 Sandstones

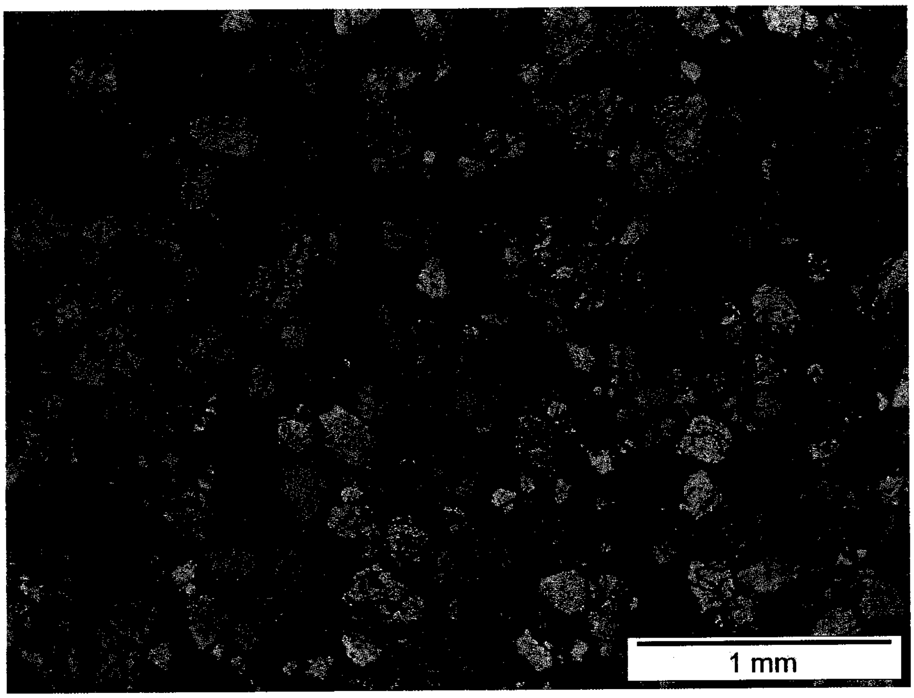


Figure 4.37: Sample SF1 of Outcrop 6 under x10 magnification and cross polarize light.

Sample Code:	SF1
Grains Size:	Medium to fine
Sorting:	Well sorted
Roundness:	3 to 4
Angularity:	3 to 4
Others:	The estimated porosity is 32.42%. It has minor linear cementation and a few fractured grains. Grains contact could be seen. The finer grains could be a result from crushed grains. It suggests that the grains were under compaction over a period of time.

4.3.6 Thin Section Analysis of Locality 6, Outcrop 7 Sandstones

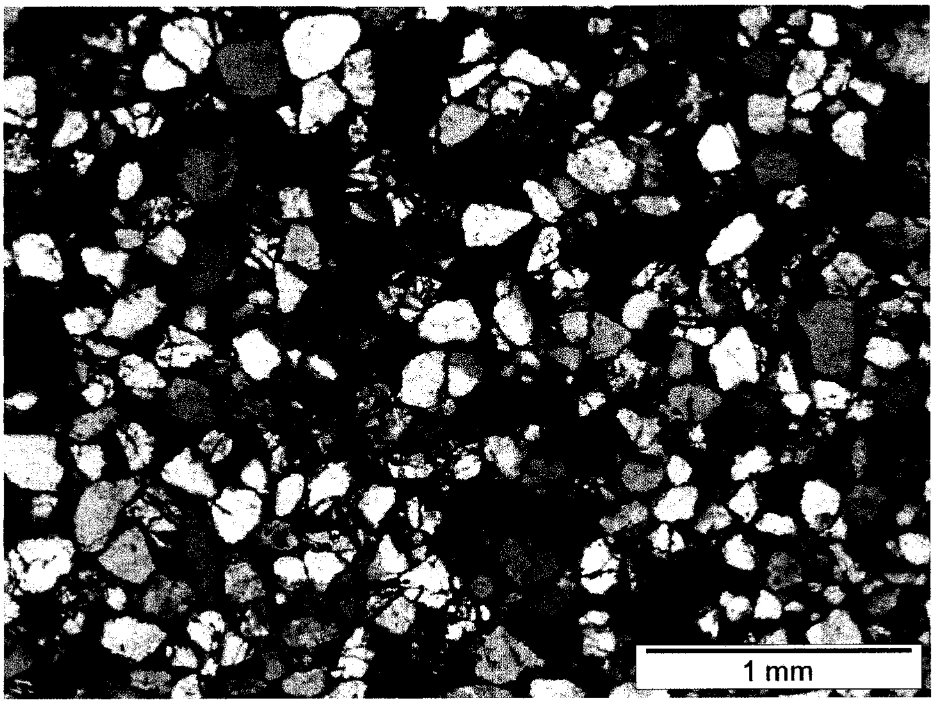


Figure 4.38: Sample SM5 of Outcrop 7 under x4 magnification and cross polarize light

Sample Code: SM5

Grains Size: Fine to very fine

Sorting: Well sorted

Roundness: 3 to 4

Angularity: 3 to 4

Others: The estimated porosity is 20.41%. It has minor linear cementation and a few fractured grains. Grains contact could be seen. It also has a few crushed grains.

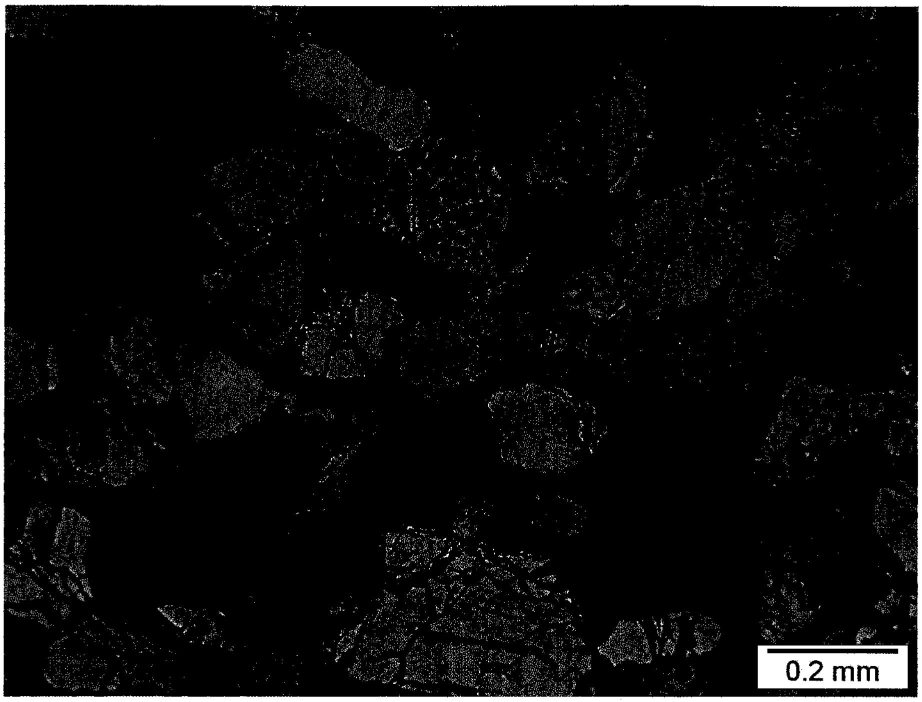


Figure 4.39: Sample SM10 of Outcrop 7 under x10 magnification and cross polarize light

Sample Code:	SM10
Grains Size:	Medium to fine
Sorting:	Well sorted
Roundness:	3 to 4
Angularity:	3 to 4
Others:	The estimated porosity is 15.23%. It has no linear cementation and almost all the grains are fractured. Grains contact could be seen. Smaller grains could be the byproduct of the fractured grains.

4.4 Biofacies Analysis

4.4.1 Palynological Result

Sample	*Rhizophora* type (Counts)	*Brownlowia* type	*Shorea* type	*Acrostichum aureum* type	Stenochlaena palustris	*Stenochlaena laurifolia*	*Polypodium* type (broken)
SA	>100	4	1			1	
SB	>100						
SC	>100	1					
SD	>40						
SE	18	2					
SF	8						
JOC 1	1	2					
JOC 3				BARREN			
JOC 5				BARREN			
JOC 6		2			2		
NC	7	1					
ND	15	1					
NH	3	4	1				
OC 1	4	2					
OC 2	1			1			
OC 3	5	2		3	1		
OC 5	6	3		1			
OC 6	3						
OC 9	5						
OC 11	4	1					1
OC 12	4	2					
TD	1	1					
AA	3						
BA	10		6	1			
BB				BARREN			

Table 4.3: Summary on the palynological of the studied area.

Palynomorphs can be referred to as palynological or botanical entities. In this report, the author uses both nomenclatures.

Botanical Nomenclature	**Palynological Nomenclature**
Rhizophora (*Rhizophoraceae)*	*Zonocostites ramonae* Germeraad et al., 1968
Browlowia (*Tiliaceae*)	*Discoidites borneensis* Muller, 1968
Shorea (*Dipterocarpaceae*)	-
Acrostichum aureum	-
Stenochlaena palustris	*Verrucatosporites usmensis* (Pflug, 1952) ex R. Potonie, 1956 (genus); Van der Hammen, 1956d, nov comb.
Stenochlaena laurifolia	*Stenochlaenidites papuanus (Cookson) Khan, 1976*
Polypodium	-

Table 4.4: Botanical affinity and palynological nomenclature of pollen and spores.

Most of the species recorded are long ranging throughout the Eocene to Quartenary interval. However, the presence of *Stenochlaena laurifolia* in sample SA from Outcrop 6, suggest an Upper Miocene and younger age for this sample (Morley, 1990).

With referral to Table 4.4, Samples SA, SB, SC and SD from Outcrop 6 show total domination of *Rhizophora* type pollen. The other samples yield relatively low count of pollen and spores. *Rhizophora* and *Brownlowia* are included in mangrove vegetation belt (eg. Poumot, 1989 & Morley 1990), *Acrostichum* is also included in this group. While *Stenochlaena palustris* is a fresh water spore (Morley, 1990). *Shorea* is common in peat swamps and other vegetation type (Morley, 1990).

The percentage of the pollens and spores were used to indicate the environment. *Rhizophora* and *Brownlowia* are from an estuarine / swampy environment, whilst *Acrosticum aurem* and *Shorea* are from a more terrestrial direction.

Samples like JOC, OC and N which have sparse distribution of all types of pollens and spores suggest that the mudstone is deposited on an offshore environment, offshore mudstone. The pollens and spores must have been flushed out by the current into the open marine system before they settle down along with the sediments.

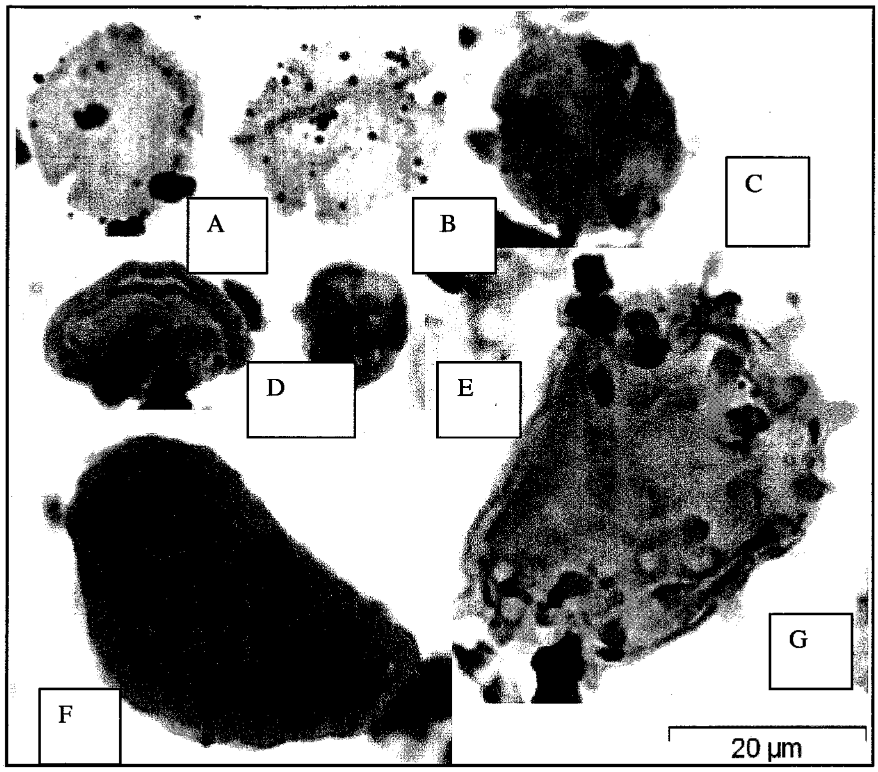


Figure 4.40: Spores and pollens found in Outcrop 4 and Outcrop 6. A) *Brownlowia* B) *Browlowia* C) *Brownlowia* D) *Florschuetzia sp.* E) *Rhizophora* F) *Polypodium* G) *Stenochleana palustris*

4.5 Nannofossils Analysis

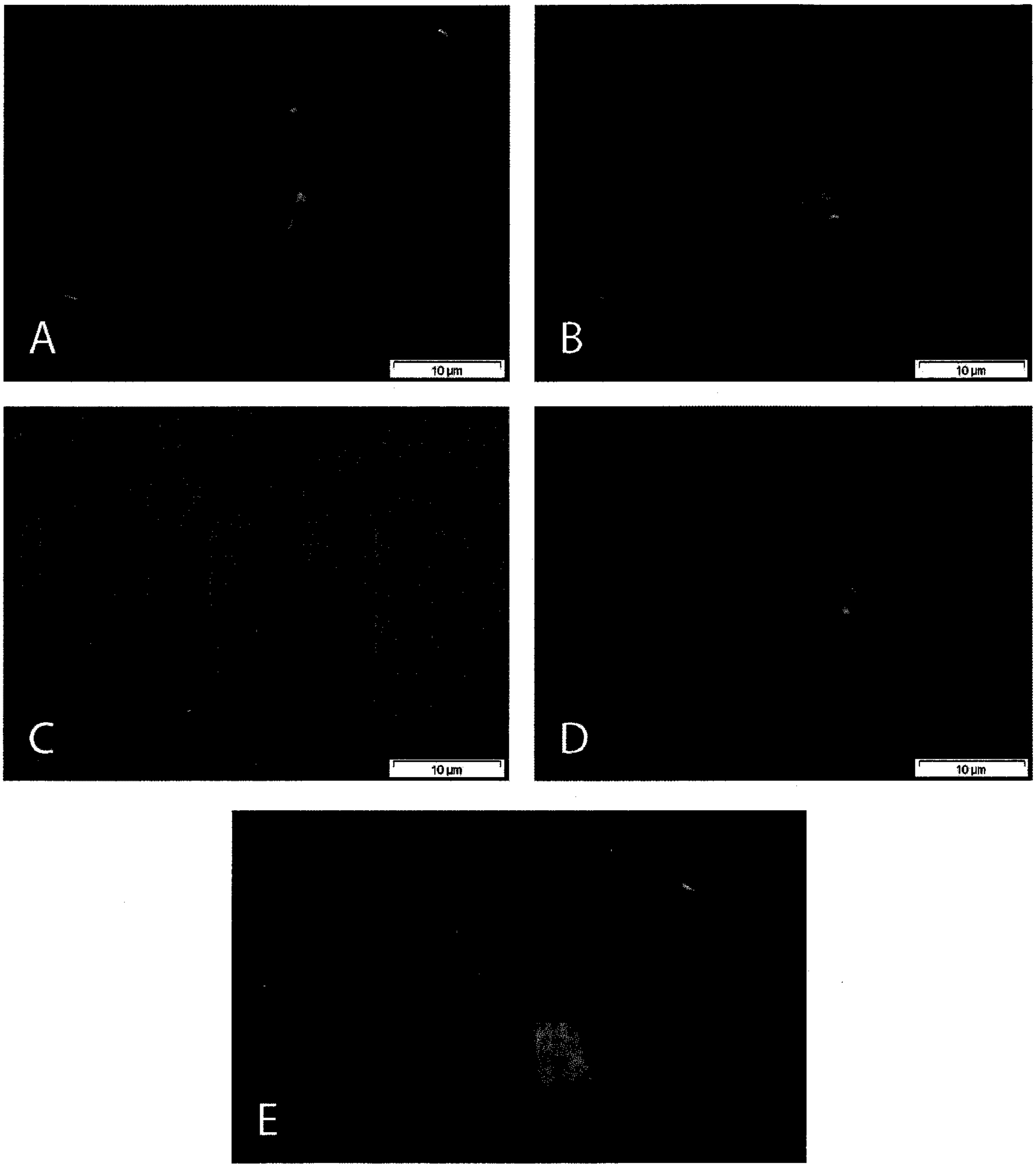


Figure 4.41: A) *Sphenolithus abies* (top view) in lambda plate mode, B) *Sphenolithus abies* (top view) in crossed nicols mode, C) *Sphenolithus abies* (top view) in normal light mode, D) *Reticulofenestra spp.* in lambda plate mode, E) *Coronocyclus nitescens* in lambda plate mode.

4.5.1 Age Determination

In sample JOC from Outcrop 3, two species, *Sphenolithus abies* (Deflandre and Fert, 1954) and *Coronocyclus nitescens* (Kamptner, 1963) Bramlette & Wilcoxon, 1967 have been recorded. The presence of *Sphenolithus abies* (Deflandre and Fert, 1954) in this sample indicates a biozonal range from NN11 till NN 15 (Persch-Nielson, 1986). These zones indicate a Late Miocene (Tortonian – Messinian) to Early Pliocene (Zanclean) age. The stratigraphic range of *Coronocyclus nitescens* is from Middle Eocene to Late Miocene (Nannoware, version 2004.1.3). Based on the concurrence of these two species, a Late Miocene age can be concluded.

4.5.2 Environment Description

Nannoplankton is a good tool to demonstrate open marine environment but it cannot distinguish between shallow or deep marine. In this research, the nannofossils are scare and are not found in a reliable quantity. Probably, this is due to weathering and leaching.

4.6 Foraminifera Analysis

None of the foraminiferas encountered in Outcrop 6 shows reaction to Hydrocloric Acid, HCl. Therefore, based on the morphological features, we are dealing with arenaceous *Ammobaculites* forams but the species could not be identified. The *Ammobaculites sp.* found are minute, areneceous and have an average diameter of 0.1 mm.

Ammobaculites is also found in other formations in the Borneo Island, namely the Garinono Formation, Baligan Formation, Liang Formation and Miri Formation (Lee, 2004). This genus of foraminifera is often found in the littoral belt, particularly in the brackish environment (Marle, 1991 & Murray 1991). This genus has also been found in deeper environment.

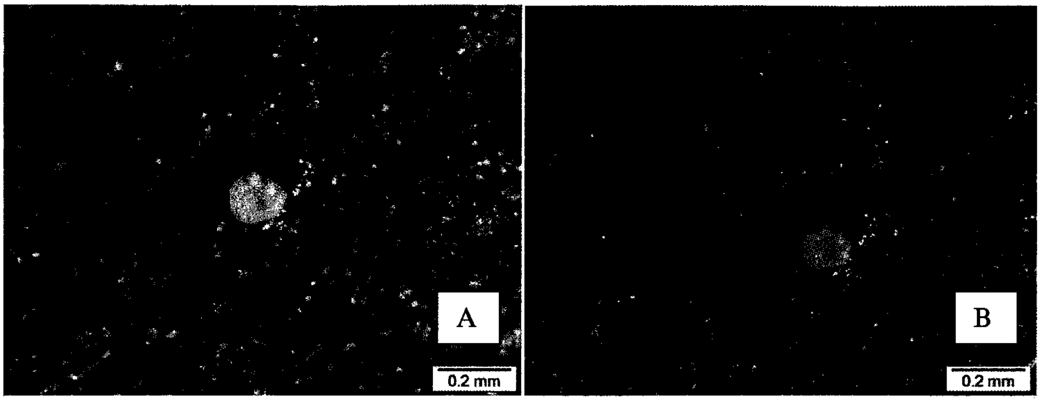


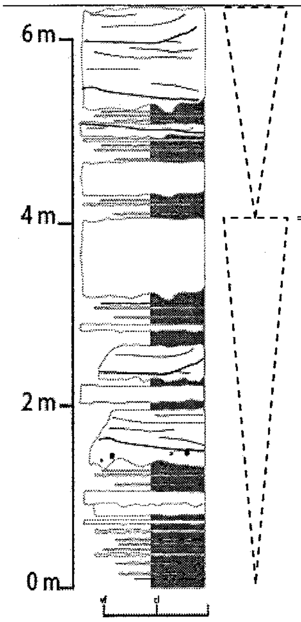
Figure 4.42: The *Ammobaculites sp.* in Outcrop 6. A) *Ammobaculites sp.* photograph captured under normal mode. B) *Ammobaculites sp.* captured under enhanced red wave mode.

CHAPTER 5

DISCUSSION

5.1 Facies Associations

From the eight lithofacies, three facies association could be identified.

<table>
<tr><th>Outcrop 1</th><th>Interpretation</th></tr>
<tr><td rowspan="2">


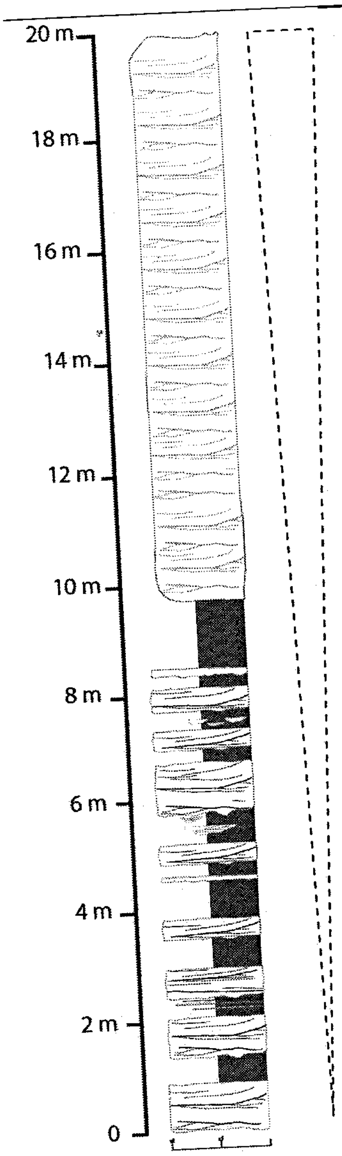
</td><td>FA 1: Gradual coarsening upward and shallowing upward.
Environment: Lower Shoreface → Middle Shoreface → Upper Shoreface
Relative- Sea Level: This sequence records a progradation event.</td></tr>
<tr><td>FA 1: Gradual coarsening upward and shallowing upward.

Environment:
Lower Shoreface → Middle Shoreface

Sea Level:
This sequence records a progradation event.</td></tr>
</table>

Figure 5.1: Stratigraphic section of Outcrop 1- Buli Sim Sim Road, summaring the organization of facies and their interpretation.

Outcrop 2.1	Interpretation



(continue to Outcrop 2.2)

FA 1: Gradual coarsening upward and shallowing upward.

Environment:
Lower-to-middle-to-upper shoreface

The thick amalgamated sandstone is deposited in the shoreface environment, suggestly, the upper shoreface-beach.

Whilst the thin sandstone beds are deposited in the transition zone.

Energy increase.

Relative-Sea Level: The succession records a shoreface progradation event, a normal regression.

Figure 5.2: Stratigraphic section of Outcrop 2 - Tshun Ngen Road, part 1, summaring the organization of facies and their interpretation.

Outcrop 2.2	Interpretation
	FA 1: Gradual coarsening upward and shallowing upward. **Environment:** Transition Zone → Lower Shoreface → Upper Shoreface Energy increase. **Relative-Sea Level:** A normal regressive succession – gradual progradation.
	FA 1: Gradual coarsening upward and shallowing upward. **Environment:** Lower Shoreface → Upper Shoreface **Relative-Sea Level:** A progradation event. (continue from Outcrop 2.1)

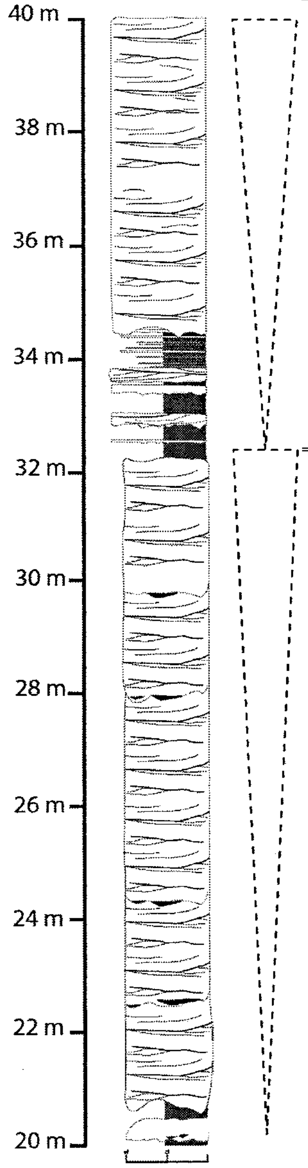
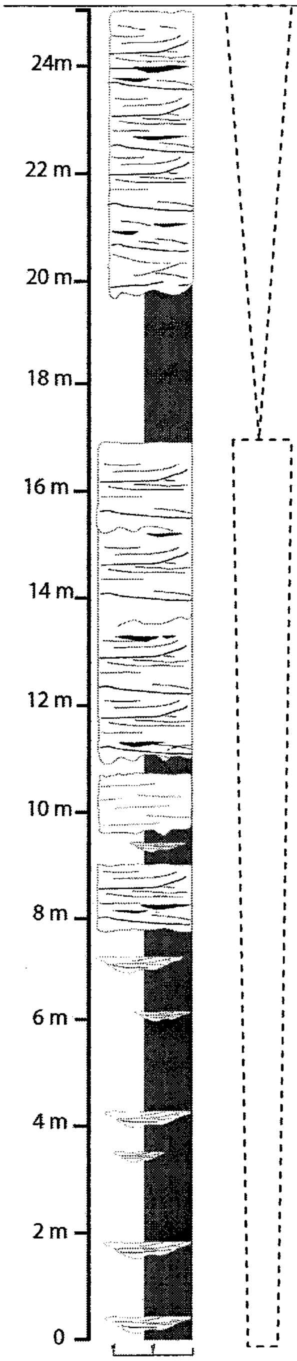


Figure 5.3: Stratigraphic section of Outcrop 2 - Tshun Ngen Road, part 2, summaring the organization of facies and their interpretation.

<table>
<tr><th>Outcrop 3</th><th>Interpretation</th></tr>
<tr><td rowspan="2">
</td><td>FA 2: Abrupt FA

Environment:
Shelfal → Upper Shoreface

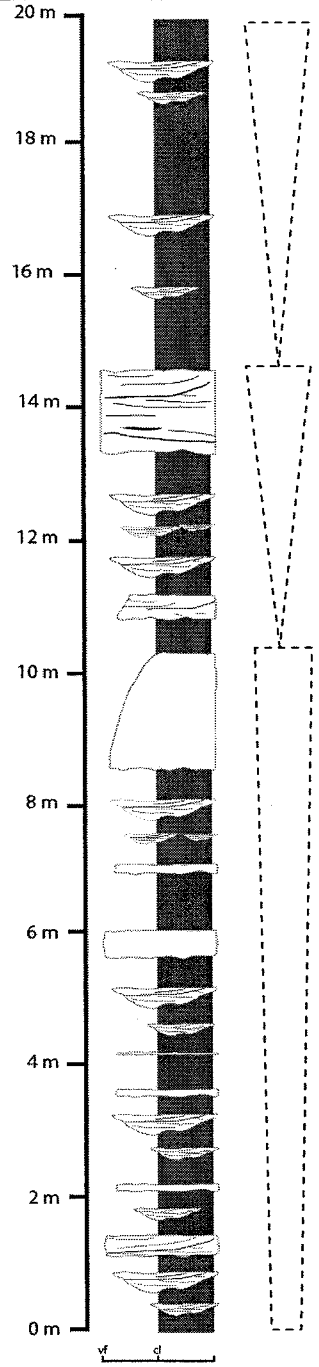
Relative-Sea Level:
Rapid fall of sea level, a forced regression event.</td></tr>
<tr><td>FA 1: Gradual coarsening upward and shallowing upward.

Environment:
Upper Offshore → Transition Zone → Shoreface

Energy increase.

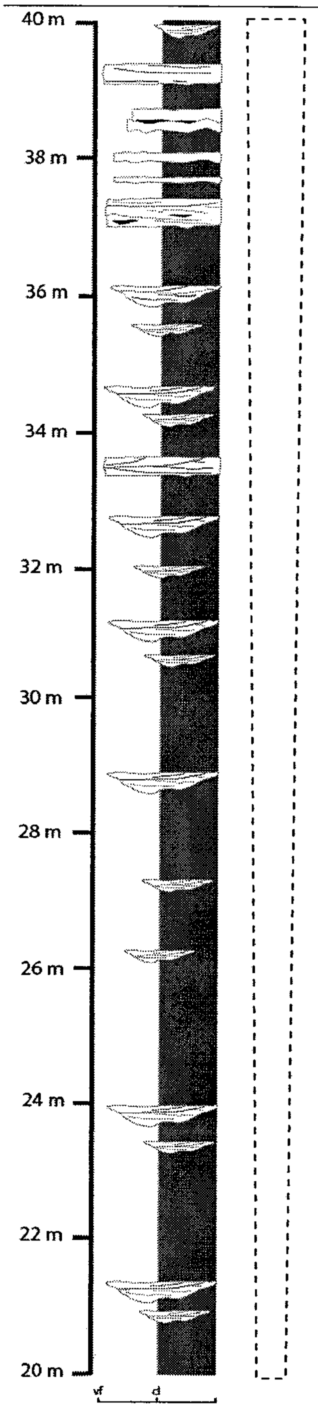
Sea Level: A normal regressive succession – gradual shoreface progradation.</td></tr>
</table>

Figure 5.4: Stratigraphic section of Outcrop 3- Road between Batu Sapi and Sibuga, summaring the organization of facies and their interpretation.



Outcrop 4.1	Interpretation
	(continue to Outcrop 4.2) **FA 1:** Gradual coarsening upward and shallowing upward. **Environment:** Upper Offshore
	FA 1: Gradual coarsening upward and shallowing upward. **Environment:** Transition Zone →Lower/Middle Shoreface . **Relative-Sea Level:** A short series of progradation event.
	FA 1: Gradual coarsening upward and shallowing upward. **Environment:** Upper Offshore → Transition Zone → Lower Shoreface → Middle Shoreface **Relative-Sea Level:** A normal regressive succession– gradual shoreface progradation.

Figure 5.5: Stratigraphic section of Outcrop 4- Road between Batu Sapi and Sibuga, part 1, summaring the organization of facies and their interpretation.

<table>
<tr><th>Outcrop 4.2</th><th>Interpretation</th></tr>
<tr><td>
</td><td>(continue to Outcrop 4.3)

FA 1: Gradual coarsening upward and shallowing upward.

Environment:
Upper Offshore → Transition Zone

Relative-Sea Level: A thick and gradual progradation event.

(continue from Outcrop 4.2)</td></tr>
</table>

Figure 5.6: Stratigraphic section of Outcrop 4- Road between Batu Sapi and Sibuga, summaring the organization of facies and their interpretation.

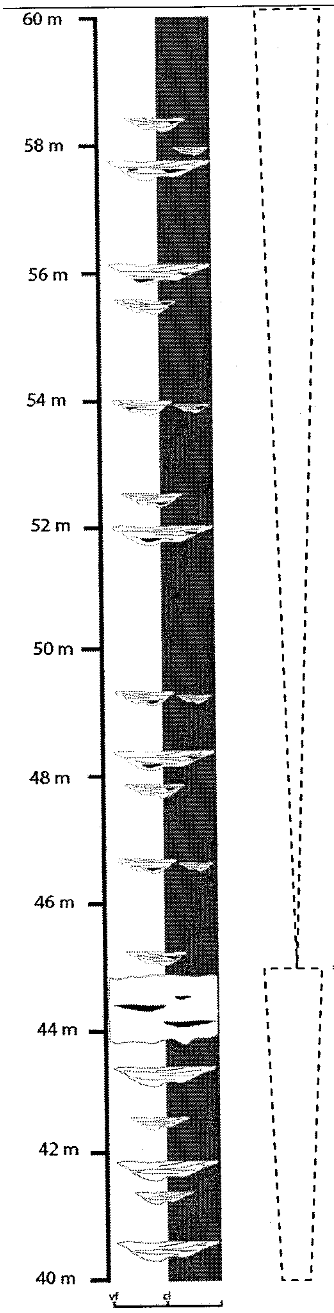
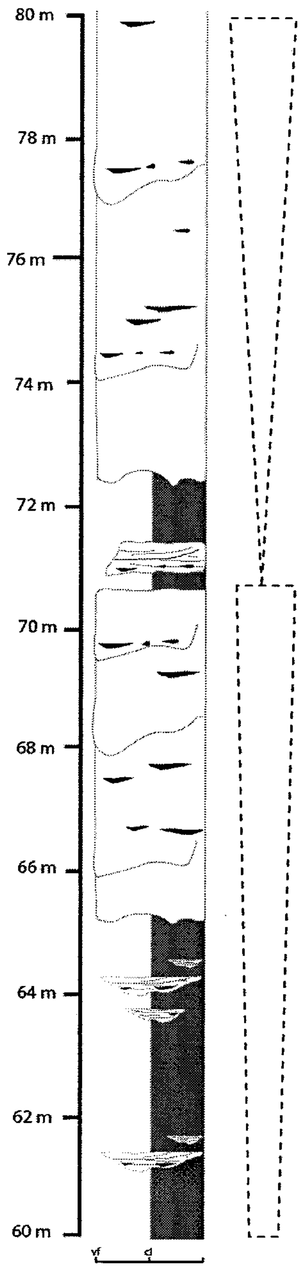
Outcrop 4.3	Interpretation
	(continue to Outcrop 4.4) **FA 1:** Gradual coarsening upward and shallowing upward. **Environment:** Upper Offshore
	FA 1: Gradual coarsening upward and shallowing upward. **Environment:** Upper Offshore → Lower Shoreface Transition zone is not recorded. **Relative-Sea Level:** A normal progradation. (continue from Outcrop 4.2)

Figure 5.7: Stratigraphic section of Outcrop 4- Road between Batu Sapi and Sibuga, part 3, summaring the organization of facies and their interpretation.

Outcrop 4.4	Interpretation



(continue to Outcrop 4.5)

FA 2: Abrupt FA

Environment:

Shelfal → Shoreface

Heavy erosion surface.

Relative-Sea Level:

Rapid fall of sea level, a forced regression event.

FA 1: Gradual coarsening upward and shallowing upward.

Environment:
Upper Offshore → Upper Shoreface

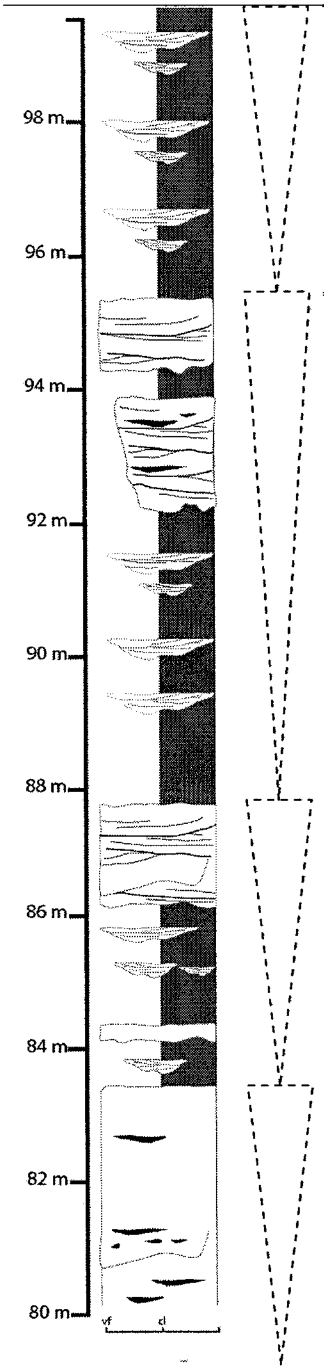
Energy gradually rise. Transition zone is not recorded.

Relative-Sea Level: A normal regressive succession– gradual shoreface progradation.

(continue from Outcrop 4.4)

Figure 5.8: Stratigraphic section of Outcrop 4 - Road between Batu Sapi and Sibuga, part 4, summaring the organization of facies and their interpretation.

Outcrop 4.5	Interpretation



(end of Outcrop 4)

FA 1: Gradual coarsening upward and shallowing upward.

Environment:
Upper Offshore → Lower Shoreface

Energy gradually rise. Transition zone is not recorded.

Relative-Sea Level:
A normal regressive succession– gradual shoreface progradation.

FA 1: Gradual coarsening upward and shallowing upward.
Environment:
Upper Offshore → Lower Shoreface
Energy gradually rise. Transition zone is not recorded.
Relative-Sea Level: A normal regressive succession– gradual shoreface progradation.

FA 2: Abrupt FA

(continue from Outcrop 4.4)

Figure 5.9: Stratigraphic section of Outcrop 4 - Road between Batu Sapi and Sibuga, part 5, summaring the organization of facies and their interpretation.

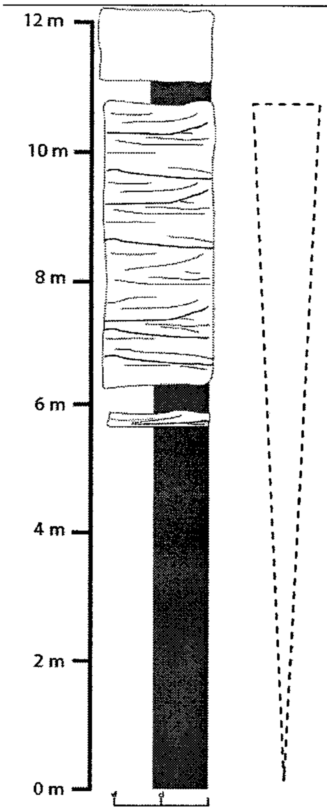
Outcrop 5.1	Interpretation
	**FA 2:** Estuary (Tidal Influence?) FA **Environment:** Estuary → Upper Shoreface **Sea Level:** A normal transgressive succession– shoreface retrogradation on a landward direction. A sign of shoreface landward stepping.

Figure 5.10: Stratigraphic section of Outcrop 5.1 - Batu Sapi Road, summaring the organization of facies and their interpretation.

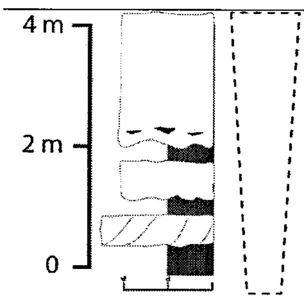
Outcrop 5.2	Interpretation
	**Environment:** Lower Shoreface → Middle Shoreface → Upper Shoreface **Relative-Sea Level:** This outcrop recorded a portion of a prograding sequence.

Figure 5.11: Stratigraphic section of Outcrop 5.2: Batu Sapi Road, summaring the organization of facies and their interpretation.

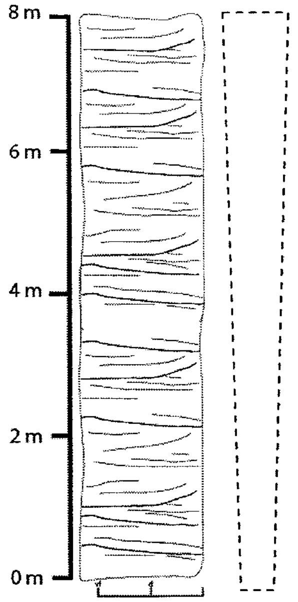
Outcrop 5.3	Interpretation
	**Environment:** Upper Shoreface

Figure 5.12: Stratigraphic section of Outcrop 5.3: Batu Sapi Road, summaring the organization of facies and their interpretation.

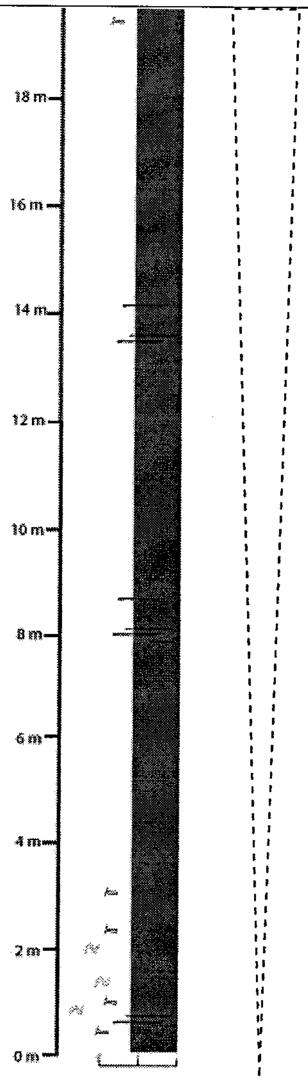
Outcrop 6.1	Interpretation
	(continue to Outcrop 6.2) **FA 2:** Estuary (Tidal Influence?) FA **Environment:** Estuary

Figure 5.13: Stratigraphic section of Outcrop 6- Sibuga Road, part 1 summaring the organization of facies and their interpretation.

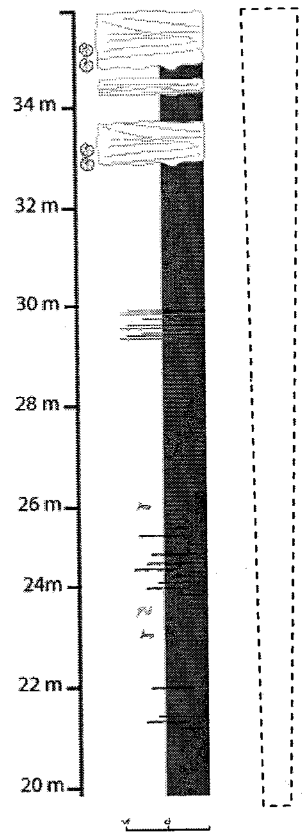
Outcrop 6.2	Interpretation
 	(end of Outcrop 6) **FA 3:** Estuary (Tidal Influence?) FA **Environment:** Estuary → Back Shore → Channel **Relative-Sea Level:** A normal transgressive succession– gradual shoreface retrogradation on a landward direction. Followed by an incision of channels. (continue from Outcrop 6.1)

Figure 5.14: Stratigraphic section of Outcrop 6 - Sibuga Road, part 2, summaring the organization of facies and their interpretation.

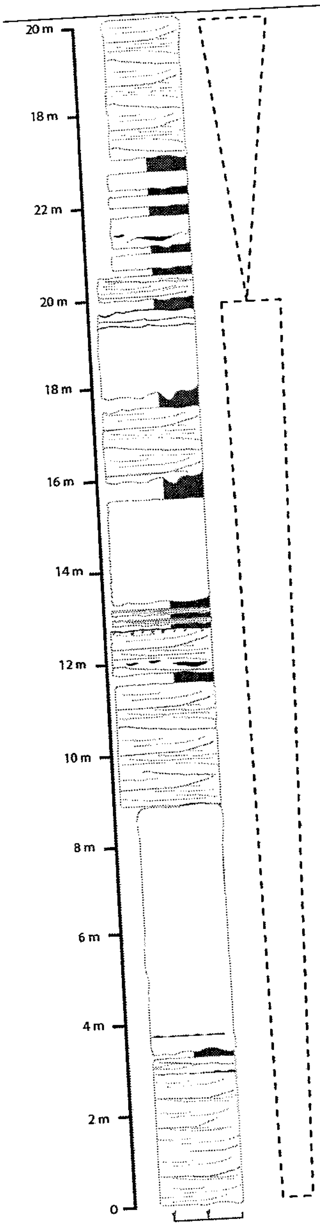
Outcrop 7	Interpretation
	**FA 1:** Gradual coarsening upward and shallowing upward. **Environment:** Upper Offshore → Lower Shoreface Energy gradually rise. Transition zone is not recorded. **Relative-Sea Level:** A normal regressive succession– gradual shoreface progradation.
	FA 1: Gradual coarsening upward and shallowing upward. **Environment:** Upper Shoreface The thin mudstone layers are whitish and weather mudstone. **Relative-Sea Level:** Energy remained high and constant. This sequence records the deposits from the upper shoreface environment.

Figure 5.15: Stratigraphic section of Outcrop 7- Cecily Road, summaring the organization of facies and their interpretation.

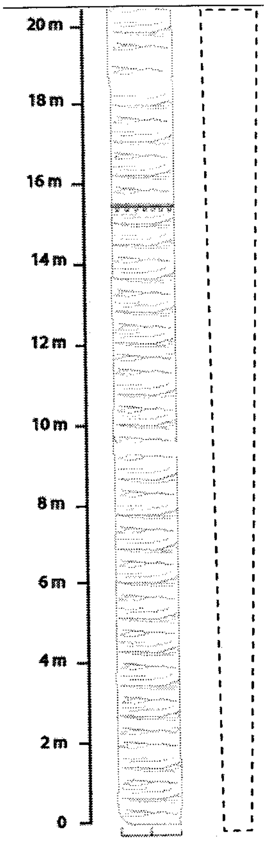
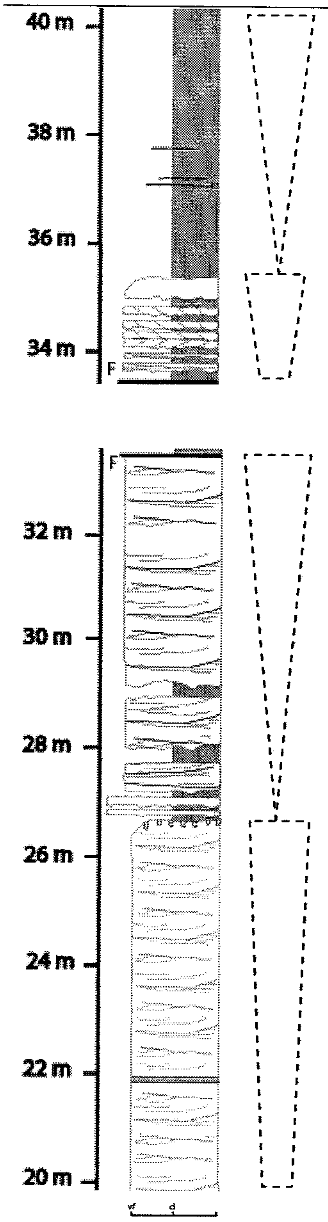
Outcrop 8.1	Interpretation
	(continue to Outcrop 8.2) **FA 1:** Gradual coarsening upward and shallowing upward. **Environment:** Upper Shoreface

Figure 5.16: Stratigraphic section of Outcrop 8 - Bokuro Road, part 1, summaring the organization of facies and their interpretation.



Outcrop 8.2	Interpretation
	(continue to Outcrop 8.3
	FA 3: Estuary (Tidal Influence?) FA **Environment:** Intertidal A regressive succession.
	FA 1: Gradual coarsening upward and shallowing upward. **Environment:** Lower Shoreface → Middle Shoreface → Upper Shoreface **Relative-Sea Level:** A normal regressive succession– gradual shoreface progradation.
	FA 1: Gradual coarsening upward and shallowing upward. **Environment:** Upper Shoreface (continue from Outcrop 8.1)

Figure 5.17: Stratigraphic section of Outcrop 8 - Bokuro Road, part 2, summaring the organization of facies and their interpretation.

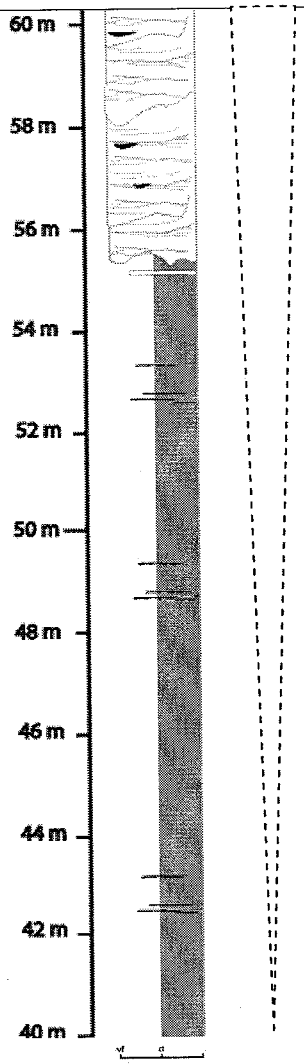
Outcrop 8.3	Interpretation
	(continue to Outcrop 8.4) **FA 2:** Abrupt FA **Environment:** Estuary → Upper Shoreface **Relative-Sea Level:** A transgressive succession – shoreface retrogradation. (continue from Outcrop 8.2)

Figure 5.18: Stratigraphic section of Outcrop 8 - Bokuro Road, part 3, summaring the organization of facies and their interpretation.

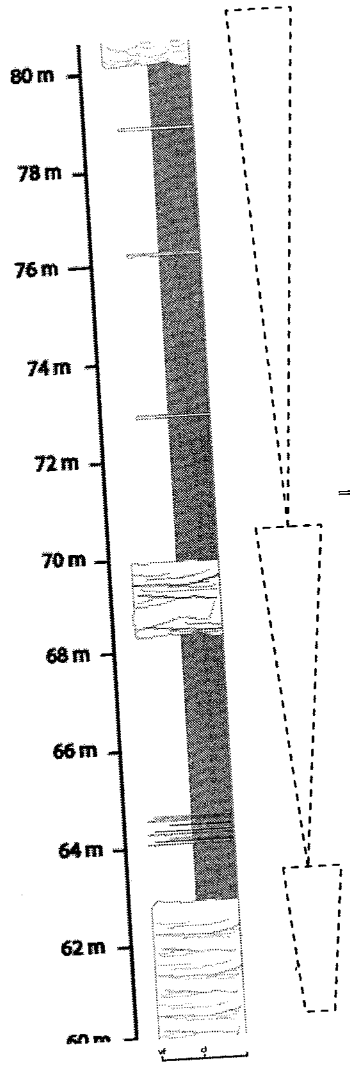
Outcrop 8.4	Interpretation
	(continue to Outcrop 8.5) **FA 2:** Abrupt FA **Environment:** Offshore → Upper Shoreface **Relative-Sea Level:** A normal regressive succession– gradual shoreface progradation on a landward direction.
	FA 2: Abrupt FA **Environment:** Offshore → Lower Shoreface **Relative-Sea Level:** A force regression, rapid drop of sea level.
	FA 2 (continue from Outcrop 8.4)

Figure 5.19: Stratigraphic section of Outcrop 8 - Bokuro Road, part 4, summaring the organization of facies and their interpretation.

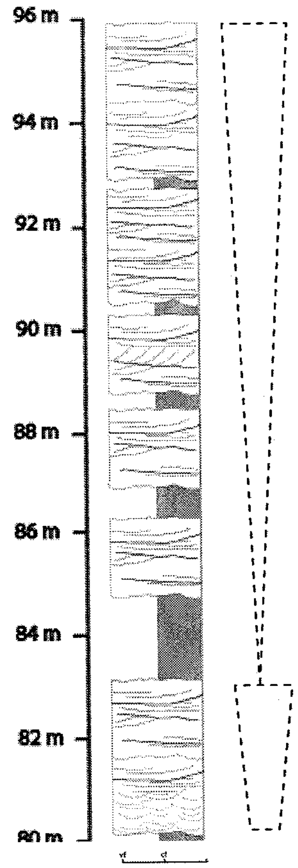
Outcrop 8.5	Interpretation
	**FA 1:** Gradual coarsening upward and shallowing upward. **Environment:** Lower Shoreface → Middle Shoreface → Upper Shoreface **Relative-Sea Level:** A normal regressive succession– gradual shoreface progradation.
	FA 2: Abrupt FA **Environment:** Offshore → Upper Shoreface (continue from Outcrop 8.4)

Figure 5.20: Stratigraphic section of Outcrop 8 - Bokuro Road, part 5, summaring the organization of facies and their interpretation.

5.1.1 Facies Association 1 (FA 1) (Refer to Figure 5.22)

FA1 comprises a lower mud–dominated interval,, an intermediate interval of thin HCS beds and capped by a thick (4 - 5m) SCS unit. Facies Association 1 shows upward coarsening from mud - dominated to sandstone dominated sediments intervals (Facies 1, F1, and Facies 3, F3). The thickness of Facies 1 (F1) varies from 1 m to 5m while F3 varies from 0.5 m to 6 m. F1 contains amalgamated sandstone with faint low angle hummocky cross stratification lamination while F3 contains mudstone with thin HCS sandstone lenses.

The mudstone with thin laminated HCS sandstone lenses of the F3 reflects a proximal input of sediments. The mudstone is mainly formed by settlement of the suspended sediments that is inferred to be no wave influence below the wave base. The lenses and gutter casts in the mudstone (which are commonly 30 cm in thickness and 3 meters in length) indicate the presence of drainage system and a high energy flow during the storm periods. Thus, F3 is deposited in the offshore transition environment where it is located right below the FWWB (Fair Weather Wave Base) and above SWB (Storm Wave Base).

This Facies Association 1 (FA 1) is a product of shallow marine deposition. This assemblage of thick amalgamated sandstone may correspond to the wave-dominated environment – upper shoreface. This indicates that the sandstones were deposited above the FWWB.

The full series of an ideal prograding shoreface could not be seen. However, this section captured almost a complete lower distal transition zone to a proximal upper shoreface environment. The beds were deposited gradually in a shallowing upwards sequence - from an offshore transition environment into lower shoreface and upper shoreface. FA 1 records a gradual coarsening upward, prograding shallow succession.

There are two possibilities that can be deduced from this succession. i) where the sediment input was high but the sea level was rising gradually, or ii) the sediment input was low but the sea level was constant (Holland, 2002).

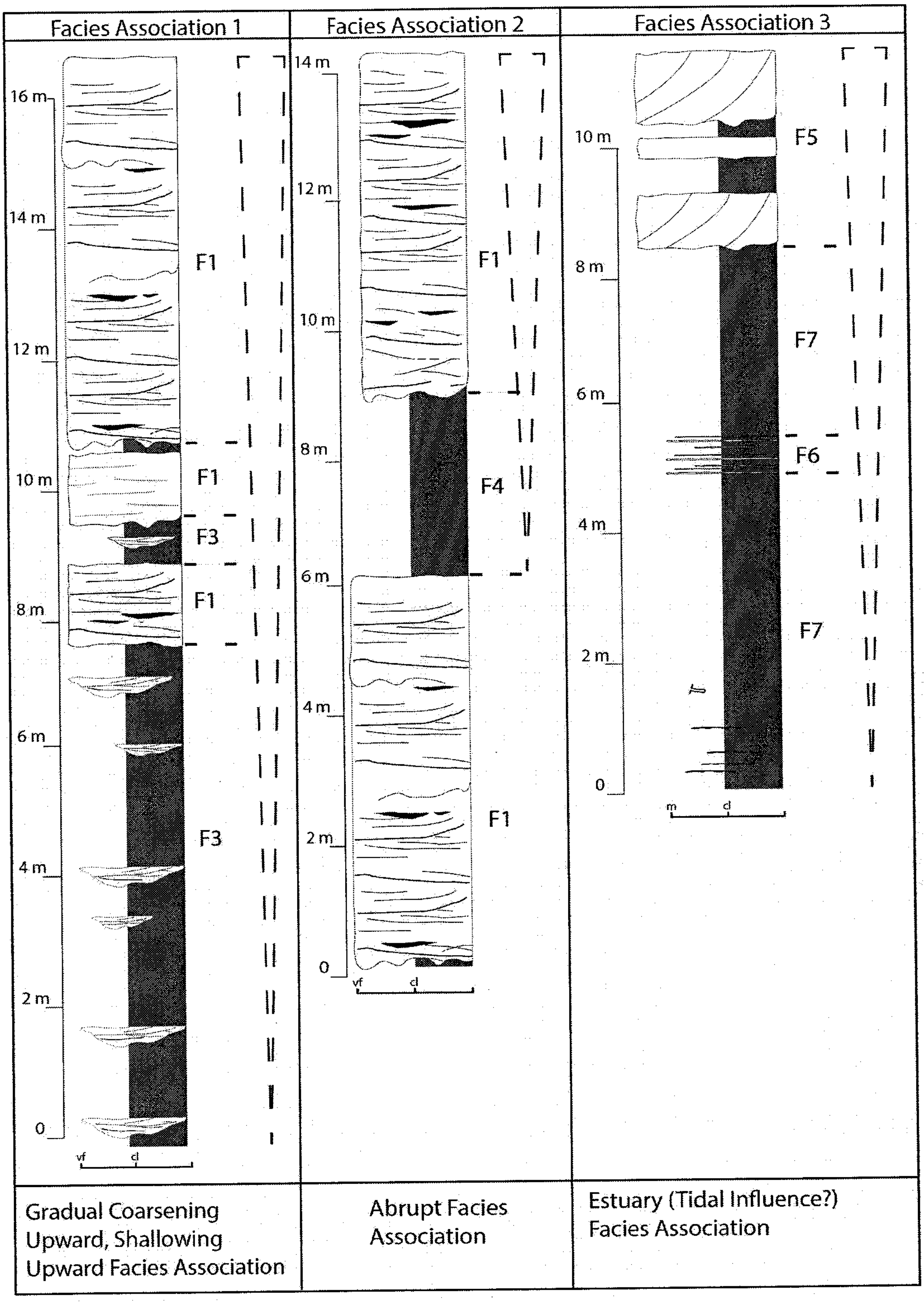


Figure 5.21: Facies Associations of Sandakan Formation in the research area.

5.1.2 Facies Association 2 (FA2) (Refer to Figure 5.22)

Facies association 2, FA 2, comprised thick amalgamated sandstone, F1, and laminated mudstone, F4. The F4 contains nannofossils (*Sphenulithus abies*) which is a marker for a depositional environment shallower than 400 meters depth. Other than the nannofossils, F4 is barren of other micropaleontological analysis, foraminifera and palynology. The 3 meters thick mudstone is interpreted to have been deposited in a shelfal condition mainly in a low energy setting.

FA2 shows an abrupt change of lithology from F4 to F1 with a high relief scouring contact (commonly 30 cm). Such an abrupt change, from shelfal to the upper shoreface environment could be explained by the rapid fall of sea level. Usually heavy erosional surface like incised valley is associated with this event. However, where the environment is below the SWB, the rapid fall of sea level will produce an abrupt change of lithology. This occasion could be explained as a 'forced regression' of a Falling Stage System Tract (FSST) (Plint, 2000).

5.1.2 Facies Association 3 (FA3) (Refer to Figure 5.22)

This facies is made up of lower F7 (laminated mudstone with *Rhizophora*), F6 (minor strip mudstone with thin laminated sandstone and siltstone) and F5 unit at the top (trough cross bedded sandstone). The thickness of F7 may individually exceed 10 m. F7 is dominated by organic rich carbonaceous mud. Some brackish environment foraminiferas, pollens and spores recorded included the *Ammobaculites spp.*, *Rhizophora, Shorea* and *Brownlowia*. The F6 also contains minor thin alternation of mudstone and sandstone slivers (F6). This thin alternation may represent the episodic flooding event.

The upper section of FA3 is dominated by 1 m – 2 m medium-grained trough cross bedded sandstone. The abrupt change from a brackish mudflow to trough-cross bedded fluvial sandstone reflects a marked change in the flow regime. The top sandstone unit is interpreted to be fluvial in origin. The trough cross bedding also represents a unidirectional flow which may be due to the fluvial current

The change in this sequence signifies that the sea level retreat further seaward. This causes the deposition of fluvial related sandstone on the thick estuary mudstone.

5.2 Depositional Model

Eight lithofacies, which have been defined, contain both muddy and sandy facies. The facies association indicates that the Sandakan Formation was once an open marine and estuarine environment in which the estuary directly met with the shoreface environment.

The presence of laminated mudstone with *Rhizophora* facies (F7), trough cross bedded sandstone facies (F5) and striped mudstone with thin sandstone facies (F6) support the estuary model. The thick laminated mudstone with high carbonaceous materials may be deposited at a brackish environment particularly the mangrove swamp (mangal). The mudstones were also deposited in varying depositional conditions of low oxygen and reducing conditions. It could be either peat-swamp environments, brackish swamps and more open water conditions (Tarek ea al, 2004). The mangrove swamp is a buffer zone between the coastal area and the land. It also acts as a natural defence line against the storm currents (Padma, 2004). Thus, thin sand slivers, disarticulated mollusc, tree branches and trunks may dissipate over the mangal mudstone.

The open marine environment that overlay the estuary environment is explained by the presence of the thick amalgamated sandstone (F1), the thin, lenticular interbedded HCS sandstones and mudstone (F7), laminated mudstone (F4) and interbedded HCS sandstone and mudstone (F3). In a typical shoreface environment, the succession is mud-dominant in the distal direction and wave related structures are significant as environment indicators (Buatois, 1998). The low angle HCS, scouring contacts, reliefs, rippled surface, thin stratified sandstone lenses and amalgamated sandstone with faint lamination are mainly found in the wave dominated condition.

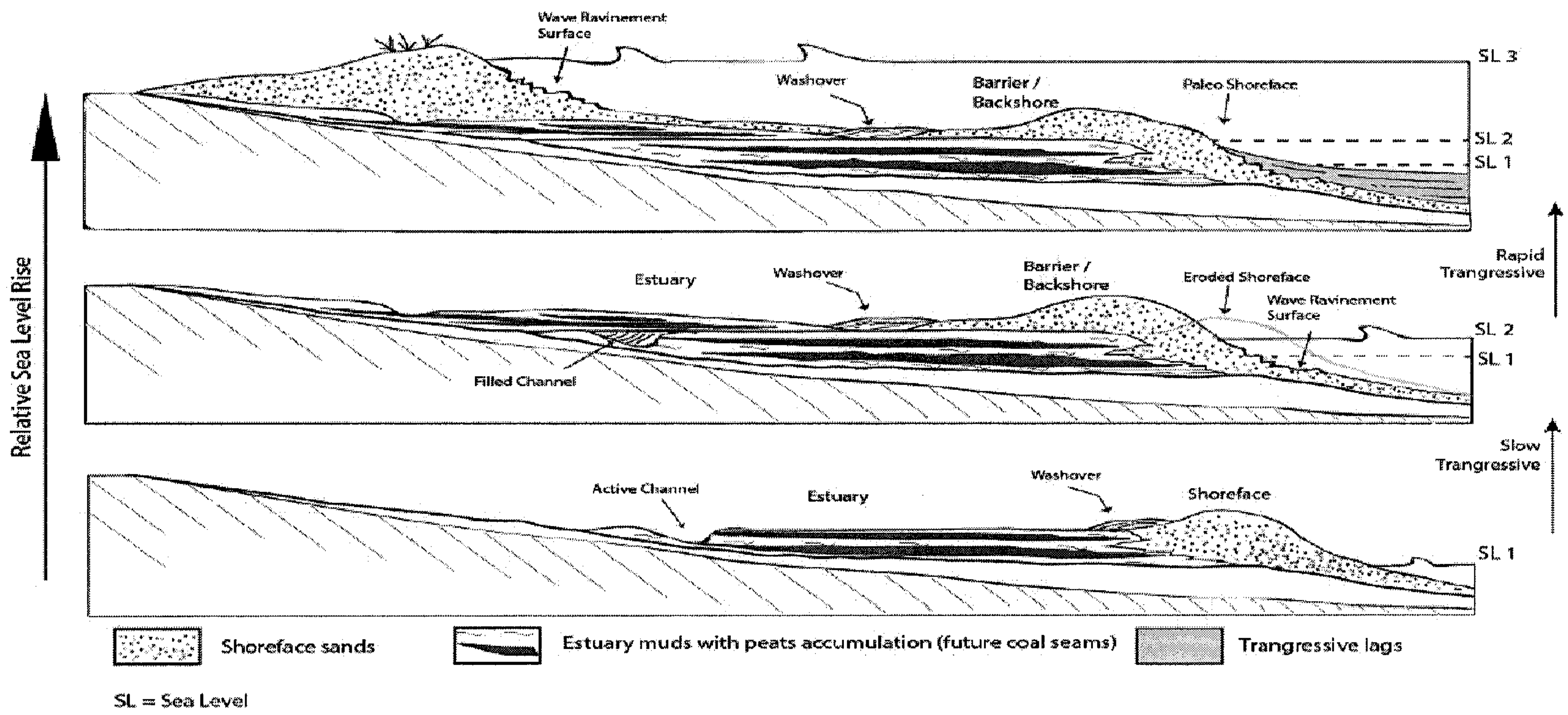


Figure 5.22: Stratigraphy Evolution of Sandakan Formation from estuary environment to shoreface. The sand barrier retrieved landwards and overlaid the estuary deposits. A continuous shoreface retreat (SL 2) followed by a punctuated shoreface retreat – in situ drowning (SL 3) (modified from Cattanaeo & Steel, 2001).

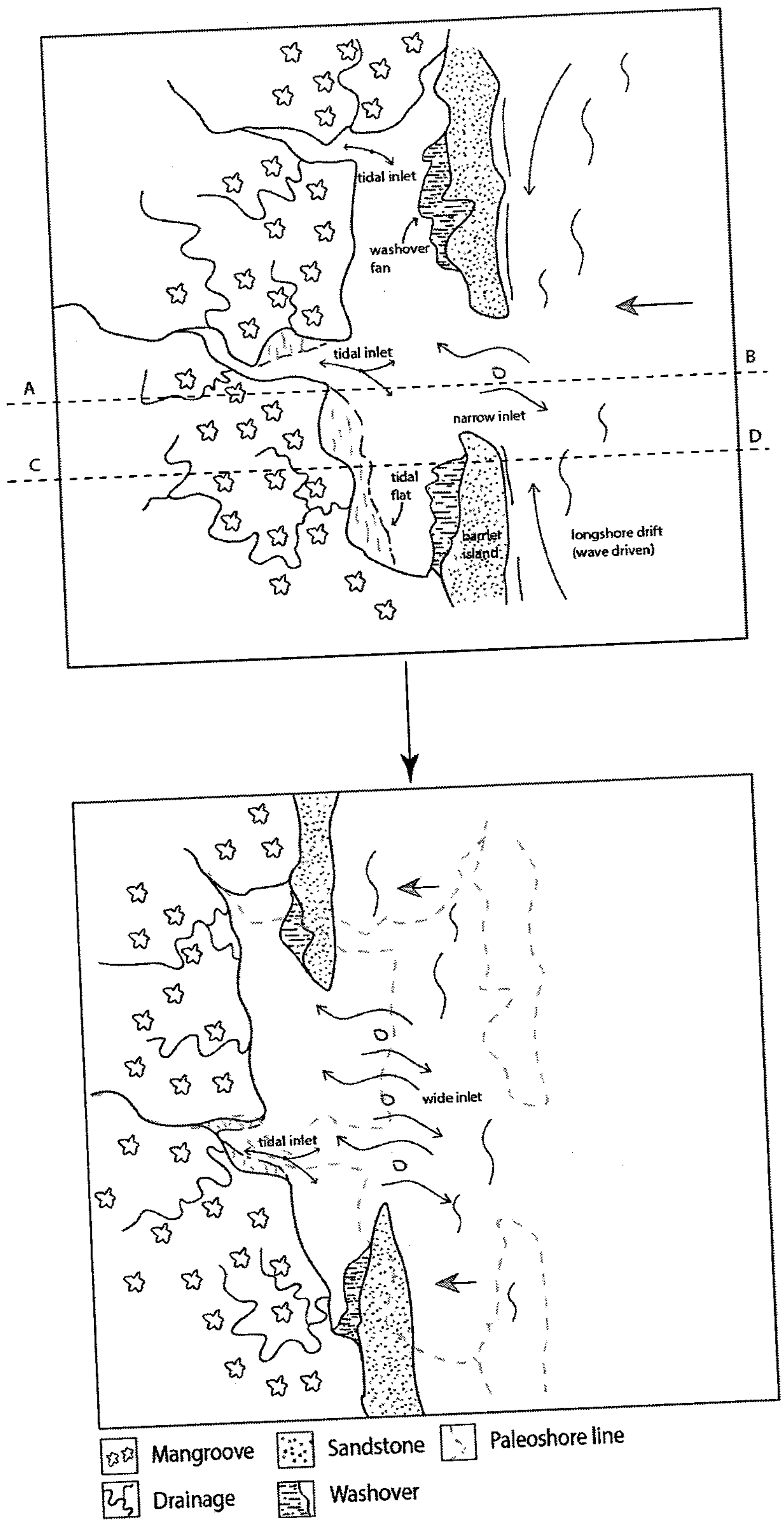


Figure 5.23: Sea level rising, shoreline transgression of a mangal estuary depositional environment model. The estuary mouth widens and shifted landwards.

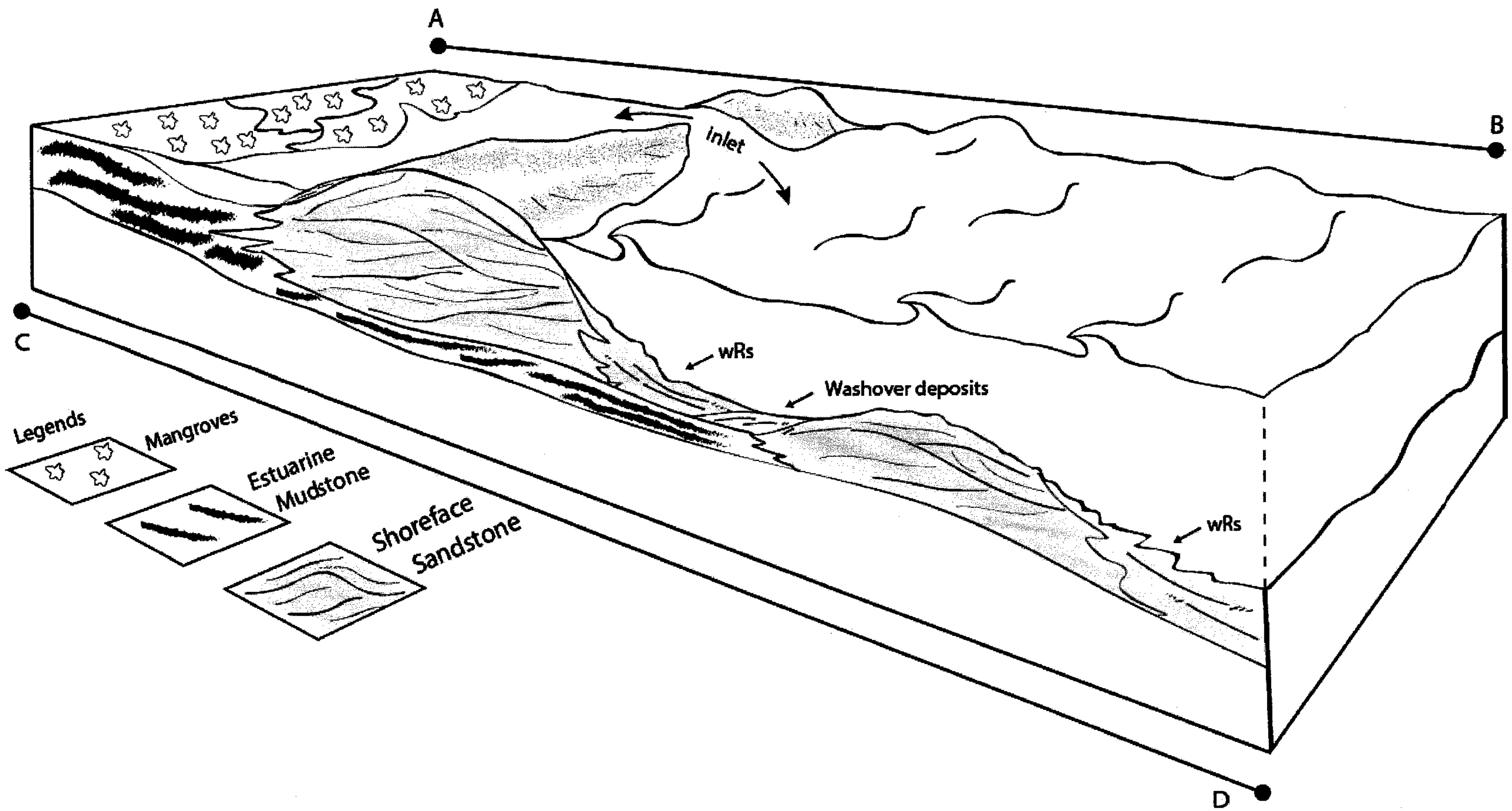


Figure 5.24: Block diagram of cross-section A- B and C – D of Figure 5.23 – illustrating a mangrove swamp to open marine system.

The modern Kinabatangan coastal swamp which is located at the southeast of Sandakan Peninsula provides a good analogue for the estuary depositional system. This mangrove-dominated swamp is brackish and contains highly carbonaceous materials (Udvardy, 1975). It is also connected to slow flowing meandering rivers. The wave energy level is considerably low as well. Thus it makes an excellent low energy deposition center for fine sediments entrapment.

Figure 5.25: (Left) Location of the modern Kinabatangan coastal swamp area in read and (Right) the aerial photographs of the Lower Kinabatangan Segama Wetland (Modified from Urvardy, 1975).

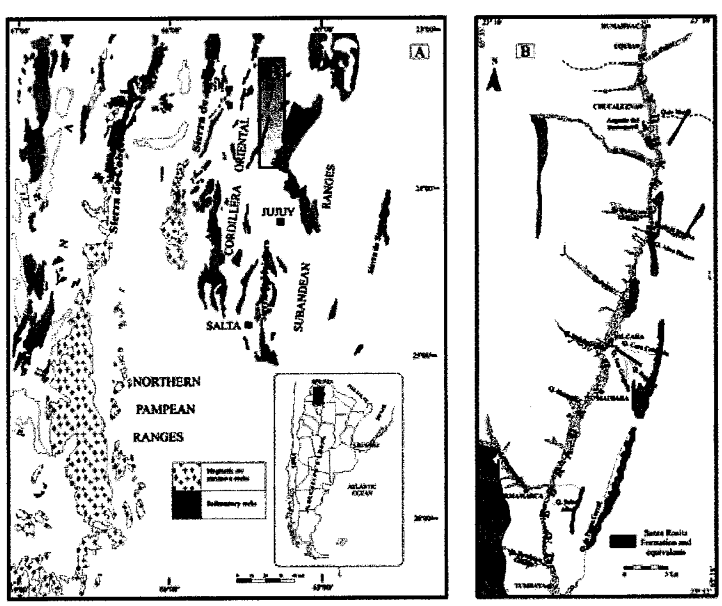


Figure 5.26: The regional distribution of Upper Cambrian- Ordovician exposures in northwestern Argentina (after Moya, 1988 and modified from Mangano et al.).

Another suitable analogue for the depositional system of Sandakan Formation is the Upper Cambrian – Lower Ordovician Santa Rosita Formation in northwest of Argentina. This formation comprises 5 different members. This formation shows similarities with the Sandakan Formation in many ways from the sedimentary structures to the stratigraphic framework, and to a better extent the depositional environment. The Santa Rosita Formation also includes a wide variety of deposits and sub-environments, such as braided fluvial, estuarine channels and bars, upper subtidal and intertidal flats, and transgressive channels. The lower section of this formation is deposited under a fluvio-estuarine environment while the upper section is deposited in an open marine; shoreface and offshore environment (Buatois, 2003).

5.3 Depositional Evolution of Sandakan Formation

The ten outcrops from my research area records an overall transgressive evolution from a brackish estuary (laminated mudstone with *Rhizophora* and trough bedding sandstone) in a broad wave-dominated sequence, storm-dominated deposits and inner shelf. The paleoenvironmental change recorded by the Sandakan Formation succession is summarized below (Figure 5.22), with reference to each lithofacies:-

Stage 1: Brackish Estuary

This is marked by the mudstone with abundant *Rhizophora* facies (F7) which represents a set of mangrove and brackish estuary. The transgressive pattern of depositional is much influenced by the balance between sediment supply and accommodation space (Cattaneo & Steel, 2002). The thick estuarine mudstone (> 19m) (Figure 5.14) (Outcrop 6) gives an estimation of the size (depth and lateral extent) of the central estuary basin. The bottom contact of this thick estuary mudstone is not captured at Outcrop 6. Thus it is only wise to assume that the recorded thickness of the mudstone is at the minimum stage and thins out laterally. The suitable analogue for this brackish environment would be the modern Kinabatangan Estuary (Figure 5.24). This mangrove swamp is more than 200 kilometer square wide with complex meandering channels (Urvady, 1975). The presence thin coal lenses and palynological analysis suggest that the in situ estuary materials became the main sediment source. At the interval of 28m to 30m, Outcrop 6 records thin slivers of sandstone suggested presence of the dynamic current condition (storm wave) as washover sediment.

Stage 2: Shallow marine sandstone

Erosional surface is produced during an episode of shoreface retreat or the wave ravinement surface (wRs) (Sixthmith et al, 2008; Embry, 2002; Cattaneo & Steel, 2002). This surface could be observed at Outcrop 6 where the estuary mudstone is cut by the low angle stratified sandstone with shell fragments. The mechanisms of landward barrier migration of Sandakan Formation could be further divided into three possibilities (refer to Figure 4.22) :-

1) The continuous shoreface retreat.
2) The punctuated shoreface retreat – in situ drowning.
3) The continuous in situ shoreface growth followed by drowning.

The overlying evident can be observed at Outcrop 6 where there is an abrupt change in facies from estuary mudstone to shoreface sandstone (Figure 5.10). This abrupt change suggests the landward stepping of the shoreface sandstone – a tranggressive succession (Reinson, 1988 and Gayes at. el., 2002). Tarek, 2003, in his research, he concluded that an outcrop at Cecily Road (located near Outcrop 7) shows similar change from an estuarine mudstone to a shoreface succession.

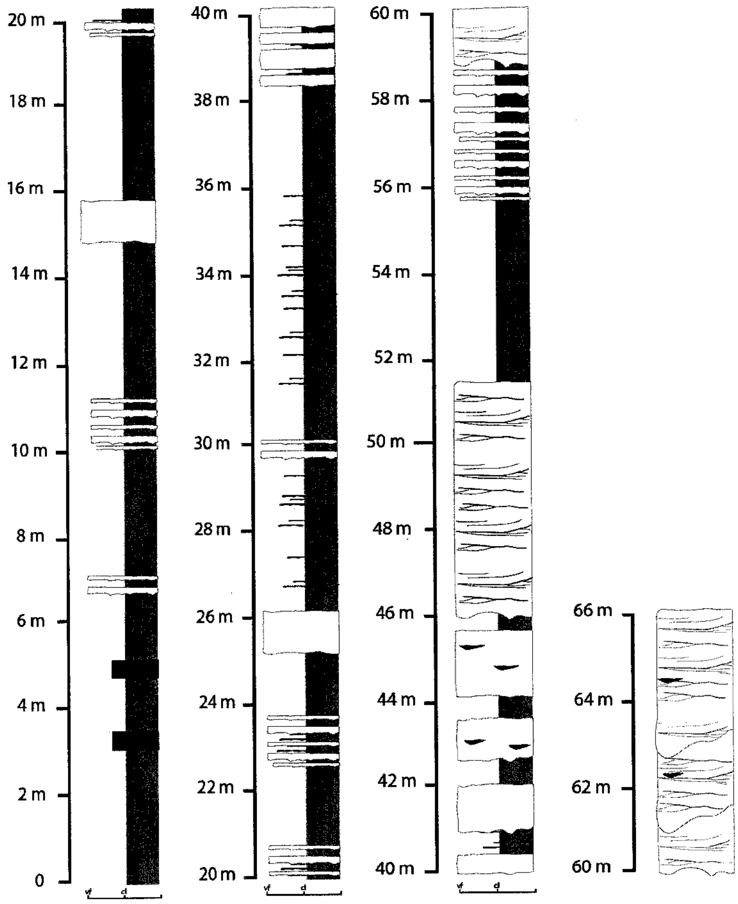


Figure 5.27: An estuarine mudstone overlying a shoreface succession. Coal layers are present at the bottom of this outcrop. Carbonaceous materials could be found at the interval of 26 m to 36 m. The top of this outcrop features a sandstone dominated sequence (modified from Tarek A.O., 2003).

Outcrop 7 and Outcrop 8 (Figure 4.16 – Figure 4.21) records thick shoreface succession (> 20m). Outcrop 7 also consists of thin weathered mudstone layers and occasionally, encrusted surfaces (highly bioturbated surfaces) are present. Such thick shoreface sandstone successions suggest an in situ growth of the shoreface with sufficient input of sediments into the system as a counterbalance to the rise in sea level (sediment supply equals to accommodation space) (Swift, 1975 and Sanders & Kumar, 1975 cited in Ryer 1977) (Plint 2000 and Cattaneo & Steel, 2002). Eventually, the growth of shoreface ceased and the barriers became drowned as a result of rapid sea level rise. New shoreface succession then formed at the inner shore overlaying the estuarine mudstone, approximately 500m landward (Figure 5.26).

All in all, Sandakan Formation features series of transgression and minor regression. This conceptual sequence stratigraphic model is discussed in the next sub-chapter (5.4 Sequence Stratigraphic Framework).

5.4 Sequence Stratigraphic Framework and Architecture of Sandakan Formation

The shallow marine sandstone of Sandakan Formation form prominent ridges in the southern-half of the peninsula (Fig 5.26). Detailed facies and stratigraph analyses show that the shoreface sandstone and offshore mudstone overlie the estuarine sandstone and coaly layers (Fig 5.22). Analyses done on Figure 5.26 show that the prominent sandstone ridges of Sandakan are arranged in the NNE – SSW trend and previous studies explained that the formation has been tilted in the southwest (Lee, 1970 & Fitch, 1950). These ridges are landward stepping sandbodies which represent the retrogradational shoreface cycles/succession/lobes which have developed due to a series of transgression. This is well illustrated by Figure 5.26.

The distance (gap) between the sandstone ridges represent the landward stepping of the shoreface sandstone. The rapid rise of the relative sea level causes this drowning of the previous shoreline (Nordfjord, 2009; Cattaneo & Steel, 2002, Reineck & Singh 1964, Einsere 1975) (refer to SL 3 of Figure 5.22). The variability of the gap distance between the previous shoreline and the newly formed shoreline is much depended on the degree of relative sea level rise.

A gradual relative sea level rise would not result in the drowning transgression event. But instead, the previous shoreface sandstone (dune) will be erorded leaving a thin shoreface sandstone behind (refer to SL 1 and SL 2 of Figure 5.22). This slow movement of shoreface in the landward direction is summarized as the climbing shoreface as a result of a slow transgressive event (Reineck & Singh 1975; Antia et al, 1994 and Einsele 2000,).

Looking at Sandakan Formation as a whole suggests that the transgressive trend comprises two continuous episodes which are the continuous in situ shoreface growth and drowning shoreface. The repetition of this mechanism produces the series of thick and separated shoreface sandstones. A major upliftment then took place in late Miocene – early Pliocene causing the formation to tilt gently in a southwest direction and thus exposing the sandstone ridges as what they are today (Figure 5.26, below).

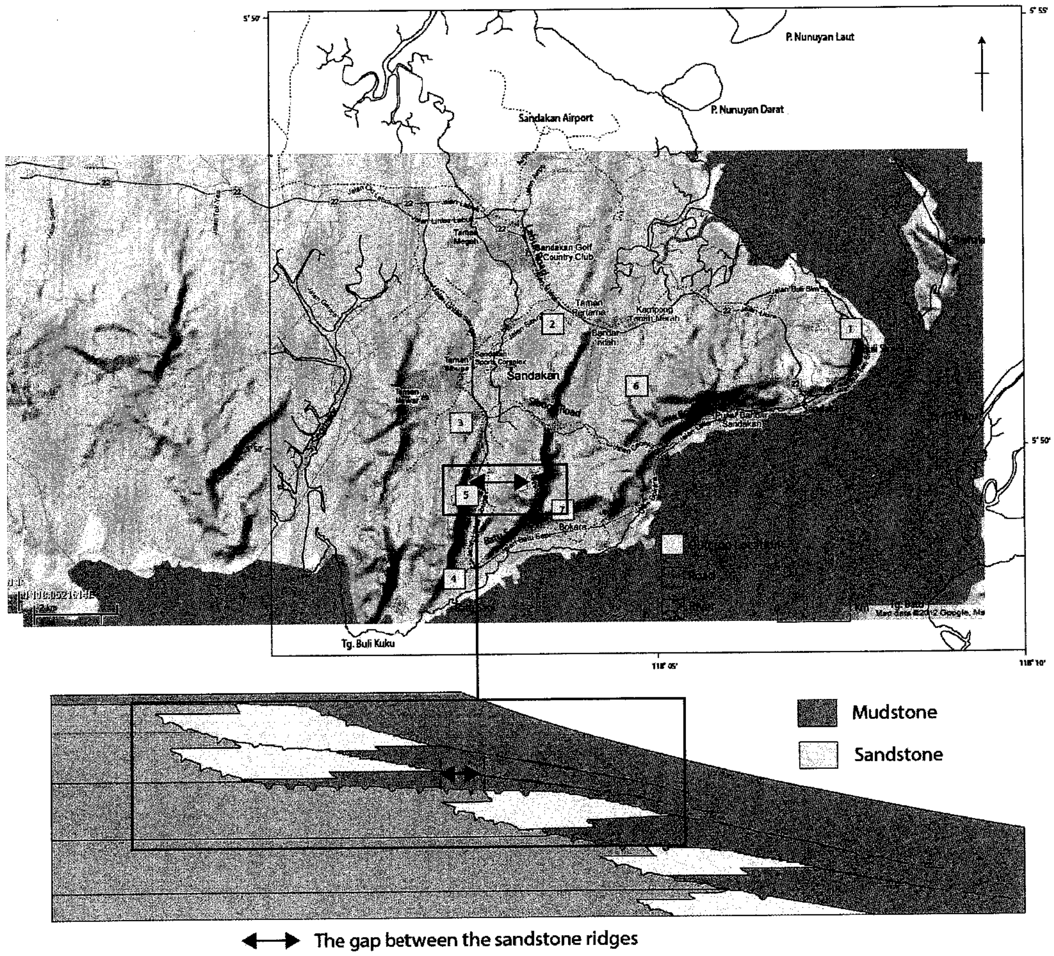


Figure 5.27: (Top) The map showing the sandstone ridges (grey) and the location of the outcrops (yellow) (modified from Google Terrain, 2012 and Lee, 1970). (Bottom) A transgressive pattern and landward stepping of

shoreface (yellow). Offshore mudstone (blue). Terrestrial deposits (green) (modified from Homewood, 2000).

CHAPTER 6

CONCLUSION AND SUGGESTIONS

6.1 Chapter Overview

This research served the specific aims and objectives as mentioned in Chapter 1of this thesis. The findings of this work solved the problem statement and provide useful suggestion for further studies.

6.2 Conclusion

1. The sedimentary facies of the Sandakan Formation based on outcrop loggings are described and interpreted. They are as displayed in Chapter 4 and chapter 5.

2. The facies association in terms of sedimentary processes and environments are identified. Three facies associations are described: - a) Gradual coarsening upwards facies association, b) Abrupt facies association c) Estuary (tidal influence?) facies association.

3. The microfossils and their paleoenvironmental implications are identified and they are as described in Chapter 4.

4. Conceptual model of the depositional environment and their evolution are described in Chapter 5. I proposed a transgressive change from estuary to shoreface depositional system for this Sandakan Formation.

6.3 Summary

1. Facies analyses of Sandakan Formation outcrops have been deposited under different settings and environment. They are as listed below:-
    a. Thick amalgamated sandstone (Lower and middle shoreface)
    b. Interbedded HCS sandstone and mudstone (Offshore transition)
    c. Thin, lenticular interbedded HCS sandstones and mudstones (Upper Offshore)
    d. Laminated mudstone *Rhizophora* (Mangrove Swamp)
    e. Sandstone with shell fragments
    f. Laminated mudstone (Offshore)
    g. Strip mudstone with thin laminated sandstone and siltstone
    h. Sandstone with herringbone crossbedding (Tidal Current)

2. The lithofacies can be grouped into three facies association. These are: i) gradual prograding open marine succession, ii) the abrupt change open marine association and, iii) the prograding estuary sequence. Two distinctive environment can be concluded from the facies analysis. They are: 1) mangal dominated estuary environment and, 2) open marine environment which includes shoreface and offshore transition environment.

3. The overall stratigraphic organization of lithofacies and facies association reflects a change from estuarine to shallow upper shoreface setting with a background of relative sea level rise.

4. The mechanism of the shoreface succession could be divided into two continuous movements:- a) the in situ growth of shoreface sandstone where the sediment supply is equal to the relative sea level rise, and, b) rapid rise of relative sea level causing the drowning of the shoreface sandstone and the newly formed shoreface stepped further into the land.

6.4 Limitations

This research on Sandakan Formation based on the outcrops has posed a few limitations.

1. Outcrop samples are well known to be exposed to heavy weathering. Such post-deposition processes would have dissolved the carbonate component in the mudstone; even in a micro scale.
2. Vegetation grows rapidly in the propical climate. The newly exposed outcrops are covered by vegetation in less than a year. Revisiting the same outcrop seems impossible.
3. The whole Sandakan Formation is not exposed and could not be solely seen on the outcrops.
4. The ichonofossils of the formation is limited. Probably the sediment supply is high.

6.5 Recommendations

While working on this research, more problems and ambiguous aspects arosed that seemed to be the constraining factors to a better outcome. It is possible for this research to be continued in the following aspects:-

1. Facies architecture analysis could be done on the series of sandstone cliffs running N-S in the south of Sandakan Peninsula. They are well exposed across the city. Each lobe may represent a parasequence.
2. A complete stratigraphic section of Sandakan Formation has yet not been completed. This research should proceed in collecting borehole data. The borehole samples would be suitable for micropaleontological analysis and biostratigraphic analysis could be carried out.

REFERENCES

Abdul Hadi Abd. Rahman. 1995. *Reservoir characterization of the upper Cycle V (Late Miocene) of Baram Field, Baram Delta, offshore Sarawak, East Malaysia*. Unpublished PhD Thesis, University of Reading, England.

Brenchley, P.J., Pickerill, R.K., Stromberg, S.G. 1993. *The role of wave reworking on the architecture of storm sandstone facies, Bell Island Group (Lower Ordovician), eastern Newfoundland.* Sedimentology 40: 359 - 382.

Bolli, H., M., Saunders, J., B. & Perch-Nielsen K., 1985. Plankton Stratigraphy. Cambridge Earth Science Series.

Buatois, A. & Mangano, G. 2003. *Sedimentary facies, depositional evolution of the Upper Cambrian - Lower Ordovician Santa RositaFormation in northwest Argentina*. Journal of South American Earth Sciences (Elsevier).

Cattaneo, A. & Steel, R., J., 2001. *Transgressive deposits: a review of their variability.* Earth-Science Reviews 62, Science Direct, Elsevier.

Clennell, M.B. 1992. *The Melanges of Sabah, Malaysia*. Ph.D. thesis, University of London.

Costa Rica Guide, 2005. *When to Travel to Costa Rica.Toucan Guides*. Retrieved on 2008-12-27.

D.T.C., Lee. 1970. *Sandakan Peninsula, Eastern Sabah, Eastern Malaysia*. Geological Survey of East Malaysia, Report no. 6.

Dalrymple, R. W., Zaitlin, B.A., and Boyd, R., 1992. *Estuarine facies models: Conceptual basis and stratigraphic implications*. Journal of Sedimentary Petrology, v. 62, p. 1130 – 1146.

Deflandre, G., and Fert, C., 1954, Pl. X, fig. 1 à 4. Reference: Observations sur les Coccolithophoridés actuels et fossiles en microscopie ordinaire et électronique. Ann. Paleontol., 40:115-76.

Fitch, H. 1958. *The Geology and Mineral Resources of the Sandakan Area North Borneo*. Kuching: Government Printing Office.

Gayes, P., T., Schwab, W., C., Driscoll, N., W., Morton, R., A., Baldwin, W., E., Denny., J., F., German, O., Y. & Park, J., Y., 2002, *Transgressive Shoreface Architecture within a Sediment Starved Arcuate Strand: Long Bay, South Carolina.* American Geophysical Union, Fall Meeting 2002.

Gullick, J. M., 1967, *Malaysia and Its Neighbours, The World studies series*, Taylor & Francis, p. 148-149, retrieved 2012-11-17

Haile, N. S. & Wong, N.P.Y. 1965. *The geology and mineral resources of Dent Peninsular, Sabah.* Geological Survey, Borneo Region, Malaysia, Memoir 16.

Holland, S., 2008.*Sequence Stratigraphy.* University of Georgia.

Homewood, P., W., 2000, *Best Practice In Sequence Stratigraphy.* ELF EP. Geosciences. Universite De Bretagna Sud.

Hutchinson, C. 2005. *Geology of North West Borneo.* Elsevier. Amsterdam.

Hutchinson, C.S. 1997. *Tectonic framework of the Neogene basins of Sabah.* Abstracts Geological Society of Malaysia Petroleum Geology Conference.

Jamalian, M., Adabi, M., Moussavi, M., Sadeghi, A., Baghbani, D. & Ariyafar, B. 2011. *Facies characteristic and paleoenvironmental reconstruction of the Fahliyan Formation, Lower Cretaceous, in the Kuh-e Siah area, Zagros Basin, southern Iran.* Facies.

Jenkins, D. 1993. *Applied Micropalaeontology.* Kluwer Academic Publishers.

Kirk, H.J.C. 1962. *The geology and mineral resources of the Semporna Peninsula, North Borneo.* British Borneo Geological Survey of Malaysia. Bulletin 5. Memoir 14.

Kamptner E., 1963, p. 187; pl. 1, fig. 5; text-fig. 37a-c. Reference: Coccolithineen-Skelettreste aus Tiefseeablagerungen des Pazifischen Ozeans. Ann. Naturhistor. Mus. Wien, vol. 66, pp. 139-204, pls. 1-9, text-figs. 1-39.

Krassay, A.A., 1994. *Storm features of siliciclastic shelf sedimentation in the mid-Cretaceous epeiric seaway of northern Australia.* Sedimentary Geology 89, 241 – 264.

Kvale, E.P., Archer, A.W., 1990. *Tidal deposits associated with low-sulfur coals, Brazil FM. (Lower Pennsylvanian)*, Indiana. Journal of Sedimentary Petrology 60, 563 -574.

Kvale, E.P., Archer, A.W., Johnson, H.R., 1989. *Daily, monthly, and yearly tidal cycles within laminated siltstones of the Mansfield Formation (Pennsylvanian) of Indiana.* Geology 17, 365-368.

Lee C. P., Shafeea Leman, Kamaludinh Hassan, Bahari Nasib & Rashidah Karim. 2004. *Stratigraphic Lexicon of Malaysia.* Malaysia Stratigraphic Central. Geological Society of Malaysia.

Leong K.M., 1976. *Miocene chaotic depostis in eastern Sabah: characteristics, origin and petroleum prospects.* Geological Survey of Malaysia Annual Report for 1975, 238.

Mangano, M., G., Buatois, L., A. & Guinea F., M., 2005, *Ichnology of the Alfarcito Member (Santa Rosita Formation) of northwestern Argentina: animal-substrate interactions in a lower paleozoic wave-dominated shallow sea.* Department of Geological Sciences, University of Saskatchewan. Ameghinian, V.42 n.4 Buenos Aires.

McGowran, B. *Biostratigraphy Microfossils and Geological Time.* The University of Adelaide, Cambridge University Press.

Murray J., 1991. Ecology and Paleoecology of Benthic Foraminifera.Longman Scientific & Technical. New York.

Morley R., J., 1990. *Tertiary stratigraphic palynology in Southeast Asia: current status and new directions.* Geological Society Malaysia Bulletin 28, November 1991; pp. 1 – 36.

Noad, J. 1998. *The sedimentary Evolution of the Tertiary of Eastern Sabah, Northern Borneo.* Ph.D thesis, Research school of Geological and Geophysical Sciences, Birkbeck College and University of London: 457.

PETRONAS. *The Petroleum Geology and Resources of Malaysia.* Kuala Lumpur: Petroluam Nasional Berhad (PETRONAS), 1999.

Pettijohn, J., Potter, P., Siever, Siever. *Sand and Sandstone.* Springer-Verlag Berlin. Heidelberg, 1972.

Pidwirny, M., 2008. CHAPTER 9: *Introduction to the Biosphere.* Physical. Geography.net. Retrieved on 2008-12-27.

Plint, A.G., Nummedal, D., 2000, *The falling stage Systems Tract: recognition and importance in Sequence stratigraphic analysis.* In: Hunt, D., Gawthorpe, R.L. (Eds.), Sedimentary Response to Forced Regression, vol. 172. Geol. Soc. London Speci. Publ, pp. 1–17.

Plint. A.G., & Walker, R.G., 2000, *Chapter 12: Wave- and Storm-Dominated Shallow Marine Systems.* Department of Geology, McMaster University, Hamilton, Ontario.

Potter P.E., J.B. Maynard, P. J. Depetris. 2005. *Mud and mudstones.* Springer.

Poumot C., 1989. *Palynological Evidence for Eustatic Events in the Tropical Neogene.* Bull. Centres Rech. Explore. – Prod. Elf-Aquitaine, 13, 2, 437 – 453, 9 fig.1 Boussens, December 4, 1989.

Reading, H. G. 1996. *Sedimentary Environments: Process, Facies and Stratigraphy.* Australia. Blackwell Publishing.

Reinson., G., E., 1988, *Transgressive Barrier Island and Estuarine Systems*, Institute of Sedimentary and Petroleum Geology, Geological Survey of Canada.

Richmond, S., 2010. *Malaysia, Singapore and Brunei.* Lonely Planet. pp. 74–75, 78–82.

Selly, R. 2000. *Applied Sedimentology.* Second Edition. United States. Academic Press.

Shanmugan, G., Poffenberger, M. & Toro, J., 2000. *Tide-Dominated Estuarine Facies in the Hollin and Napo ("T" and "U") Formations (Cretaceous), Sacha Field, Oriente Basin, Ecuador.* AAPG Bulletin, V. 84, No. 5: 652 – 682.

Sinha, D. 2007. *Micropaleontology, Application in Stratigraphy & Paleoceanography.* Narosa Publishing House, New Delhi.

Sixthsmith,

Staufer, P.H. & Lee, D.T.C. 1972. *Sedimentology of the Sandakan Formation, east Sabah.* Geological Survey of Malaysia: 1, 10 - 17.

Tarek, O., 2002. *Geochemistry of Sandakan Formation, East Sabah.* Unpublished Master of Science Thesis. University Malaya.

Tarek, O., Hasiah, W., A. & Abdul Hadi A., R., 2004. *Biomarkers as palaeoenvironment and Thermal Maturity Indicators of the Sandakan Formation (Late Miocene) East Sabah, Malaysia.* Malaysian Journal of Science 23(2). P 165 - 174.

Teoh, Y. J. 2008. *Characteristics of Sedimentary Facies and Reservoir Properties of some Tertiary Sandstones in Sabah and Sarawak, East Malaysia.* Penang: University Sains Malaysia.

Tongkul, F. 1992. *Tectonic Control on the Development of the Neogene Basin in Sabah, East Malaysia*. Geological Society of Malaysia Bulletin 33: 95 - 103.

Tjia, H.D., Ibrahim Komoo, Lim, P.S. and Tungah Surat. 1990. *The Maliau Basin, Sabah: geology and tectonic setting*. Bulletin of the Geological Society of Malaysia, 27, 261 – 292.

Tulot, S. 2002. *Sedimentology and Reservoir Properties of Sandakan Formation Shorface Sandstones, Sabah, Malaysia.*

Walker, T.R., 1993. *Sandakan Basin prospects rise following modern reappraisal.* Oil and Gas Journal May 10: 43 – 47.

Yoshida, S., H., Johnson, K., Pye & R., Dixon. 2004. *Transgressive changes from tidal estuarine to marine embayment depositional systems: The Lower Cretaceous Woburn Sands of southern England and comparison with Holocene analogs.* AAPG Bulletin, v. 88, NO. 10: 1433 – 146.

PUBLICATIONS

1. Khor, W., C., Chow, W., S. & Abdul Hadi A., R., 2012, *Sedimentology, Stratigraphy and Biofacies of Sandakan Formation, East Sabah.* International Conference on Intergrated Petroleum Engineering and Geosciences 2012 (ICIPEG 2012).

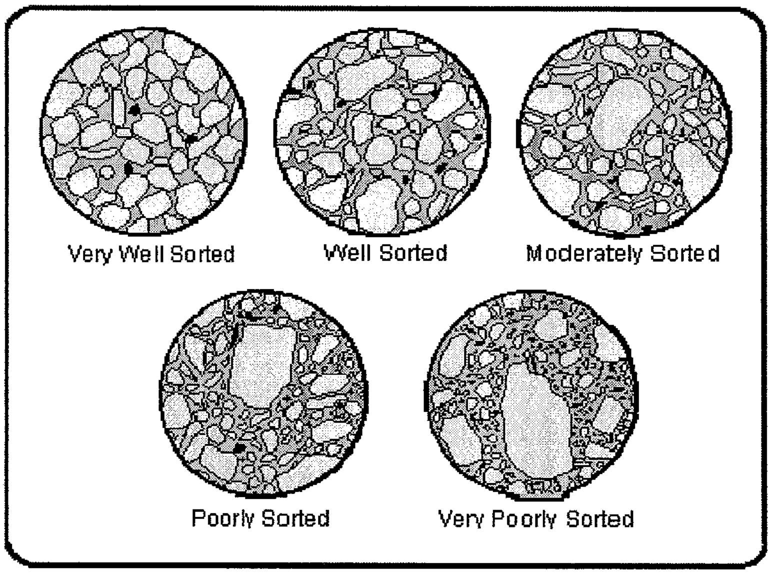
2. Khor, W., C., Chow, W., S. & Abdul Hadi A., R., 2013, *Stratigraphic Succession and Depositional Framework of Tertiary Deposits in East Sabah, Borneo.* Sains Malaysiana Journals. Status: On Review, 4th June 2013.

APPENDIX A

Sorting

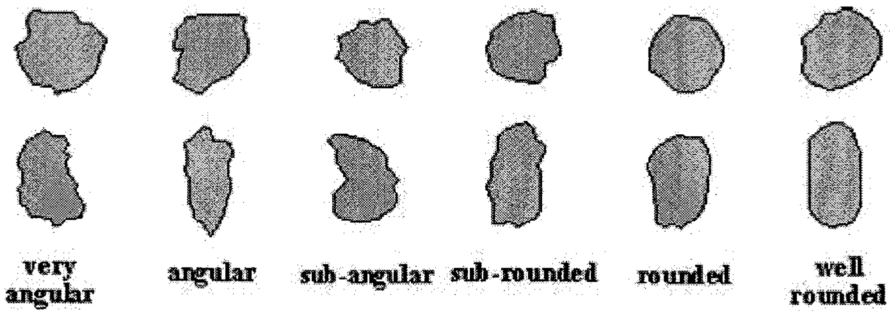
Sorting is based on the range of particle sizes. A well sorted clastic sediment has grains approximately the same size and poorly sorted means there is a wide range in particle size.

The sorting scheme is as shown below:-

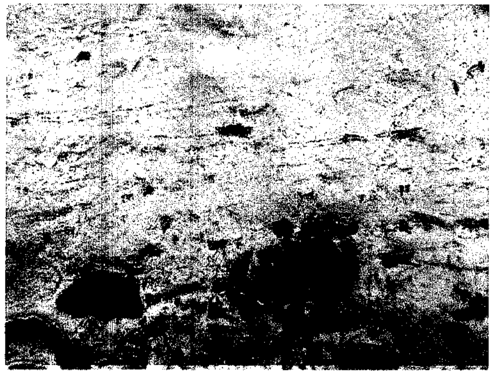
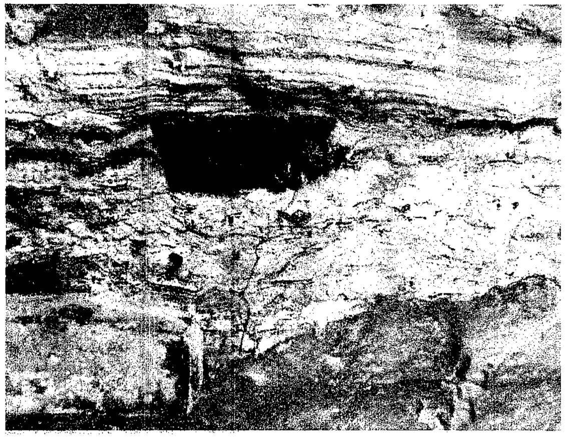


Sorting Scheme is based on the diagram from Zhongshan University which could be found at http://gs.sysu.edu.cn website.

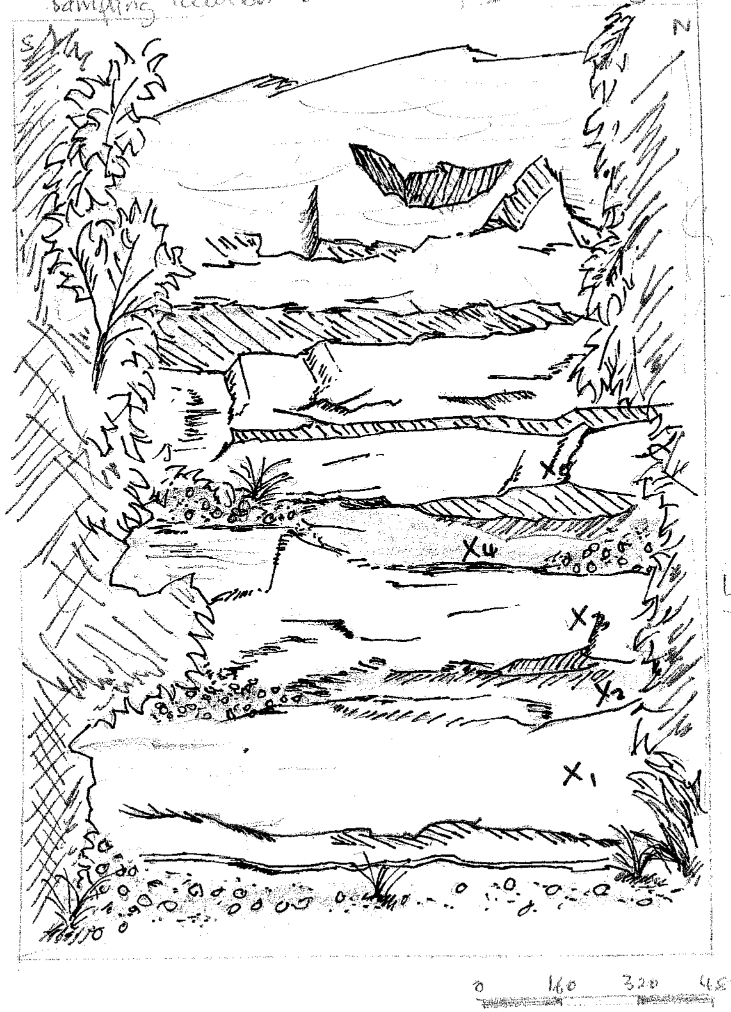
Grain Shape Scheme



This grain shape scheme could be found at http://newterra.chemeketa.edu website.

Photographs and Hand Sketch of Outcrop 1	Description
	Coal clasts are aligned laterally. The sandstone shows faint HCS lamination.
	Coalified tree trunk in laminated fine to very fine sandstone (siltstone?)

Sampling location of outcrop 1, locality 1



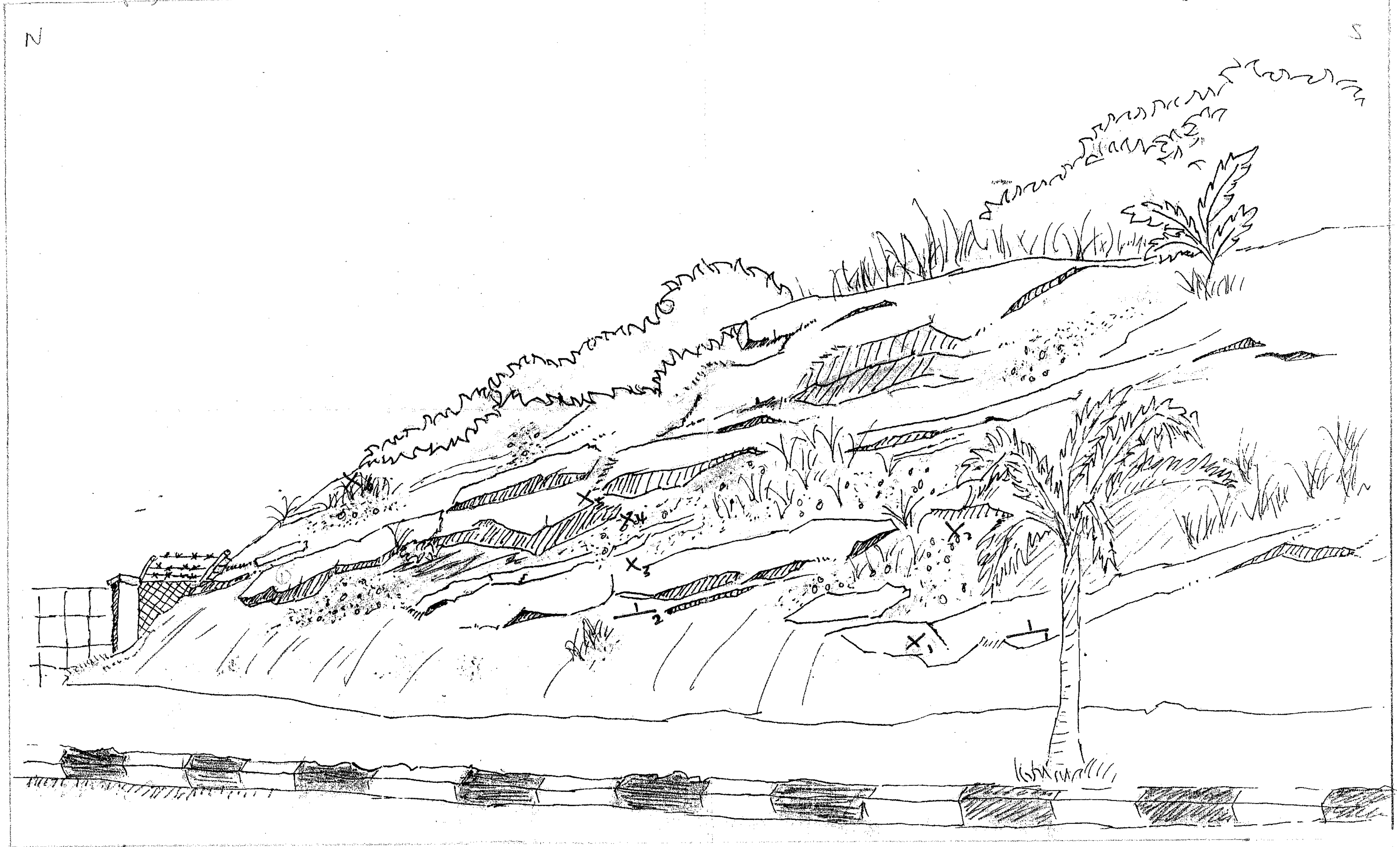
Samples

X_1 – TA
X_2 – TB
X_2 – TC
X_4 – TD
X_5 – TE

Legend

X_n samples

sampling location and strike & dip Reading of BDK-2



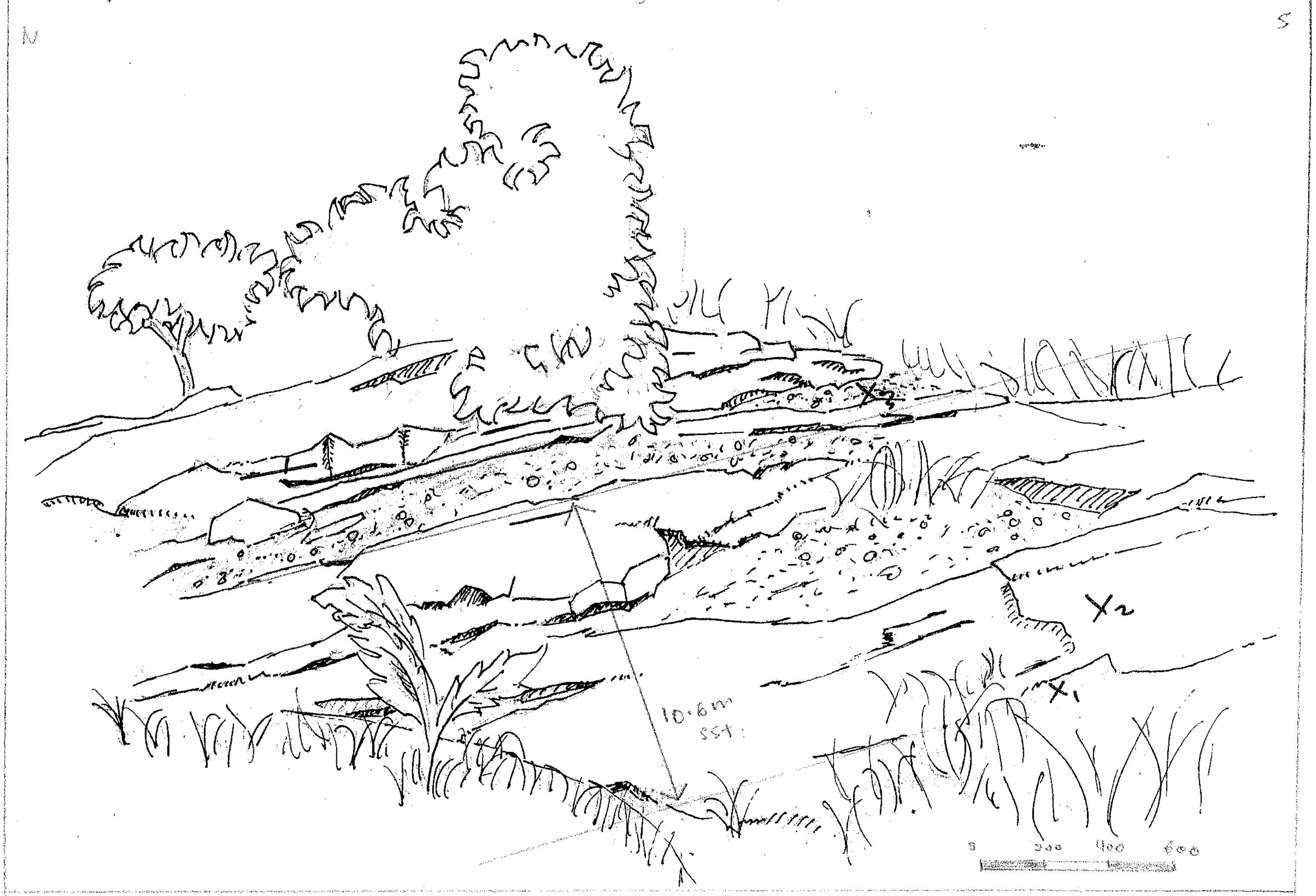
Legends

Samples

Strike & Dip

Photographs and Hand Sketches of Outcrop 2	Description
	Thin interbedded sandstone and mudstone.
	Overall view out the upper part of this outcrop. The stratigraphy is as shown in Outcrop 2.2 Fine to very fine grained mudstone with faint HCS lamination.

Sampling location and strike & dip Reading of outcrop 22 locality 2



Legends

X_n	sampling location.
(strike & dip symbol)	Strike & Dip

Samples

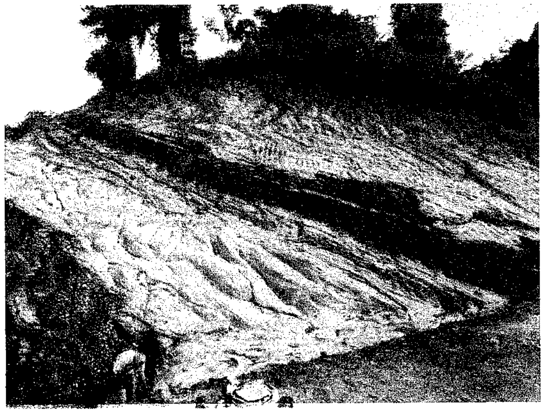
X_1 - NH

X_2 - NI

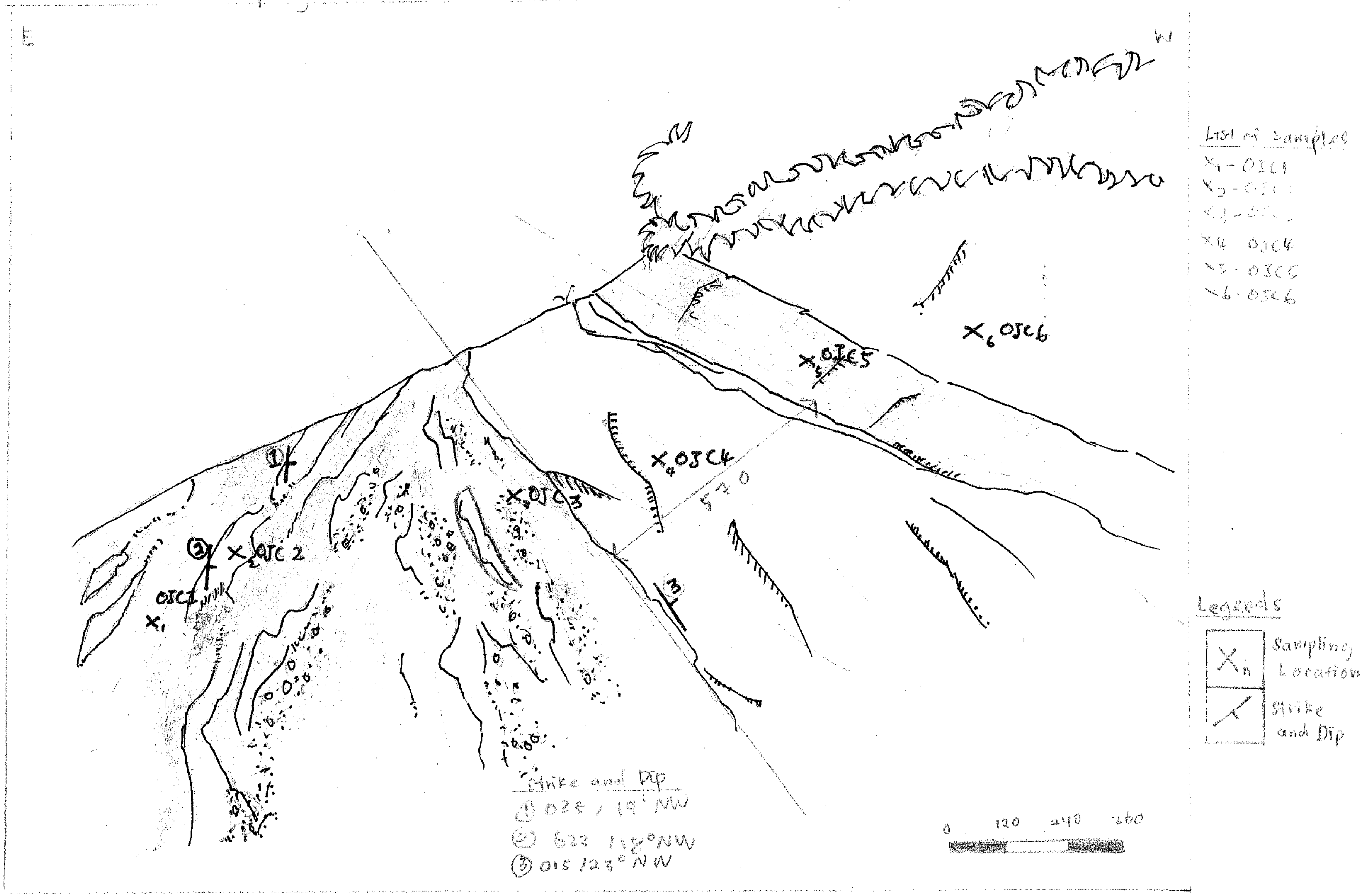
X_3 - NJ.

Strike & Dip

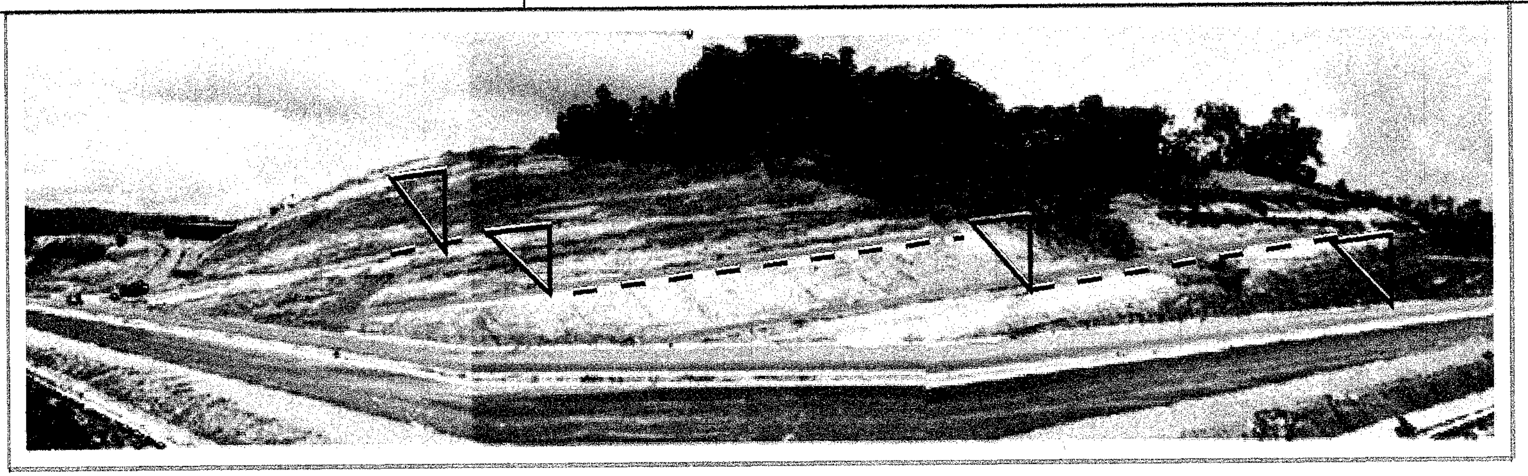
060/16° NW.

Photographs and Hand Sketch of Outcrop 3	Description
	The sandstone lenses at the bottom left of this outcrop. The sandstone at the top layer is scouring into the mudstone. The sandstone in the middle shows a gradual fining upwards, from fine to very fine sandstone to muddy sandstone and to mudstone.
	This picture features a fairly sharp contact between the sandstone and the mudstone. The sandstone also captured the low angle HCS. The leaching / weathering of the sandstone enhanced the colour of the lamination.

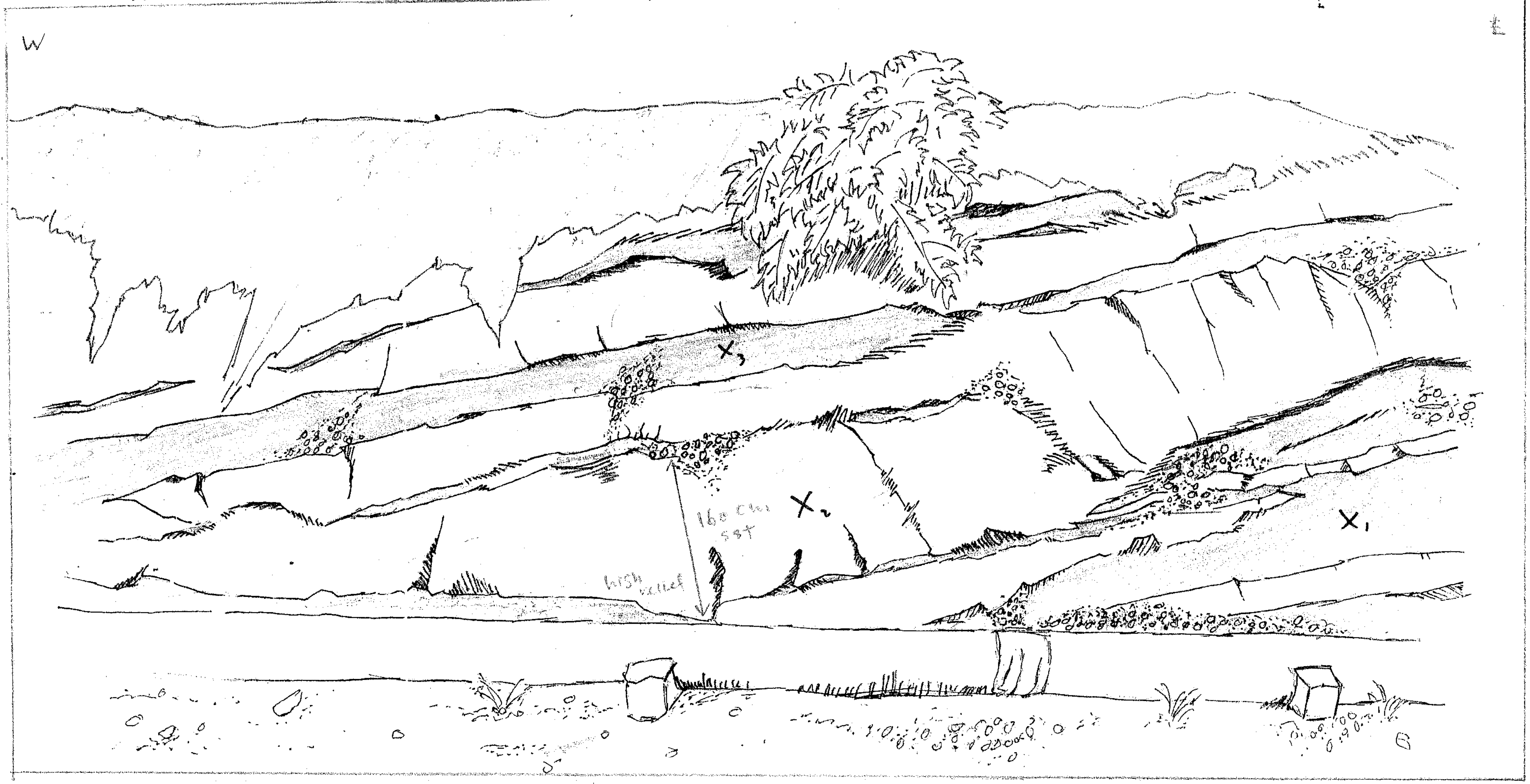
Sampling location and Strike & Dip of outcrop, Locality 3



Photographs and Hand Sketch of Outcrop 4	Description
	← Left: Tiny Shell cast found in the mudstone. Probably, it is a exsitu deposit – being transported and redistributed by the wave, Bottom: The upwards coarsening sequence of this outcrop.



A Portion of outcrops sketch with sampling location and strike & Dip reading, Locality 3

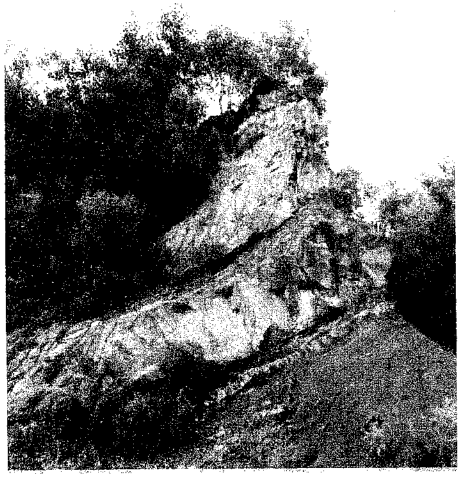
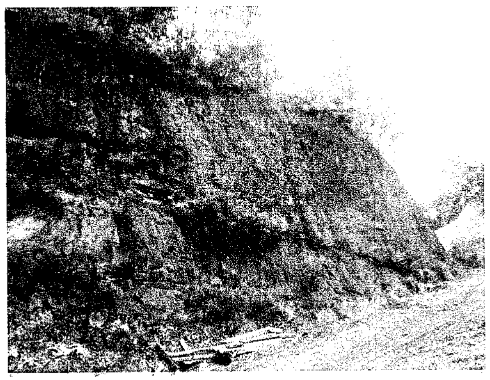


Legends

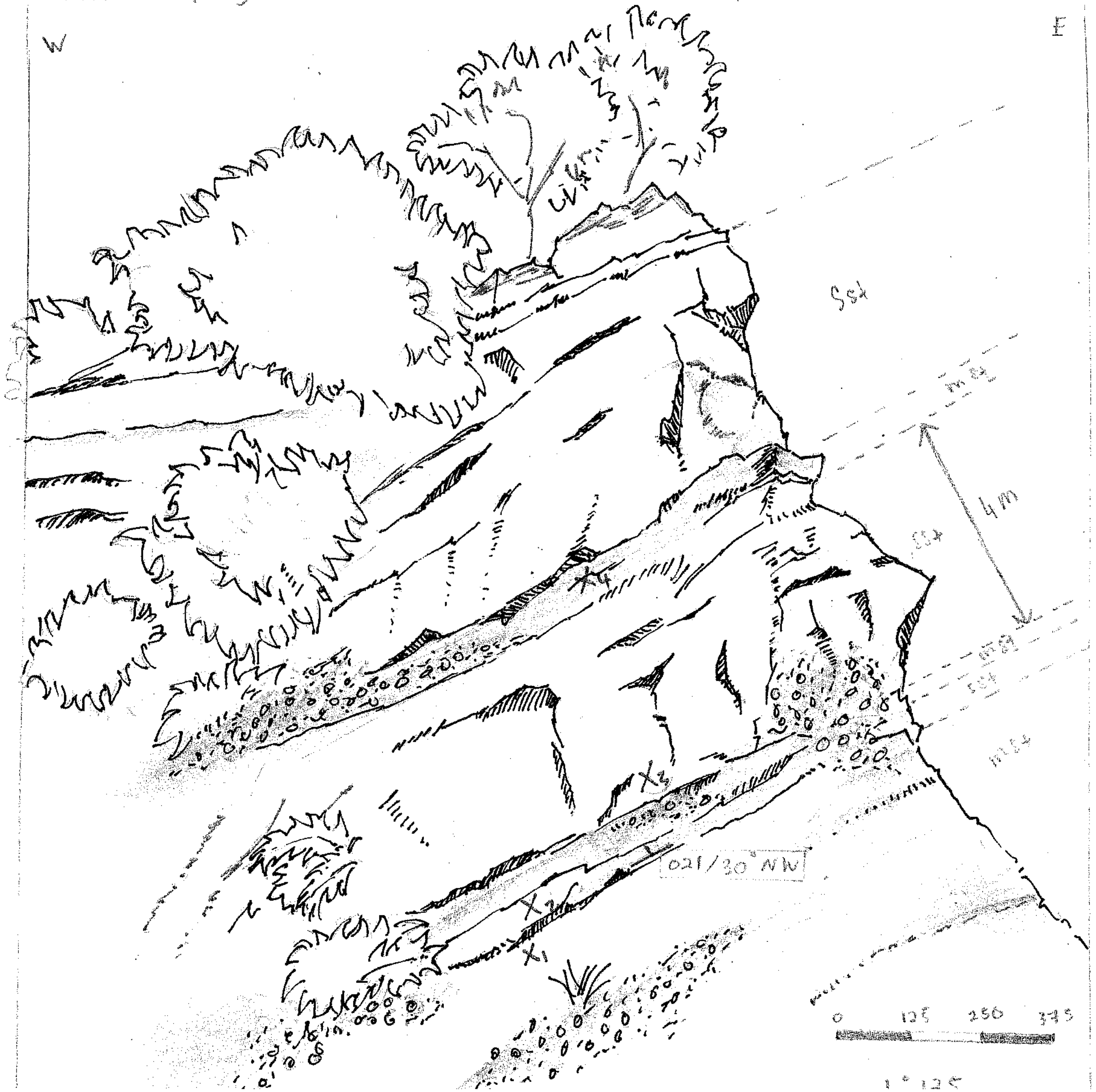
X_n samples

Samples

X_1 - OC1
X_2 - OC2
X_3 - OC3

Photographs and Hand Sketches of Outcrop 5	Description
	**This outcrop is outcrop 5.1. It shows a sharp contact between the shoreface sandstone and the estuarine mudstone. It records an abrupt change in facies. It is an evidence for a transgressive system.**
	**This outcrop comprises only shoreface sandstone. The top of this sandstone shows rippled surface. This sandstone is thick and features faint low angle HCS.**

sampling Location and Strike & Dip of outcrop 5.1, Locality 4



Samples

X1 - AA
X2 - AB
X3 - AC
X4 - AD

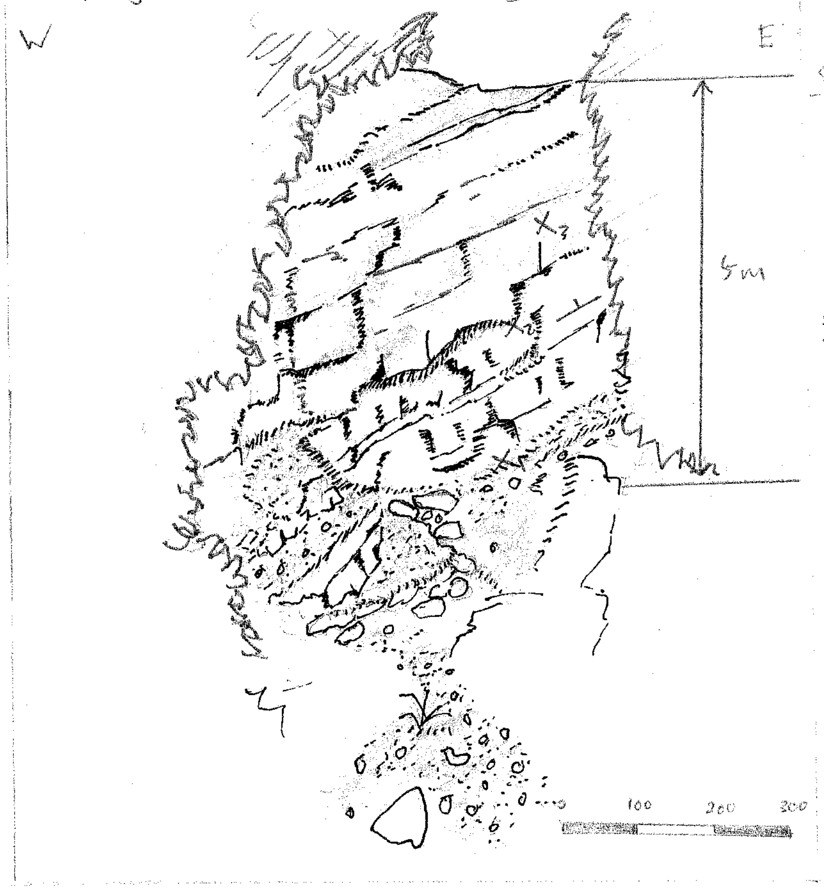
Strike & Dip

021/30°NW

Legend

	Sandstone
	mudstone
	Strike & Dip
X_n	Sample Location

Sampling and Strike & Dip Reading of outcrop 5.2, Locality 4



Samples

X_1 - BA
X_2 - BB
X_3 - BC

Strike & Dip

056/21°NW

Legends

X_n	Sampling Location
	Strike and dip

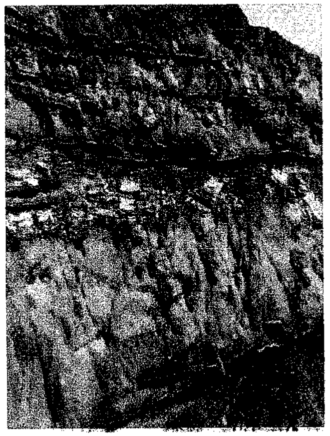
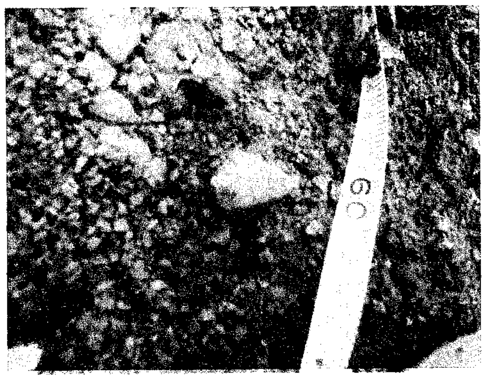
Sampling location and strike & dip of SDK 5.3, Locality 4

Samples

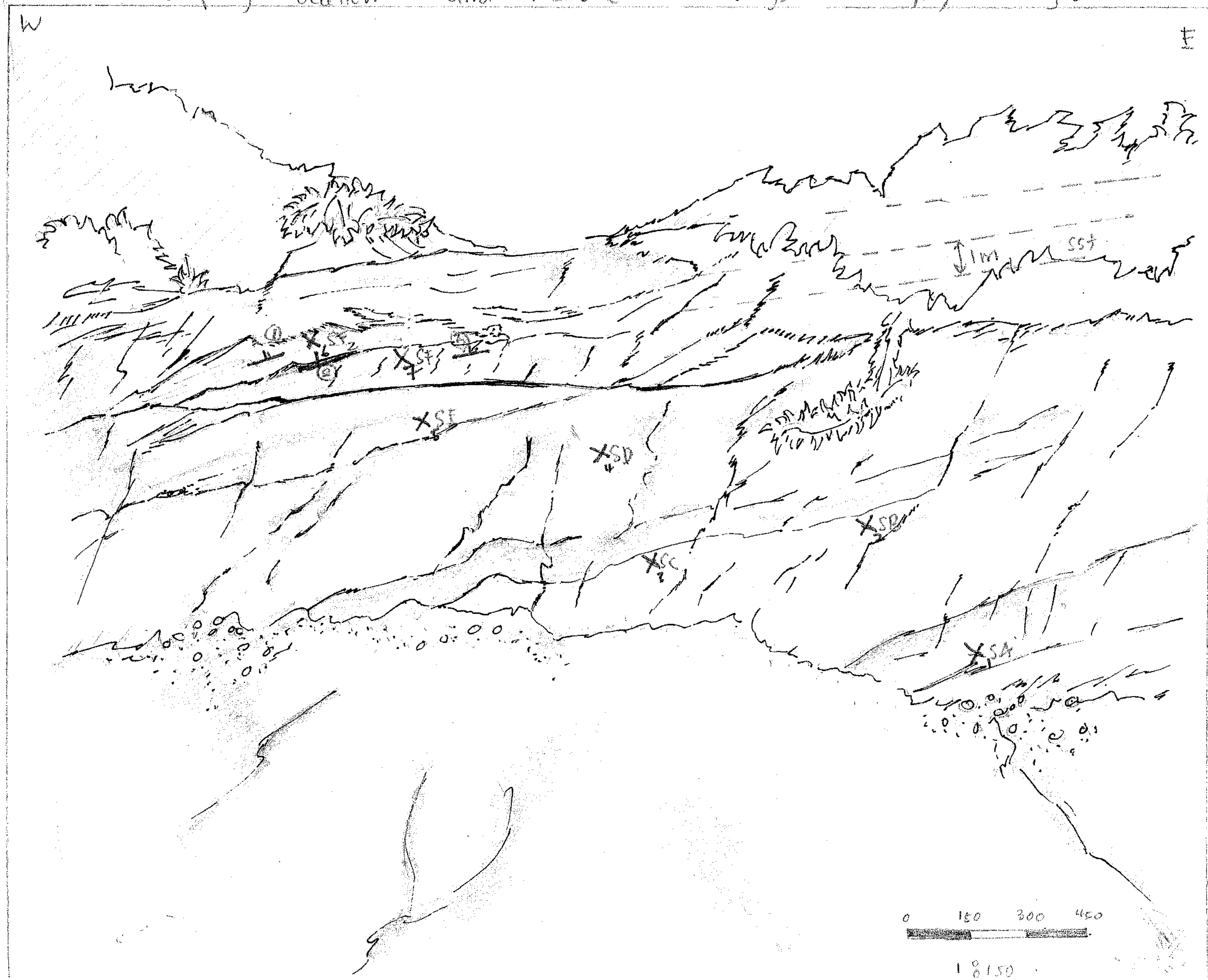
X_1 – CA
X_2 – CB
X_3 – CC

Legends

X_n Samples

Photographs and Hand Sketch of Outcrop 6	
	Medium to fine grained sandstone. Thin mud layers are present.
	Broken sandstone cast of gastropod. An ex situ deposit. Tree trunks, leaf casts can be found too.

Sampling location and Measurement Readings of Outcrop 6, Locality 5



Samples

X_1 SA
X_2 SB
X_3 SC
X_4 SD
X_5 SE
X_6 SF_2
X_7 SF

Readings

1) 002/26 NW
2) Tabular - 086/71SE
3) 010/18° NW

Legends

X_n	samples

Photographs of Outcrop 7	
	**This outcrop comprises thick shoreface sandstone and thin mudstone layers (whitish and grayish).** **Some of the sandstone is massive.** **The sandstones also feature rippled surface, low angle HCS and a low relief scouring surface (> 30 cm).**