ธรณีวิทยาปิโตรเลียมของแอ่งสงขลาในอ่าวไทย

นางสาวสญชวัล อัคโกศล

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิทยาศาสตรมหาบัณฑิต

สาขาวิชาธรณีวิทยา ภาควิชาธรณีวิทยา

คณะวิทยาศาสตร์ จุฬาลงกรณ์มหาวิทยาลัย

ปีการศึกษา 2544

ISBN 974-03-0473-7

PETROLEUM GEOLOGY OF THE SONGKHLA BASIN IN THE GULF OF THAILAND

Miss SONCHAWAN AC-KAGOSOL

A Thesis Submitted in Partial Fulfillment of the Requirements

for the Degree of Master of Science in Geology

Department of Geology

Faculty of Science

Chulalongkorn University

Academic Year 2001

ISBN 974-03-0473-7

Thesis Title | Petroleum Geology of the Songkhla Basin in the Gulf of Thailand
By | Miss Sonchawan Ac-kagosol
Field of Study | Geology
Thesis Advisor | Assistant Professor Pongsak Phongprayoon
Thesis Co-advisor | Bundit Chaisilboon

Accepted by the Faculty of Science, Chulalongkorn University in Partial Fulfillment of the Requirements for the Master 's Degree

.... Dean of Faculty of Science

(Associate Professor Wanchai Phothiphichitr, Ph.D.)

THESIS COMMITTEE

.... Chairman

(Assistant Professor Somchai Nakapadungrat, Ph.D.)

.... Thesis Advisor

(Assistant Professor Pongsak Phongprayoon, M.A.)

.... Thesis Co-advisor

(Bundit Chaisilboon, M.Sc.)

.... Member

(Khajohn Bhasavanija, Ph.D.)

สญชวัล อัคโกศล : ธรณีวิทยาปิโตรเลียมของแอ่งสงขลาในอ่าวไทย (PETROLEUM GEOLOGY OF THE SONGKHLA BASIN IN THE GULF OF THAILAND). อ. ที่ปรึกษา : ผศ. ปองศักดิ์ พงษ์ประยูร, อ.ที่ปรึกษาร่วม : บัณฑิต ชัยศิลบุญ, 116หน้า.
ISBN 974-03-0473-7.

การศึกษาธรณีวิทยาปิโตรเลียมของแอ่งสงขลาในอ่าวไทย โดยศึกษาจากข้อมูลหลุมเจาะ และธรณีฟิสิกส์ สามารถอธิบายธรณีวิทยาใต้ผิวดิน, ธรณีโครงสร้าง, วิวัฒนาการของการเกิดแอ่ง พร้อมทั้งประเมินศักยภาพปิโตรเลียมเบื้องต้น

ผลการศึกษาพบว่า แอ่งสงขลาเกิดในยุคเทอร์เชียรีมีลักษณะเป็นฮาร์พกราเบน วางตัวในแนวเหนือ-ใต้ มีรอยเลื่อนปกติเกิดขึ้นทางด้านตะวันตก ซึ่งเป็นปัจจัยควบคุมพัฒนาการของแอ่งรวมถึงการสะสมตัวของตะกอนภายในแอ่ง ตะกอนส่วนใหญ่สะสมตัวแบบเนินตะกอนรูปพัด แบบทะเลสาบและแบบแม่น้ำพา ซึ่งได้รับอิทธิพลของทะเลเกี่ยวข้องเป็นครั้งคราว ความหนาสูงสุดของตะกอนประมาณ 3,500 เมตร ในที่นี้ได้จัดแบ่งลำดับชั้นหินของตะกอนยุคเทอร์เชียรีออกเป็น 5 หมวดหินเรียงจากล่างขึ้นบนดังนี้ หมวดหิน SK-1, SK-2, SK-3, SK-4, และ SK-5 นอกจากนี้ ผลการวิเคราะห์ธรณีเคมีพบว่าหินต้นกำเนิดปิโตรเลียมซึ่งเป็นหินโคลนหรือหินดินดานสีดำซึ่งมีปริมาณอินทรีย์วัตถุสูง ส่วนมากสะสมตัวอยู่ในสภาวะแวดล้อมแบบทะเลสาบ โดยประเภทของอินทรีย์วัตถุประกอบด้วย ชนิดที่1, 2, และ 3 ซึ่งมีศักยภาพสูงที่จะให้น้ำมันและก๊าซ หินต้นกำเนิดปิโตรเลียมอยู่ในระดับความลึกมากกว่า 2,000 เมตร สามารถเริ่มให้ปิโตรเลียมออกมา ส่วนหินกักเก็บปิโตรเลียมเป็นหินทรายอยู่ในหมวดหิน SK-1, SK-2 และ SK-3 ซึ่งมีชั้นหินโคลนหรือหินดินดานแทรกสลับซึ่งทำหน้าที่เป็นหินปิดกั้นในเวลาเดียวกันปิโตรเลียมสะสมในภายในโครงสร้างกักเก็บของแอ่ง ดังนั้นแอ่งสงขลาจึงเป็นแอ่งที่น่าจะมีศักยภาพในการให้กำเนิดปิโตรเลียม

ภาควิชา	ธรณีวิทยา	ลายมือชื่อนิสิต..
สาขาวิชา	ธรณีวิทยา	ลายมือชื่ออาจารย์ที่ปรึกษา.......................................
ปีการศึกษา	2544	ลายมือชื่ออาจารย์ที่ปรึกษาร่วม................................

4172465223 : MAJOR GEOLOGY
KEY WORD: PETROLEUM GEOLOGY / SONGKHLA BASIN / GULF OF THAILAND

SONCHAWAN AC-KAGOSOL : PETROLEUM GEOLOGY OF THE SONGKHLA BASIN IN THE GULF OF THAILAND. THESIS ADVISOR : ASSISTANT PROFESSOR PONGSAK PHONGPRAYOON, THESIS CO-ADVISOR : BUNDIT CHAISILBOON, 116 pp.
ISBN 974-03-0473-7.

The study of petroleum geology of the Songkhla basin by used of well and geophysical data explains subsurface geology, geological structure, and basin evolution with additionally preliminary petroleum potential assessment.

The Songkhla basin formed an elongate N-S trending and is a half-graben bounded to the west by the major extensional fault controlling the basin development and sedimentation. The Tertiary sedimentary sequence in the Songkhla basin is almost entirely non-marine sediments of alluvial fan dominated in the west while lacustrine and fluvial deposited from central to the east with occasionally marine transgression. The maximum thickness of accumulation is approximately 3,500 meters. The proposed stratigraphy is subdivided into 5 formation, namely: SK-1, SK-2, SK-3, SK-4, and SK-5 Formation in ascending order. From geochemical study, most of source are dark organic rich lacustrine claystone or shale. The source rock materials contain organic Type I/II/III kerogens that have a high potential for oil and gas generation. The source rock below 2,000 meters are mature enough to generate hydrocarbon. The sandstone reservoir are in the SK-1, SK-2 and SK-3 Formation and interbeded claystone or shale act as seal at the same time. Most hydrocarbon accumulations are in structural traps. As the results, the Songkhla basin is proven to possess some potential for oil generation.

Department Geology Student's

Field of study Geology Advisor's

Academic year 2001 Co-advisor's

ACKNOWLEDGEMENTS

The author is indebted to Assistant Professor Pongsak Phongprayoon, thesis advisor and Mr. Bundit Chaisilboon, thesis co-advisor for their guidance, encouragement, valuable discussion and reading of manuscript.

Grateful acknowledgements are extended to Department of Mineral Resources of Thailand (DMR), Mineral Fuels Division, Energy Resource Information and Data Unit for the permission to study the confidential data. Deep appreciation is given to Mrs. Jutamas Sangsuwan, Mrs. Malai Pitchayakul and Ms. Kanitta Danukul for kindness in providing the data.

Special acknowledgements are due to Mr. Nares Sattayarak and his staffs for their assistance and valuable suggestions. Deep appreciation is given to Mr. Rungsan Charusirisawad and Mr. Tananchai Mahattanachai for teaching the Charisma and CPS-3 programs. Besides that, thanks are also extended to Schlumberger's staffs who give the useful guidance for application of programs. Special thanks are given to Dr. Khajohn Bhasavanija for comments and reading of manuscript.

The author would like to express her appreciation to Graduate School, Department of Geology, Chulalongkorn University continuously providing numerous facilities and financial support.

Moreover, special thank is given to Mr. Natthawoot Putprasit and Miss Pannipa Tain who help in the preparation this manuscript during all phases of the work.

Finally, this thesis can not be completed without the help and encouragement of her family and friends who patiently provided both moral and physical support.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER I

INTRODUCTION

General

Sedimentary basins are economically important due to the accumulation of mineral and energy resources especially oil shale, coal, natural gas and oil. Sedimentary basins are different according to their geological ages. Tertiary basins are the main target of petroleum exploration and production in Thailand. There are approximately 70 Tertiary basins in various parts of Thailand both onshore and offshore; the northern, the central plain, the southern, the Andaman Sea, and the Gulf of Thailand (Chaodamrong et al., 1983). Most of them consist of non-marine sediments except Mergui basin in the Andaman Sea which is marine sediments deposited widely over the basin. Moreover, there are about 30 basins that have or possibly possess petroleum potential (Figure 1.1) (Chinbunchorn et al., 1989). Among them, 9 basins have been proved to generate significant quantities of petroleum, namely Fang, Phitsanulok, Petchabun, Suphan Buri, Kampheangsan, Chumphon, Songkhla, Pattani and Malay basins (Polachan et al., 1989).

The offshore petroleum exploration in the Gulf of Thailand has begun since 1968 (Polahan, 1986). More than 1,800 wells have been drilled all over the Gulf of Thailand, and most of them are located in Pattani and Malay basins. The Gulf of Thailand are separated by N-S trending Ko Kra Ridge into two main parts; the Western Graben and Basinal Area (Sattayarak, 1992). The Western Graben consists of 10 basins namely Sakhon, Paknam, Hua Hin, North Western, Western, Prachuap, Kra, Chumphon, Nakhon and Songkhla while Basinal Area is composed of only two enormous basins, Pattani trough to the north and Malay basin to the south. Most hydrocarbons in the Gulf of Thailand have been discovered in the Tertiary successions, except Nang Nuan oil field in Chumphon basin where they have been discovered in Pre-Tertiary, Permian limestone.

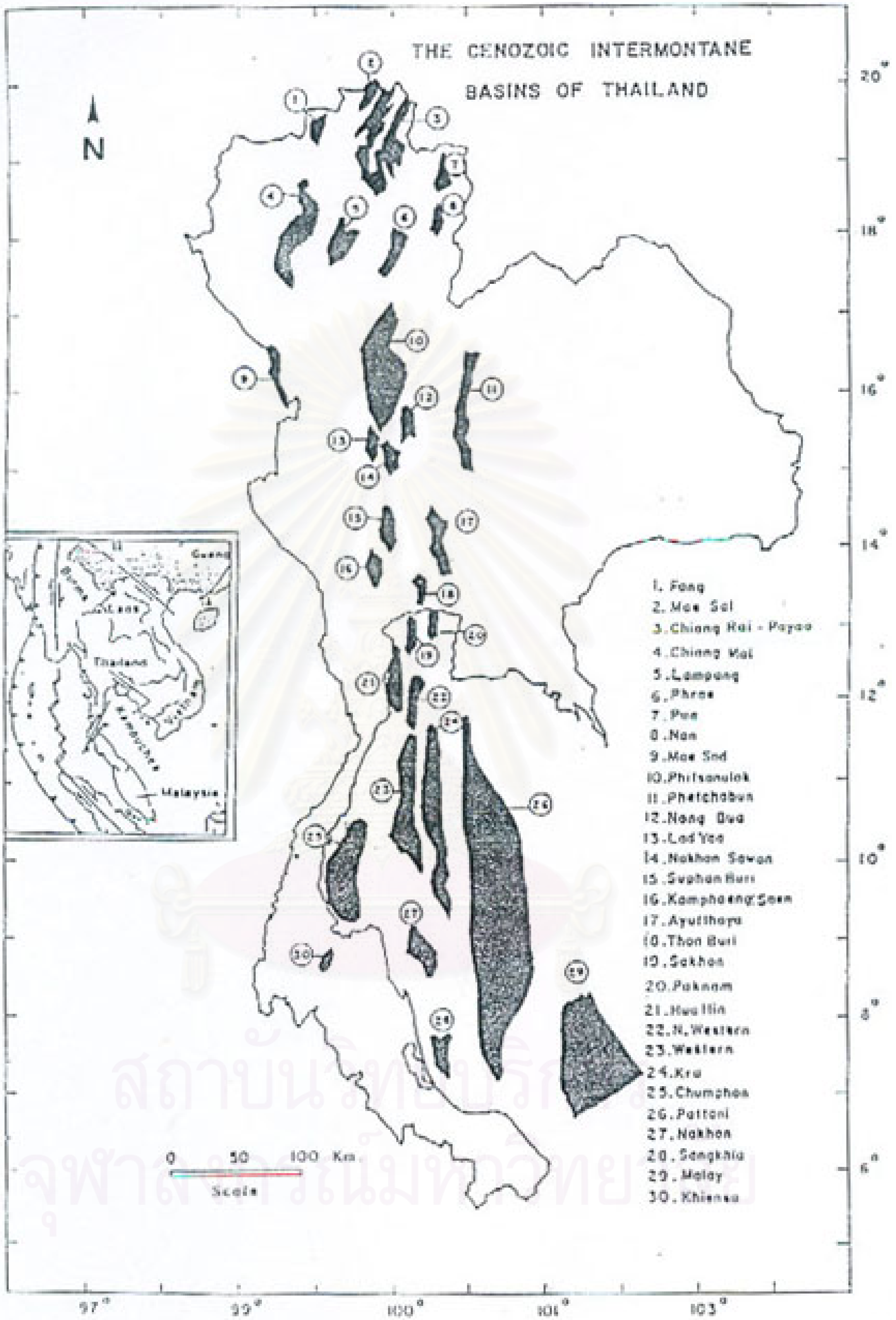


Figure 1.1 Significant Cenozoic basins in Thailand (Chinbunchorn et al., 1989).

The petroleum potential and development in the Gulf of Thailand is quite interesting. In 1999 petroleum produced in the Gulf of Thailand are approximately 1,709 MMscfd of gas, 48,982 bpd of condensate and 8,279 bpd of crude oil (DMR, 1999).

Study Area

The Songkhla basin is situated in the southwestern part of the Gulf of Thailand and parallel to the coastline of Songkhla province. The basin lies approximately between latitudes 7° 10’ N to 7° 48’ N and longitudes 100° 30’ E to 100° 50’ E. The study area covers about 1,800 square kilometers. It was previously the B11/27 concession and currently the concession belongs to Thai Government (Figure 1.2). The basin is elongated, approximately 70 kilometers long, and varies in width between 20 and 40 kilometers. The depth of sea level to seabed is between 18.5 and 30 meters.

There are 5 exploratory wells, namely Songkhla-1, Bua Ban-1, Songkhla South-1, Songkhla Southwest-1 and Benjarong-1 (Figure1.3). All of them were drilled by Premier Oil Pacific Limited since 1989 until 1996 and two of them, Songkhla-1 and Bua Ban-1 wells, are oil discoveries.

Data Source

The data of study area has been kindly provided by the Mineral Fuels Division, Department of Mineral Resources, Thailand. The data consists of seismic, final well reports, biostratigraphy reports, geochemical evaluation reports and electrical wireline logs. Figure1.3 is a map showing location of 33 reflection seismic data, approximately 1,500 line-kilometers. The electric wireline logs comprise caliper, sonic, gamma ray and resistivity logs, and mud logs and composite logs are also available.

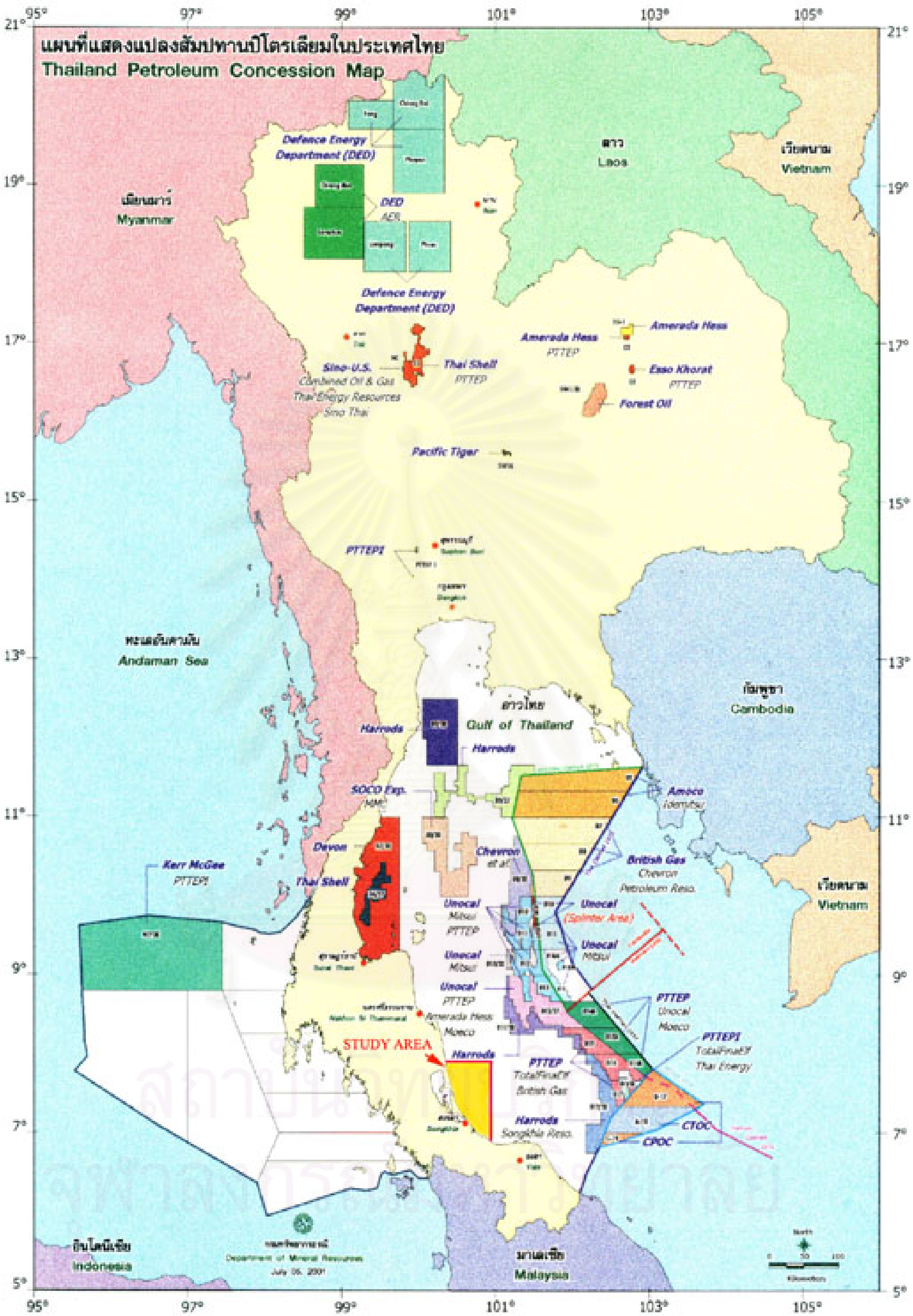


Figure 1.2 Location map of the study area.

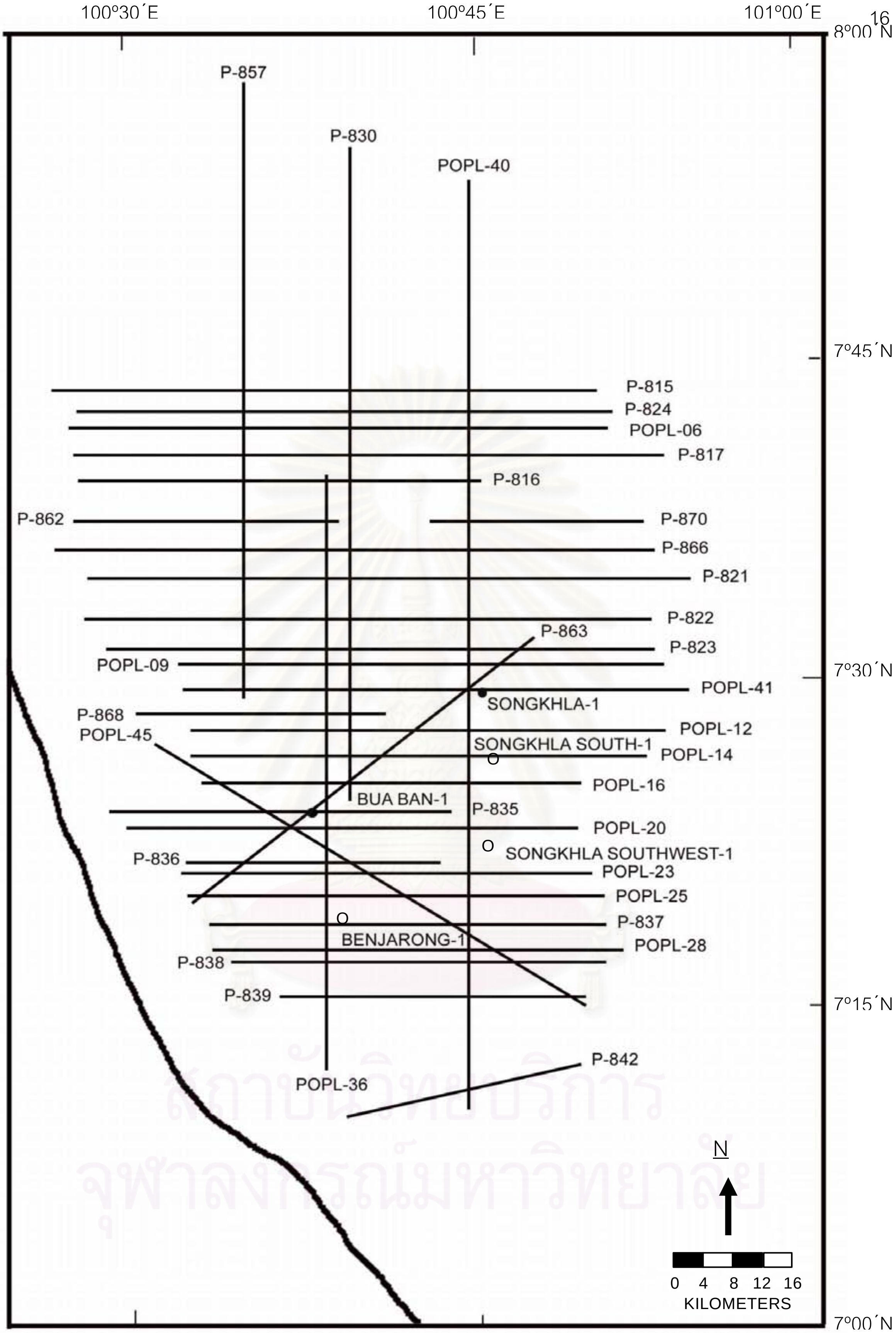


Figure 1.3 Map showing seismic line and well locations.

Objectives of the Study

Petroleum potential of Basinal Area is clear to oil explorationists but in the Western Graben, some basins are doubtful and under investigation of its petroleum potential. The Songkhla basin which is in the Western Graben is selected to study and to improve the knowledge of petroleum potential in this area. Therefore, the purpose of this research is to study on petroleum geology and preliminary assessment of petroleum potential of the Songkhla basin. The geological setting, geological structure, stratigraphy and geological evolution of the basin are analyzed to support these objectives.

Methodology

Firstly, all information on regional geology of the Gulf of Thailand are reviewed to serve as a background of the present study. Then, the geological setting of the Songkhla basin and other basins in the Gulf of Thailand from previous studies are also reviewed in order to give basic understanding about the geological history, tectonic evolution and general stratigraphy.

Secondly, the data is collected and prepared to serve the objective of the study. The electric wireline logs from five drilled holes are studied together with mud logs and biostratigraphic data. The results of this study are compared and correlated to define and establish stratigraphy of the basin.

Thirdly, seismic data is selected and analyzed to search for regional boundaries of depositional sequence and important geological structures. Seismic markers are identified by biostratigraphic data of the Songkhla-1, Bua Ban-1 and Benjarong-1 well. Seismic interpretation is undertaken by using 33 sections of 2D seismic covering the study area. Then, the two-way time (TWT) structural contour maps of four horizons were drawn. The results of these studies are used to establish tectonic evolution of the Songkhla basin.

Fourthly, the results of source rock studied by Premier Oil Pacific Limited including TOC, rock eval pyrolysis, and vitrinite reflectance are reinterpreted. In addition, Lopatin's Method is used to determine maturation and generation of hydrocarbon in the basin.

Finally, all results of the study are analyzed to conclude petroleum geology and preliminary assessment of petroleum potential of the Songkhla basin.

Previous Works

The Gulf of Thailand has been explored for petroleum since 1968. At present, there are a number of geophysical surveys and over 1,800 wells have been executed. However, published papers on geology of the Gulf of Thailand are very limited.

The earliest geological study of the Gulf of Thailand was conducted by Emery and Niino in 1963, including subsea topography, bottom sediments and sediment dispersal pattern of the Gulf.

Woolland and Haw (1976) described in more details on the Tertiary stratigraphy and sedimentary deposition of the Gulf of Thailand, by using primary results of three wells drilled by BP Petroleum Development of Thailand Limited.

Achalabhuti and Udom-Ugsorn (1978) wrote the paper concerning the petroleum exploration in the Gulf of Thailand. In 1981, Achalabhuti also delivered a paper on the geology and hydrocarbon potential in the Gulf of Thailand, particularly, the gas and condensate fields of the southern Pattani trough and the northern of Malay basin of Union Oil of Thailand and Texas Pacific Co., Ltd. respectively.

Bunopas and Vella (1983) pointed out that the opening of the Gulf of Thailand indicated a rift tectonic regime during the Cenozoic Era. The evidences were shown from geological and geophysical data.

Lekuthai et al. (1984) studied the petroleum potential of Chumphon basin by using the 9-466/IX well data.

Lian and Bradley (1986) presented the stratigraphy of the Pattani basin in more details and established four stratigraphic units. They also detailed the petroleum geology of the basin.

Polahan (1986) reviewed the petroleum activities, geology of Tertiary basins, and oil potential in the Gulf of Thailand.

Burri (1989) explained the hydrocarbon potential of Tertiary intermontane basins in Thailand, including important parameters such as geological setting, structural style, sedimentary environments, burial history and maturation.

Chinbunchorn et al. (1989) discussed the geology and petroleum potential of Tertiary intermontane basins in Thailand. Four basins were emphasized in the study, namely Phitsanulok, Fang, Chumphon and Pattani. The results of these studies summarized the characteristics of each basin and could be applied to other basins.

Polachan and Sattayarak (1989) reviewed the previous tectonic models and presented the new idea on the formation and development of basins based on structural geometry, paleomagnatic data and recent earthquake analyses.

Polachan et al. (1991) summarized the development and stratigraphy of the Cenozoic basins in Thailand from studying of four major basins, Mergui, Pattani, Malay and Phitsanulok basins. Furthermore, they reviewed the tectonic models and evolution of the Cenozoic basins.

Prадidtan (1989) showed that characteristics of the Tertiary lacustrine deposit, especially the lacustrine deposit of the Chumphon and the Fang basins. Furthermore, he suggested that there were influences of the lacustrine conditions on these basins and other basins in the Gulf of Thailand.

Bhuthaung (1990) described the subsurface geology of Hua Hin basin in the Upper part of the Gulf of Thailand. Moreover, she studied petroleum geology and assessed petroleum potential of the basin.

Noibanchong (1990) proposed the facies model of the north Malay basin. A model was established from electrical wireline logs and lithological description.

Pradidtan et al. (1990) defined Tertiary stratigraphy of the Gulf of Thailand and established four stratigraphic units of the Tertiary basins. The study was analyzed from the available and releasable data, especially wireline logs, seismic sections and palynological reports.

Bottomley (1991) studied the Oligocene lacustrine sediments of the Songkhla basin. There were four wells which were drilled by Premier Oil Pacific Limited, two of them are suspended oil discoveries at Songkhla-1 and Bua Ban-1. A depositional model was analyzed by core data calibrated with wireline logs and integrated with seismic data, tectonic setting and petroleum geochemistry.

Pradidtan and Dook (1992) summarized the stratigraphy, structure and petroleum geology of the Tertiary basins in the northern part of the Gulf of Thailand.

Williamson (1992) explained the petroleum geology of Funan Field which is the first gas production from the eastern Pattani basin. This included historical exploration, geology, hydrocarbon composition, field structure and 3D seismic techniques used for planning of platform and well location in the complex geological setting.

Lawwongngam and Philp (1993) examined samples of crude oil and source rocks from six Tertiary basins in the central plain and the Gulf of Thailand. The results of geochemical analysis indicated that organic sources were from algal and higher plant materials deposited in lacustrine environment. The different maturity of each basin was due to geothermal gradient and/or subsidence rate of the basin.

Pigott and Sattayarak (1993) analyzed sedimentary basin evolution by assessment of tectonic subsidence from seven boreholes representing five basins of the northern Gulf of Thailand.

Vacher (1995) researched on petroleum geology in the northern part of the Western basin in the Gulf of Thailand. He divided Cenozoic stratigraphy into four units and used Lopatin's method to assess source rock maturation and petroleum potential.

Chaisilboon (1997) researched on the Basin Modeling of the Hua Hin South Basin of the concession block B3/32 in the Gulf of Thailand. The study also included geologic setting, tectonic framework, stratigraphy and petroleum geochemistry of the basin. The study is used to predict the maturity of potential source rocks and petroleum potential of the basin.

Prадidtan et al. (1999) described the stratigraphy and petroleum systems of the Tertiary petroliferous basins, particularly to the Phitsanulok, Pattani and northern Malay basins.

This chapter gives basic information such as general background, objective, methodology and literature reviews for understanding about the research. More details will be presented in the next chapter.

CHAPTER II

GENERAL GEOLOGY OF THE GULF OF THAILAND

Tectonic Setting of the Gulf of Thailand

In South East Asia, Tertiary tectonics have largely been caused by the collision of the Indian and Eurasian plates. The Indian plate separated from Africa during Late Cretaceous time and through northward movement, eventually collided with the Eurasian plate in the Eocene. With continued penetration to the north, South East Asia was slowly pushed out to the southeast and progressively rotated clockwise, with the angle of subduction changing from perpendicular to oblique (Tapponnier et al., 1986). This led to movements on the strike-slip faults associated with the development of transtensional basins in this region (Polachan and Sattayarak, 1989, and Polachan et al.,1991) as shown in Figure 2.1.

The Cenozoic basins in the Gulf of Thailand are related to N-S trending extensional fault that associated the movement on the NW-SE and NNE-SSW trending strike-slip faults which have been active since Oligocene time (Polachan and Sattayarak, 1989). The NW-SE trending, Three Pagodas fault, is principal right lateral strike-slip fault whereas NNE-SSW trending, Ranong and Klong Marui Fault, is conjugate left lateral strike-slip fault which is terminated by this right lateral strike-slip (Figure 2.2).

As the result, Tertiary basins in the Gulf of Thailand are classified as intracratonic rift basins (Woolland and Haw, 1976, Achalabhuti, 1978, and Chinbunchorn et al., 1989) and as transtensional pull-apart basins (Polachan and Sattayarak, 1989). The basins are mainly N-S trending grabens and half-grabens with narrow and elongated shape. Ko Kra Ridge separates the basins in the Gulf of Thailand into two main parts such as Western Graben and Basinal Area.

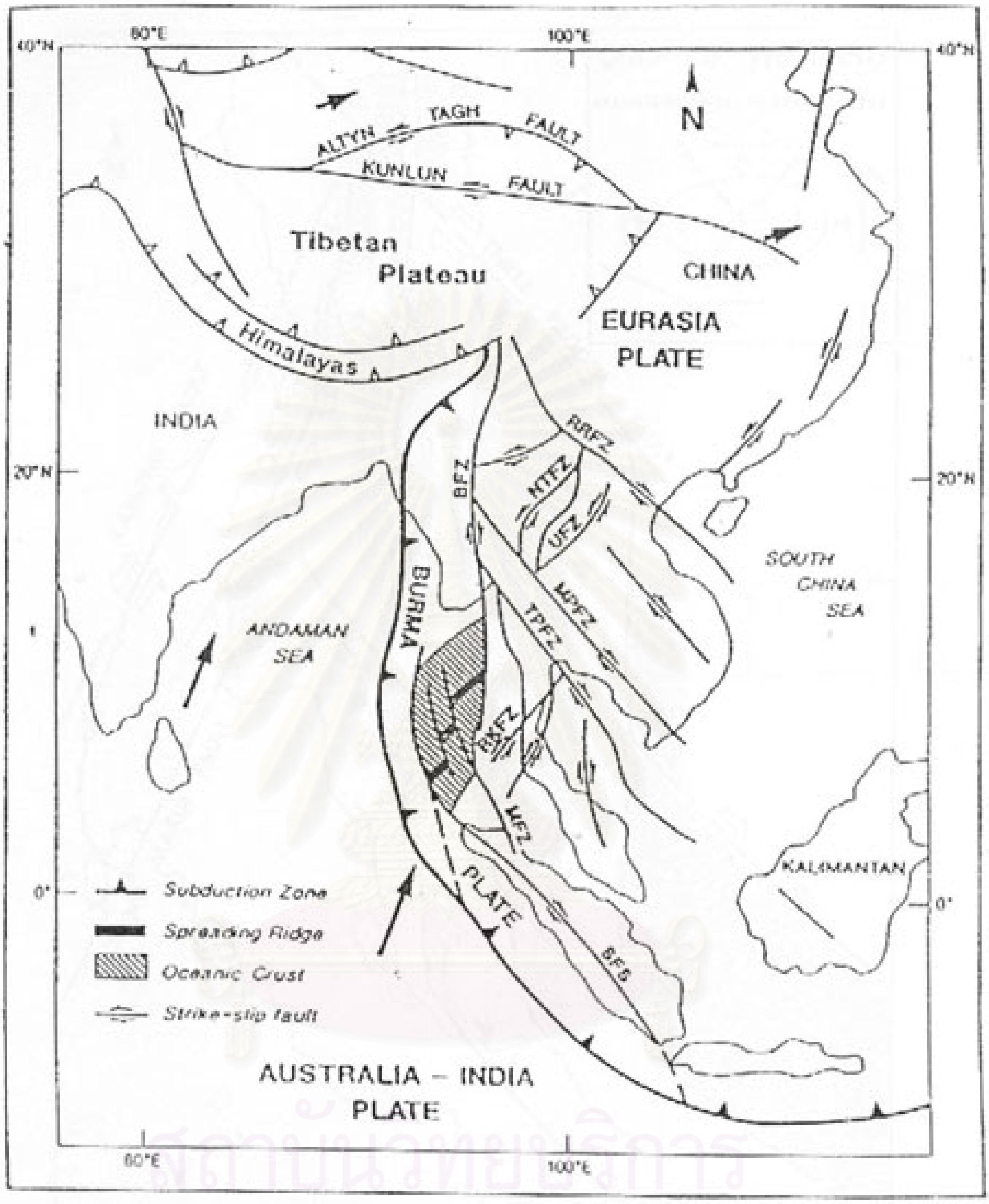


Figure 2.1 Regional tectonic map showing patterns of major faults and their relative movements. SFS (Sumatra Fault System); MFZ (Mergui Fault Zone); SFZ (Sagaing Fault Zone); RKFZ (Ranong and Klong Marui Fault Zone); TPFZ (Three Pagodas Fault Zone); MPFZ (Mae Ping Fault Zone); UFZ (Uttraradit Fault Zone); NTFZ (Northern Thailand Fault Zone) and RRFZ (Red River Fault Zone) (Packham, 1993).

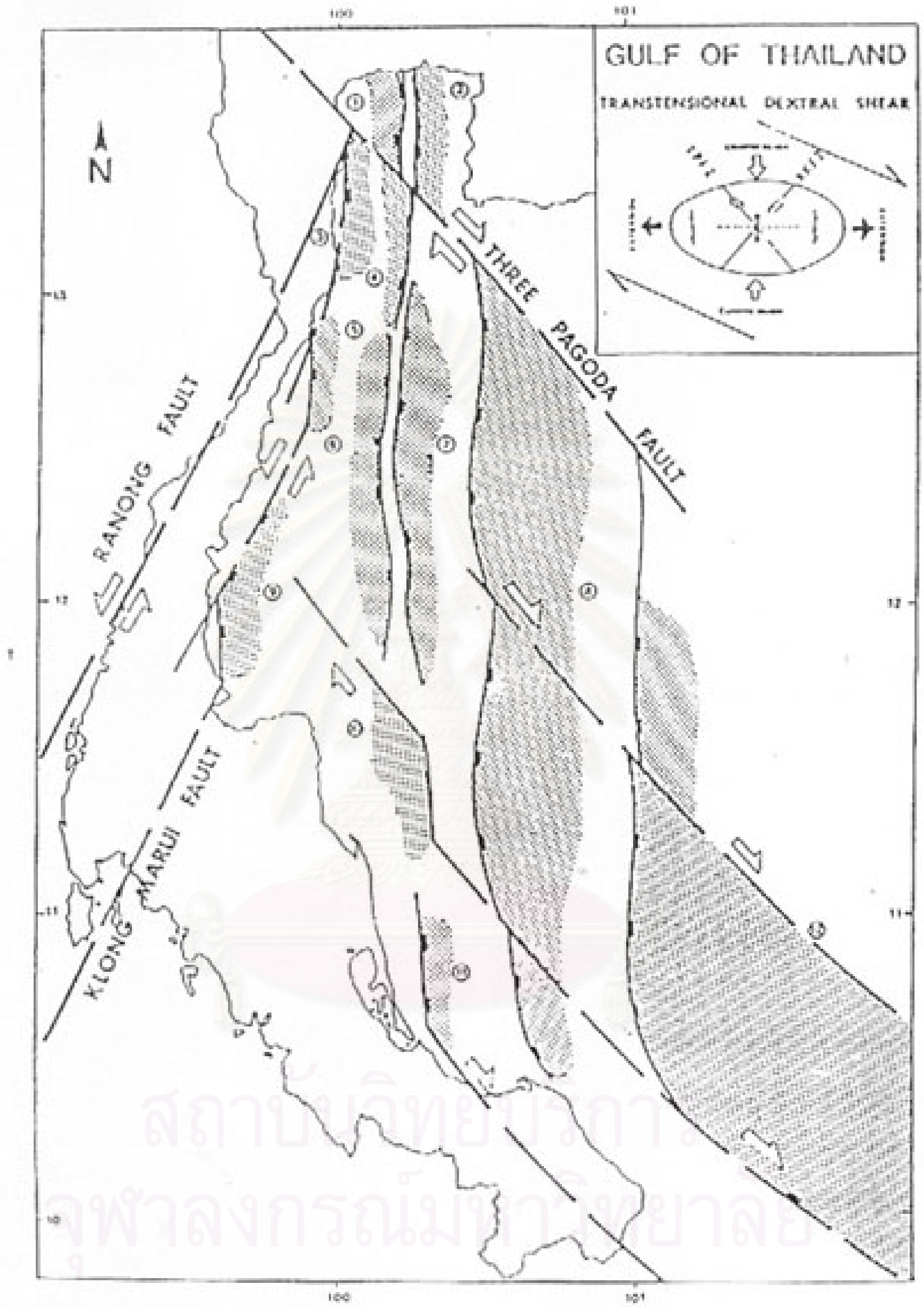


Figure 2.2 Structural map of the Gulf of Thailand, showing relationship between conjugate strike-slip faults and the development of N-S trending pull apart basins. 1.Sakhon, 2.Paknam, 3.Hua Hin, 4.N.Western, 5.Prachuap, 6.Western, 7.Kra, 8.Pattani, 9.Chumporn, 10.Nakhorn, 11.Songkhla and 12.Malay (Polachan and Sattayarak, 1989).

Basin evolution of the Tertiary basins in Gulf of Thailand

Basin evolution of the Cenozoic basins in the Gulf of Thailand was described in term of four periods by Polachan et al. (1991) as follows:

Firstly, Oligocene (or possibly older) to Early Miocene represented the greatest tectonic activity (Paul and Lian, 1975) and main phase of strike-slip faults. The E-W rifting was extensively, rapidly extension, high rates of sedimentation and uplift of the surrounding mountain ranges. The oldest sediments are Late Oligocene. Alluvial and fluvial sediments were mainly deposited with occasionally swamp and ephemeral lake.

Secondly, Early Miocene to Middle Miocene, there were widespread of lacustrine depositions. This possibly associated with increased structural activity which culminated in a widespread depression. The increasing fluvial condition was related to climatic changes. The were influences of brackish and marine conditions in the Pattani and Malay basins.

Thirdly, Middle Miocene to late Middle Miocene, the tectonic and/or climate changed during the Middle Miocene were indicated by disappearing of perennial lake. The alluvial and fluvial influenced throughout of the Gulf of Thailand. The extension decreased dramatically and the cessation of listric fault occurred near Middle to late Middle Miocene boundary. The unconformity appears to represent an uplift and the end of main extensional phase.

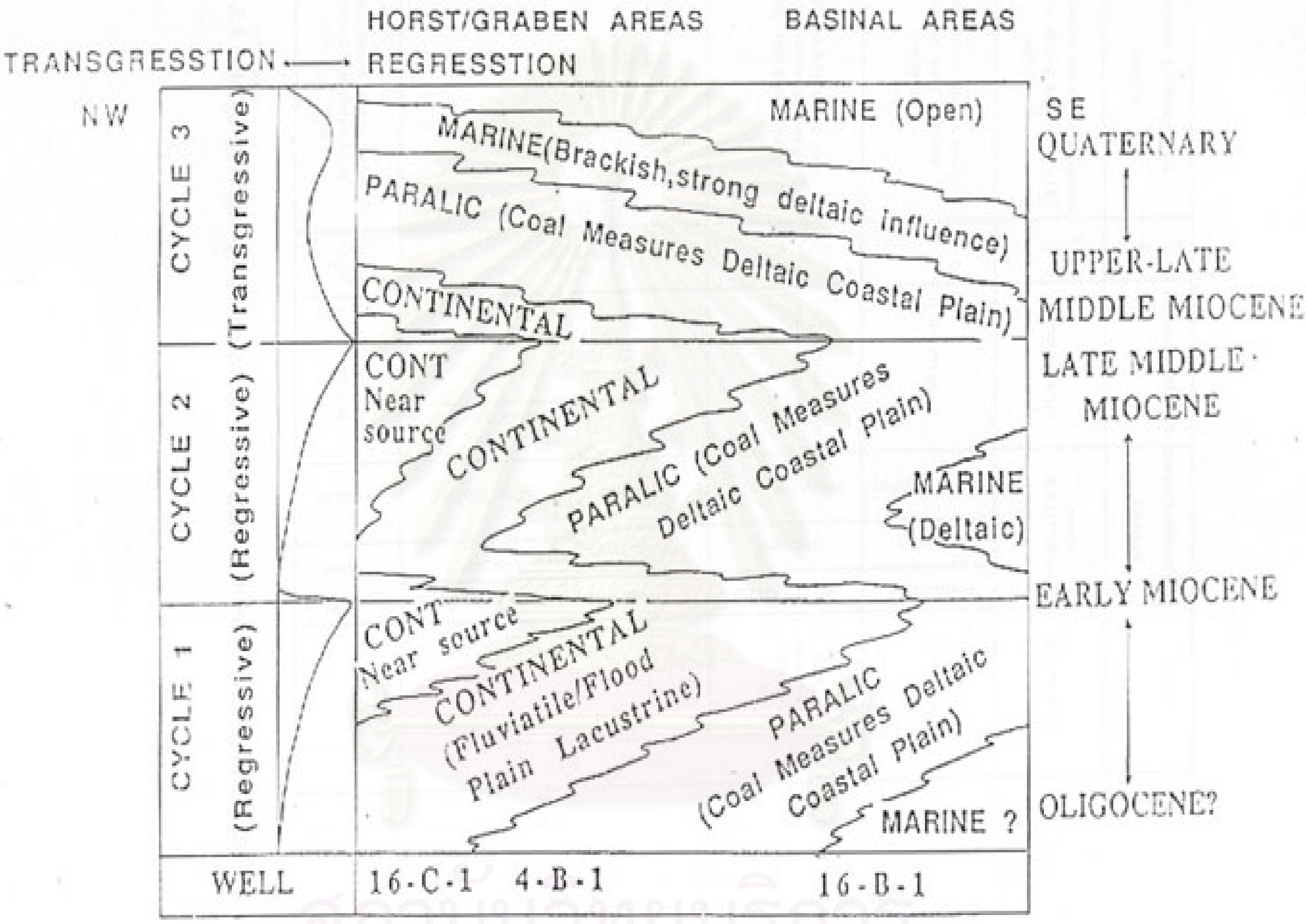
Lastly, Late Miocene to Recent, there were marine transgression and fine grained sediments predominantly deposited in paralic and paludal swamp.

General stratigraphy of the Tertiary basins in the Gulf of Thailand

The Gulf of Thailand is divided into two parts, Western Graben and Basinal Area. The basements of the Cenozoic basins in the Gulf of Thailand comprise of Permian carbonates, Mesozoic carbonates, Paleozoic metaclastics, and Cretaceous granite. Many authors have established the general stratigraphy of the Cenozoic basins in the Gulf of Thailand. Tertiary sequences, unconformably overlying the Pre-Tertiary basement, are almost entirely non-marine deposits. Woolland and Haw (1976) subdivided the stratigraphy of the Cenozoic basins in the Gulf of Thailand, particularly focused on the Pattani trough and the Malay basin, into three major sedimentary cycles by patterns of marine transgressive and regressive sequences (Figure 2.3). Cycle I, resting unconformably on Pre-Tertiary basement, is the lowest sequence of Oligocene – Early Miocene age. This cycle is regressive sequence that represented by continental deposits especially fluviatile, flood plain and lacustrine deposits. These consist of red variegated shales, siltstones, and sandstones with occasional gray shales. Cycle II, on the top of Cycle I, is a regressive sequence of Early Miocene – late Middle Miocene. Fluviatile, flood plain, lacustrine and deltaic coastal progradation into a brackish marine environment represented in the cycle. The end of Cycle II appears widespread regional unconformity of the late Middle Miocene. Cycle III, overlying the Cycle II, is transgressive sequence of upper late Middle Miocene – Recent. This sequence, paralic and marine deposits, consists of clay, silts and sands with lignite beds scattered throughout the section.

Due to the fact that, the Tertiary sediments in the Gulf of Thailand are mainly non-marine and marginal marine deposits, so the foraminifera in these sediments are very limited. Thus the palynology is used in biostratigraphy for both dating and correlations and it also served to establish stratigraphic columns of the Cenozoic basins in the Gulf of Thailand. Achalabhuti (1981) reported on the results of micropaleontological and palynological analyses of the Gulf of Thailand. Five palynolgical zones were identified from drilled wells that penetrated sedimentary sequences ranging in age from Oligocene to Holocene. Generalized stratigraphic section of the Gulf of Thailand from his study was shown in Figure 2.4.

Figure 2.3 Three major Cycles of the Tertiary sedimentation in the Gulf of Thailand (Woolland and Haw, 1976).



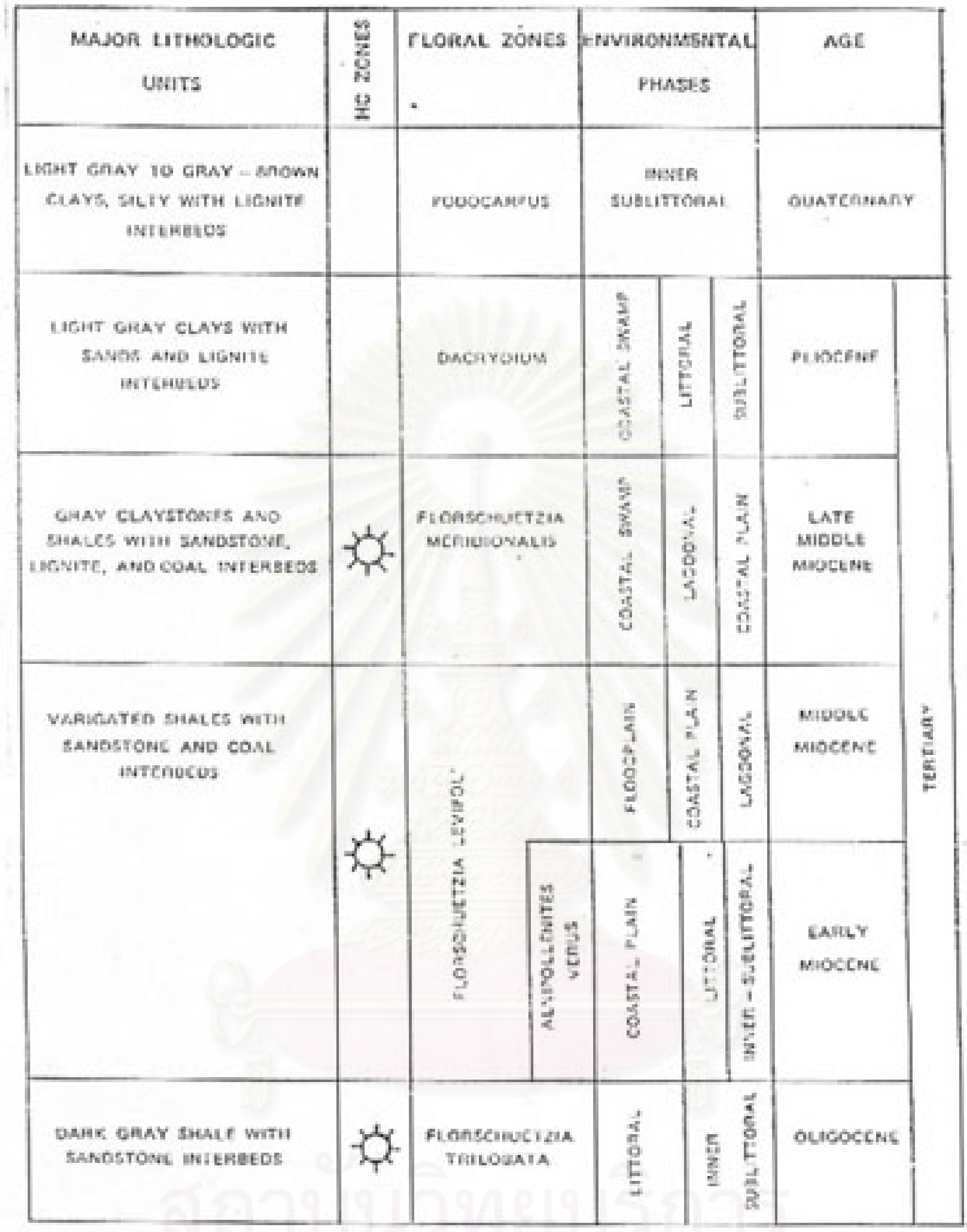


Figure 2.4 The general stratigraphic section of the Gulf of Thailand (Achalabhuti, 1981).

Polachan et al. (1991) divided the Cenozoic stratigraphy in the Gulf of Thailand into four units with addition of palynomorphs as shown in Figure 2.5. The lowermost unit, Unit I, consists of brown-gray shale and fine-coarse grained sandstone which deposited in alluvial and floodplain. Unit II contains organic rich shale with fine to medium grained sandstone that deposited in lacustrine environment. Unit III is composes of varicolored shale, claystone and sandstone with some limestone and lignite that deposited in floodplain. The uppermost unit, Unit IV, overlies on the unconformity. It consists of clay, shale and sandstone deposited in floodplain with more mangrove and marine in the upper part.

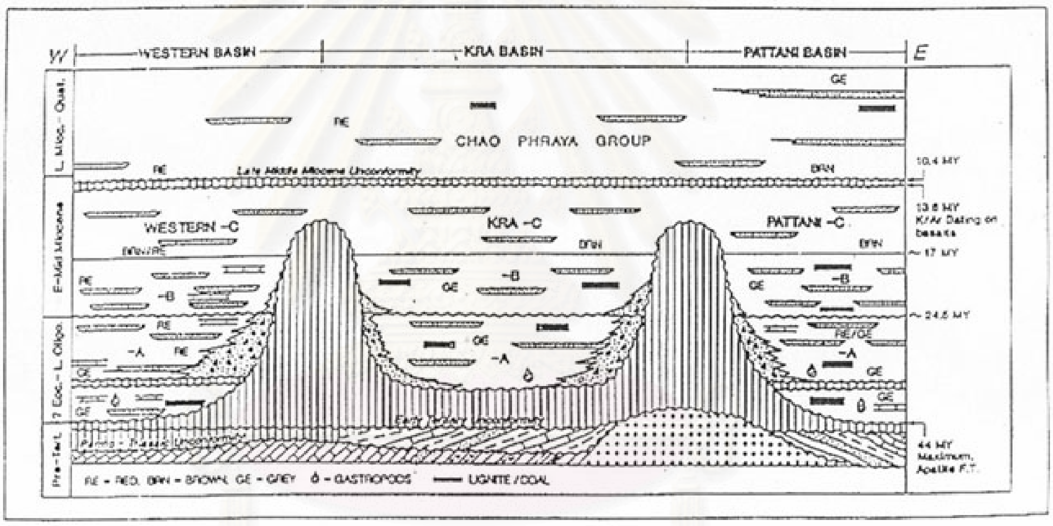
Chinbunchorn et al. (1989) presented the new style of the stratigraphic sequences of Cenozoic basins in the Gulf of Thailand by subdividing into 2 sequences: syn-rift and post-rift sequences. Syn-rift sequence deposited during active rifting period from Oligocene to Middle Miocene age. It is subdivided into 3 units namely: lower, middle and upper units. The lower unit, Late Oligocene-Early Miocene, consists of red brown claystone with minor coarse to fine lithic sandstone of fluvial, alluvial plain and lacustrine deposits. The middle unit, Early Miocene - Middle Miocene, contains thick lacustrine sediments, high organic claystone or shale with minor thin bedded sandstone. The upper unit is composed of fluvial deposits. The other sequence, Late Miocene to Quaternary, is post-rift sequence which unconformably overlies the syn-rift sequence. It consists of high energy, fluviatile coarse sand and gravel with some organic clay and thin coal.

Pradidtan and Dook (1992) also presented the Tertiary sequence of the northern part of the Gulf of Thailand in term of syn-rift and post-rift sequences by used of unconformity. Overlying the unconformity is Chao Phraya Group or post-rift sequence. The second group beneath the unconformity is syn-rift sequence that is divided into three units: Upper, Middle, and Lower unit which is named after the basin in which it occurs as illustrated in Figure 2.6.

AGE	UNIT	THICKNESS (UP TO)	LITHOLOGY		ENVIRONMENT	FOSSILS
			WESTERN GRABEN AREA	PATTANI & MALAY BASINS		
LATE MIOCENE-RECENT	IV	1,700 m.	SHALE/CLAYSTONE/SANDSTONES Clays / Shales, brown-grey, varicolored, silty Sandstones, fine-very coarse grained, occasionally gravel.	SHALE/CALYSTONE/SANDSTONES Clays / Shales, grey, silty Sand(stones), grey fine-very coarse grained, channel characteristics.	Flood Plain with more Mangrove Swamp and Marine in upper part	Dacrydium Podocarpus Florschuetzia meridionalis Stenochlaena lauriforia
MIDDLE MIOCENE - LATE MID-MIOCENE	III	1,200 m.	SHALES / CLAYSTONES / SANDSTONES Shales / Claystones, varicolored, redbrown, silty, Sandy. Sandstones, brown, varicolored, fine-coarse grained, average thickness 5 m. restricted lateral extent. Limestone streaks & lignite are occasionally present.		Flood Plain with Local Delta Plain	Florschuetzia meridionalis Spinizonocolpites echinatus
EARLY MIOCENE - MIDDLE MID-MIOCENE	II	800 m.	SHALES / SANDSTONES Shales / grey organic rich. Sandstones, brown-grey, very fine-medium grained, average thickness 4.5 m., significant lateral extent.		Lacustrine and Restricted Marine	Florschuetzia levipoli Echiperiporites estelae Pediastrum
LATE OLIGOCENE - EARLY MIOCENE	I	5,000 m.	SHALES / SANDSTONES Shales / brown-grey, varicolored. Sandstones, brown-grey, fine - coarse grained, fining upwards, channel characteristics.		Alluvial & Flood Plains with Ephemeral Lacustrine	Monoporites annulatus Magnastriatites howardi Picea, Pinus, Pediastrum
PRE-TERTIARY BASEMENT			MESOZOIC CLASTICS AND GRANITES, PALEOZOIC CLASTICS AND CARBONATES			

Figure 2.5 Stratigraphy of Cenozoic basins in the Gulf of Thailand (Modified from Polachan et al.,1991).

Figure 2.6 Generalized chronostratigraphic summary of the basins in the northern part of the Gulf of Thailand (Pradidtan and Dook, 1992).



Pradidtan et al. (1990) defined stratigraphic sequences of Tertiary basins in the Gulf of Thailand, based on lithology, seismic reflector characteristics, wireline log patterns and palynology of Western Grabens Area and Pattani and Malay Basins (Figure 2.7). Tertiary stratigraphy can be divided into two groups, above and below the regional unconformity. Chao Phraya Group, is above the regional unconformity, represented both the Western Grabens Area and the Main Basinal Area. This group consists of fluvial and floodplain sediments in the lower part and mainly mangrove swamp sediments in the upper part. The other group is below the unconformity. The Western Grabens Area is divided into three units while Main Basinal Area is divided into four units. In the Pattani and Malay basins, the oldest unit which is Late Oligocene or older, was probably deposited in lacustrine environment. The second unit, Oligocene age, is mainly fluvial and floodplain sediments. The third unit, Early Miocene age represents a widespread fluviolacustrine condition with some marine influences. The forth unit, late Early to Middle Miocene age, is generally red beds of subaerial deposition.

In 1997, Jardine presented the five main depositional sequences in the Pattani basin (Figure 2.8). There are two unconformities, the Mid-Tertiary Unconformity (MTU) and the Mid- Miocene Unconformity (MMU). Sequence 1 began with lacustrine and alluvial deposits in Oligocene. After that, in Sequence 2, the deposition increasingly changed to mostly fluvial and alluvial deposition in Early Miocene. In the early Middle Miocene, Sequence 3 deposited in transgressive fluvial and marginal marine environment. Then, overall regressive fluvial and alluvial deposited in the upper middle Miocene of Sequence 4 and Sequence 5 is predominantly transgressive marginal marine environment.

Highton et al. (1997) reviewed the stratigraphy and biostratigraphy of the Neogene in the Gulf of Thailand (Figure 2.9 and 2.10). The Tertiary sequences were largely deposited in non-marine and marginal marine environment. Lithologically the sediments are composed of the clastics with coal, mudrock and occasional freshwater limestones that deposited in lacustrine, fluvialtile, lagoonal and shallow marine environments. The oldest Tertiary rocks penetrated in the Gulf of Thailand to date are thought to be of Late Oligocene age, even though seismic data show that the older undrilled sediments would be presented in the deeper part of the area.

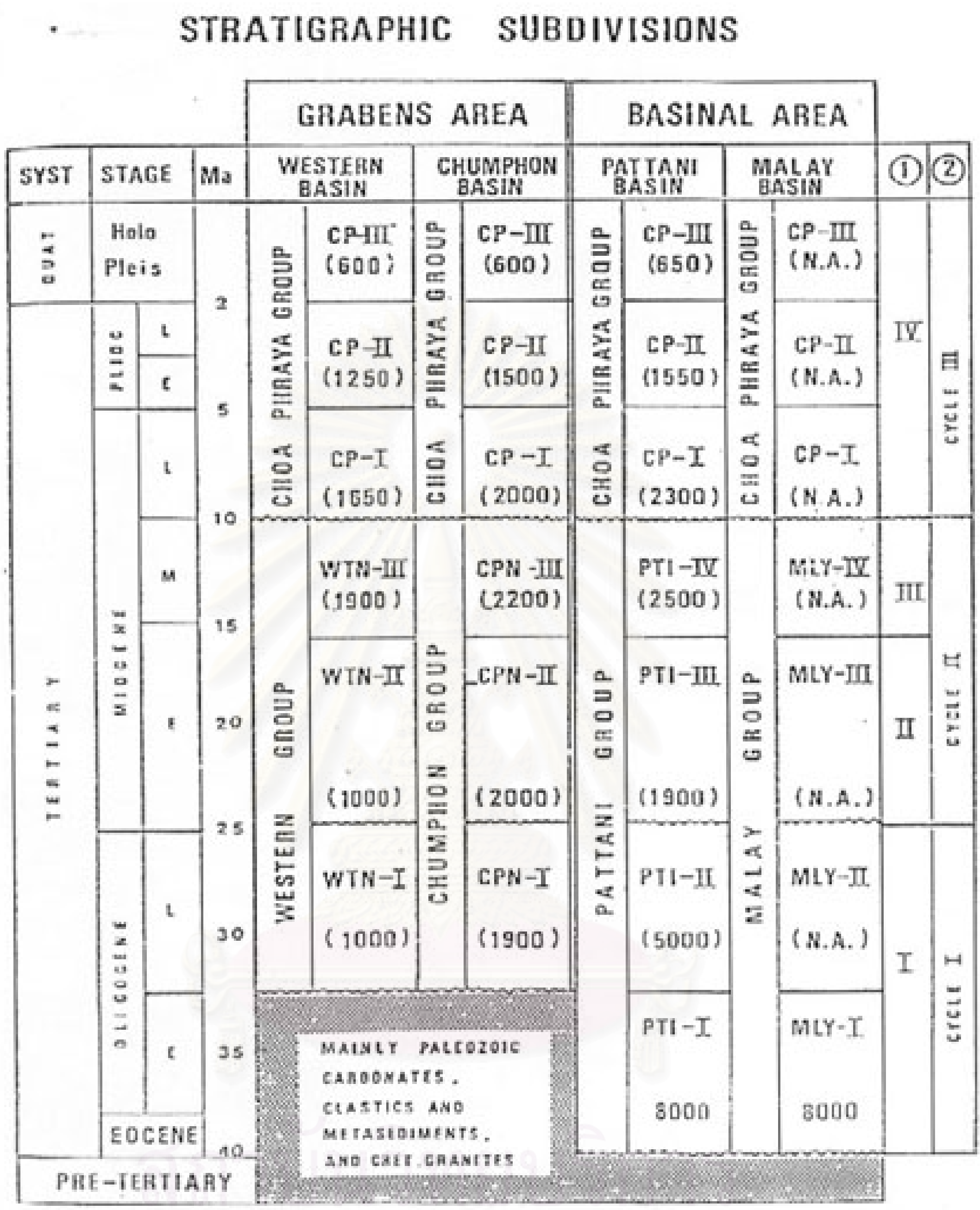


Figure 2.7 Stratigraphic of the Tertiary basins in the Gulf of Thailand, (1) Lain & Bradley (1986) and (2) Woolland and Haw (1976) (Pradidtan et al.,1990).

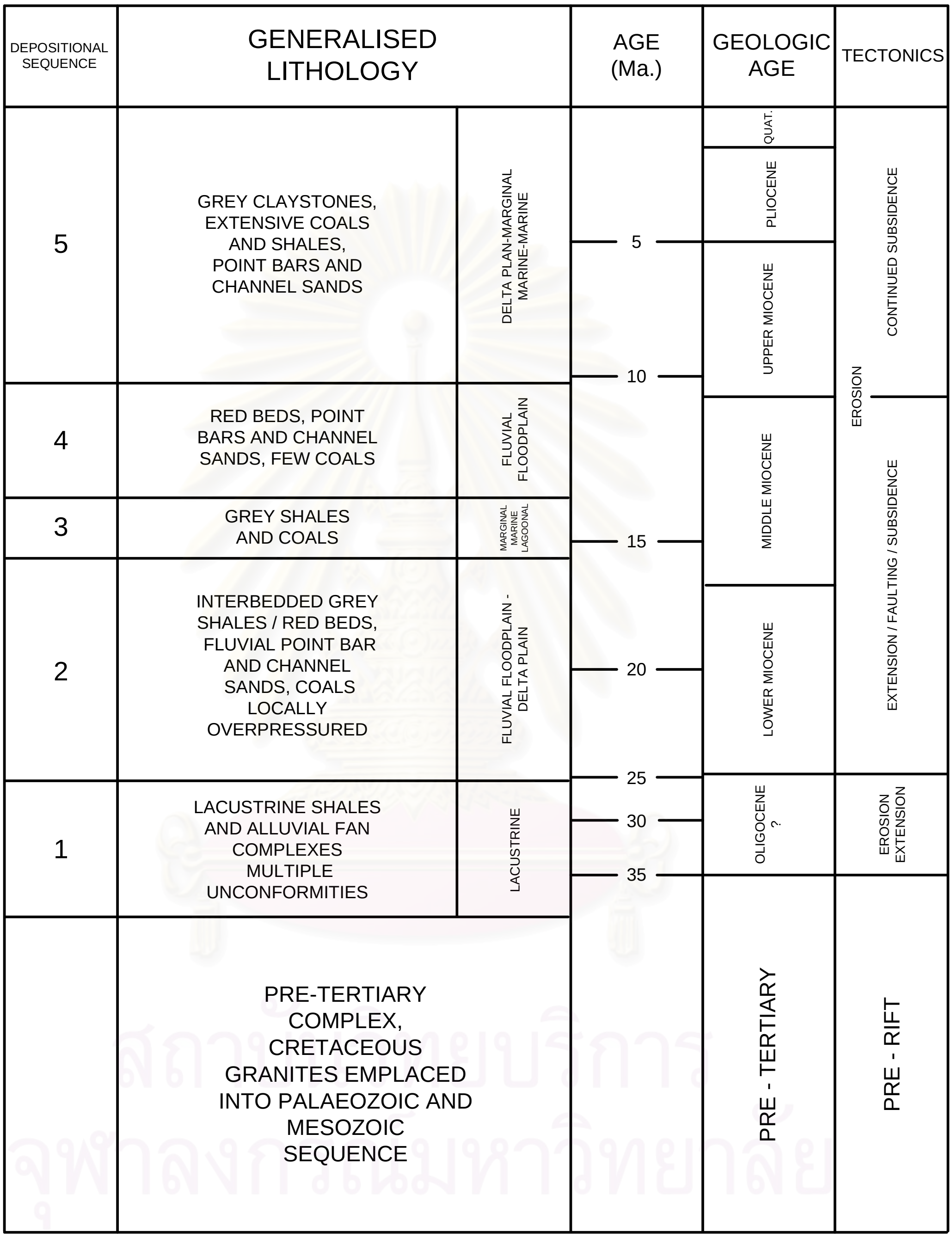


Figure 2.8 Stratigraphic summary of the major depositional sequences within the Pattani basin (Modified from Jardine, 1997).

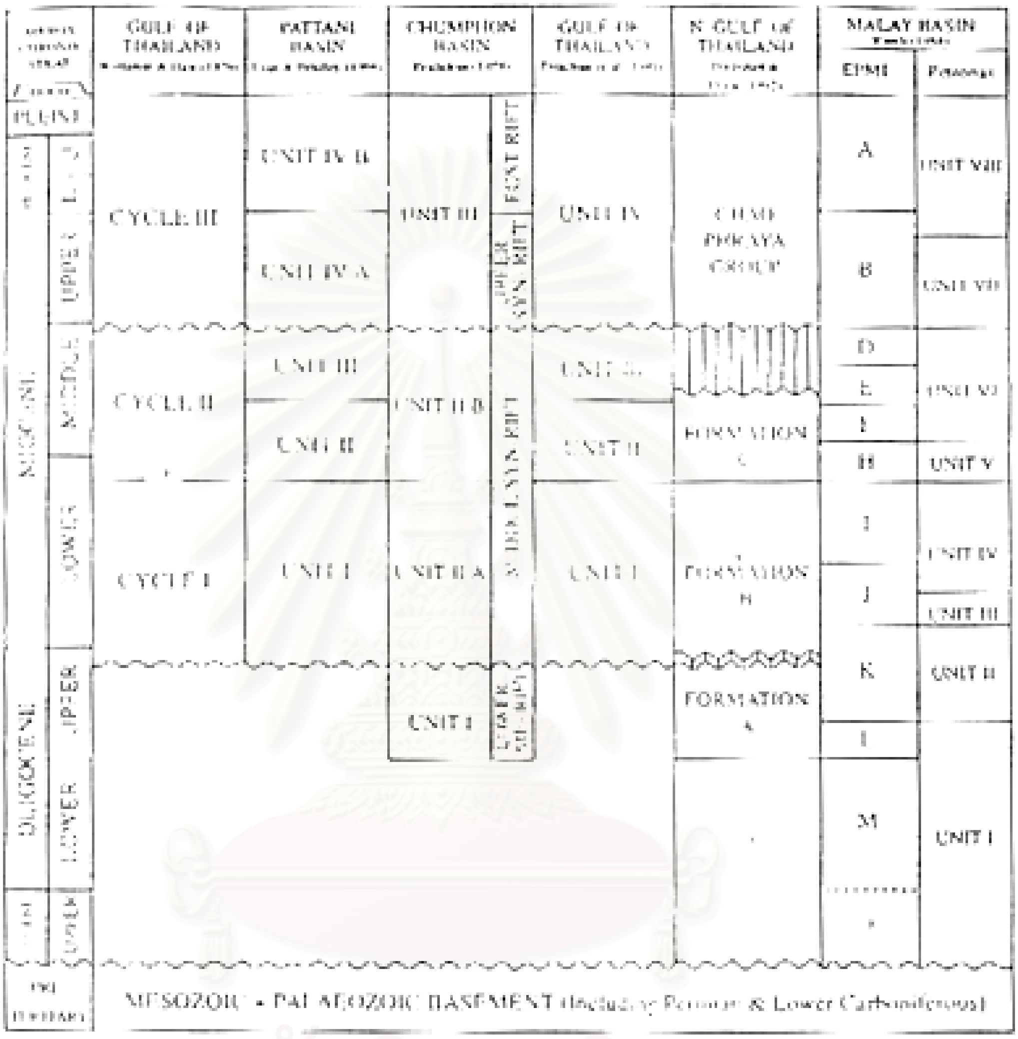


Figure 2.9 Published lithostratigraphic schemes for the Gulf of Thailand (Highton et al., 1997).

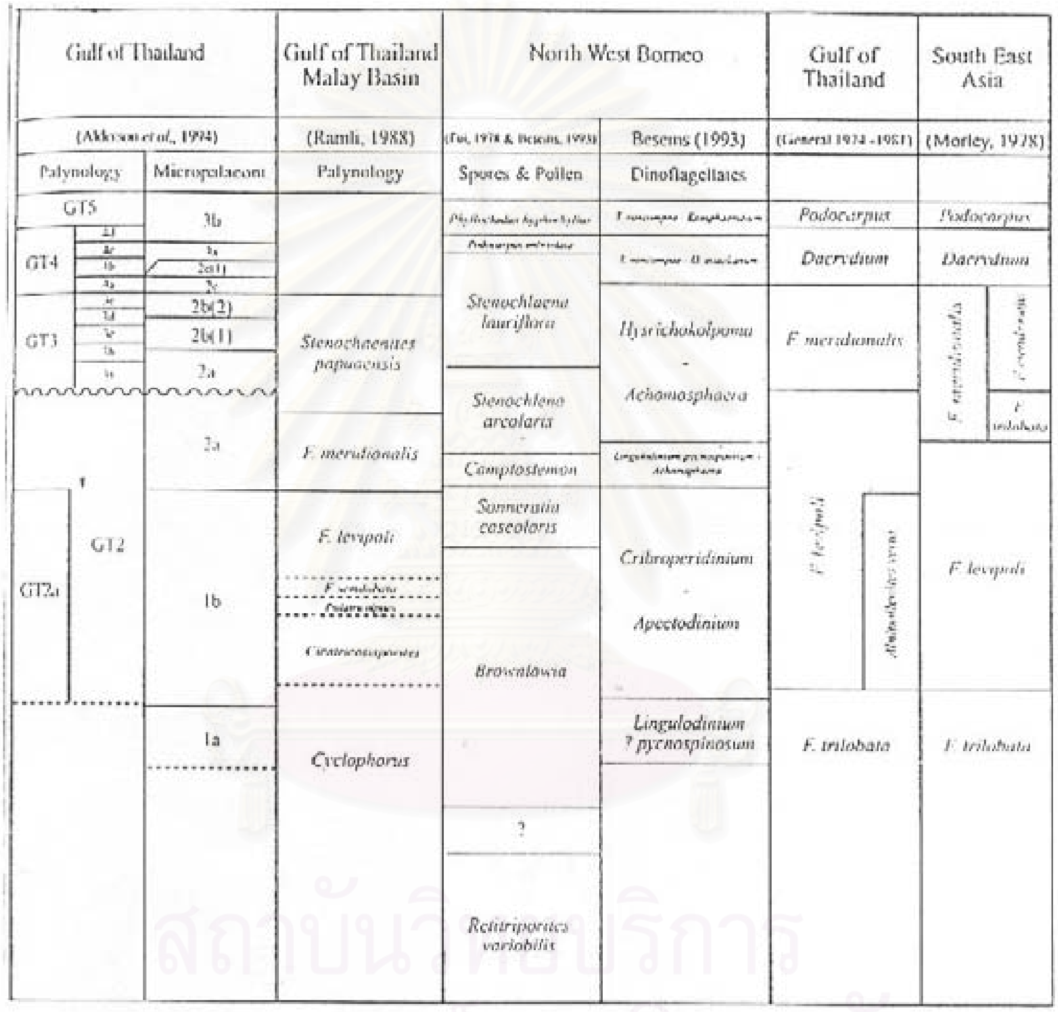


Figure 2.10 Biostratigraphic schemes for the S.E. Asian Neogene (Highton et al., 1997)

CHAPTER III

GEOLOGY OF THE SONGKHLA BASIN

Tectonic Setting of the Songkhla Basin

The Indian plate progressively collided with Eurasia plate in Eocene. With continued penetration to the north caused clockwise rotation of S.E. Asia, resulting in increasingly oblique subduction of the Indian Oceanic plate beneath the western edge of S.E. Asia. As the result, it led to movement on strike-slip faults. Three Pagoda is the dextral NW-SE trending principal strike-slip fault. Ranong and Klong Marui are sinistral NNE-SSW trending conjugate faults. The strike-slip faults associated with transtensional basin (Polachan and Sattayarak,1989).

The Songkhla basin, one of the Cenozoic basins in the Gulf of Thailand, is located in the Western Graben area and lies on the south of major strike-slip faults. The Songkhla basin is a pull-apart basin formed during Early Tertiary by fault stepping of Three Pagoda and conjugate set, Ranong and Klong Marui. It governed by series of N-S trending extensional faults which associated en echelon faults and related to the movement on NW-SE and NNE-SSW trending strike-slip faults. The extensional faults controlled extensional rifting of basin as half-graben. The western of basin is bounded by listric boundary faults. The information obtained from seismic reflection surveys and two-way time structural map of the basement illustrate that the configuration of Pre-Tertiary basement of the Songkhla basin is elongated, N-S trending basin (Figure 2.2). The Songkhla structural extends approximately 70 kilometers from north to south and 20-40 kilometers from east to west. The maximum depth of the basin is more than 3,500 meters.

Geological Structures of the Songkhla Basin

The Songkhla basin is a small, narrow and elongated basin. The basin was formed as a series of N-S trending half-graben. From seismic section, four stratigraphic markers have been identified as Red, Blue, Green and Yellow Markers that are illustrated in Figure 3.1. Additionally, the important geological structures of the Songkhla basin are recognized by seismic data such as border faults, intrabasinal faults and rollover anticline that related to tectonic activities. Moreover, the geological structures of the basin deal to petroleum migration and accumulation. Petroleum traps occur as a result of structural activities so that different types of structures produce different types of traps.

1. Border Faults

The half graben geometry of the Songkhla basin is illustrated by Figure 3.1 and 3.2, which shows the western boundary faults by the eastern dipping faults. The major boundary faults lying in the series of N-S trending are listric normal faults that are products of transtensional tectonic associated right lateral movement so that the basin formed as a narrow and elongated N-S trending basin. The border faults cut through the Pre-Tertiary basement and joined into detachment faults at depth. Besides, the border faults controlled the basin formation. The sediment accumulation is in downthrown block while the sediments deposited in the basin are actively growing in breath and depth. The sediment thickness is thickening westward and thinning eastward. As the result, the border faults are growth faults or syn-depositional faults characteristic as shown on Figure 3.3. The border faults occurred in the early stage of the development of the basin since Early Tertiary, and ceased at or near the late Middle Miocene unconformity.

2. Intrabasinal Faults

The intrabasinal faults of the basin are defined from seismic cross sections and TWT structural maps (Figures 3.2 and 3.3). The intrabasinal faults mostly appear postdated the deposition of Tertiary strata preserved in the hanging wall but some of them cut trough the basement. The synthetic and antithetic faults, often presenting in sequences between Early Oligocene and end of Early Miocene, are also recorded along the seismic reflections as shown in Figure 3.4. The synthetic and antithetic faults associated border faults resulted from the load induced subsidence that collapse of hanging wall. These faults mainly occurred in the western margin of the basin; however the eastern margin of the basin was slightly deformed with few N-S trending fault blocks. The density of the intrabasinal faults appears higher in the northern part where it consists of numerous N-S trending faults that are both eastern and western dipping faults through the basin than in the southern where contains mainly N-S trending faults along the western and eastern margin.

3. Rollover Anticline

Rollover anticline indicating syn-deposition is an important feature associated to the listric normal growth fault that mostly appears in the south and central of basin along the western margin. It develops in hanging wall block of normal faults. The rollover anticline results from the movement of the sedimentary strata downward to the fault and become fold in such a way that dipping towards the fault surface. In addition, the strained effect of rollover anticline can also be achieved by collapse featuring the down dropping of fault bound block (Figure 3.5) such as synthetic and antithetic faults. Generally, the rollover anticline is clearly presented between Early Oligocene and Early Miocene sequence.

Stratigraphy of the Songkhla Basin

The available and releasable data comprising of geophysical logs, mud logs, seismic sections and palynological reports of Premier Oil Pacific Limited are analyzed to establish the stratigraphic units, environment of deposition, and stratigraphic correlation among five wells which were drilled in the Songkhla basin. The stratigraphy that established is based on lithological, biostratigraphic and geophysical log data.

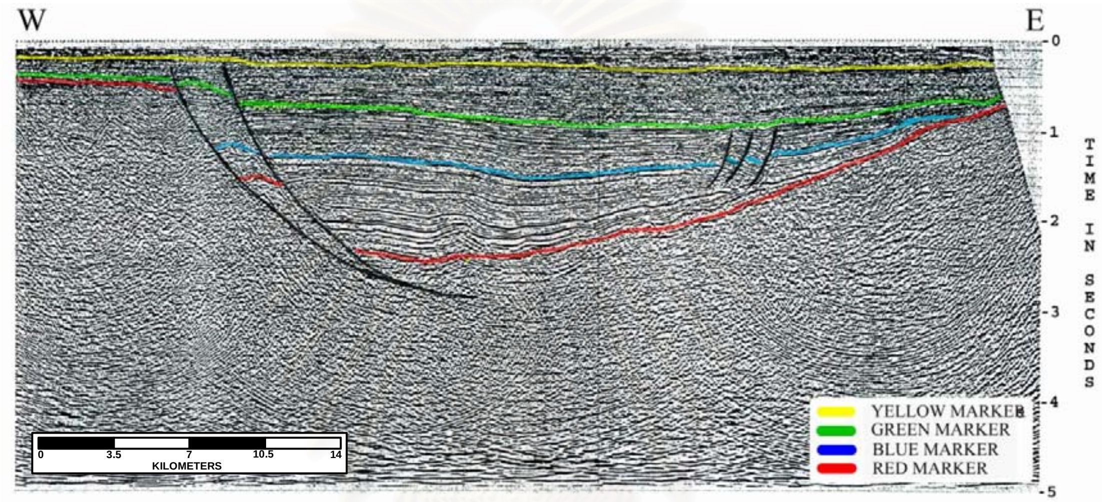


Figure 3.1 Interpreted seismic section of line POPL-23, showing geometry of the Songkhla basin.

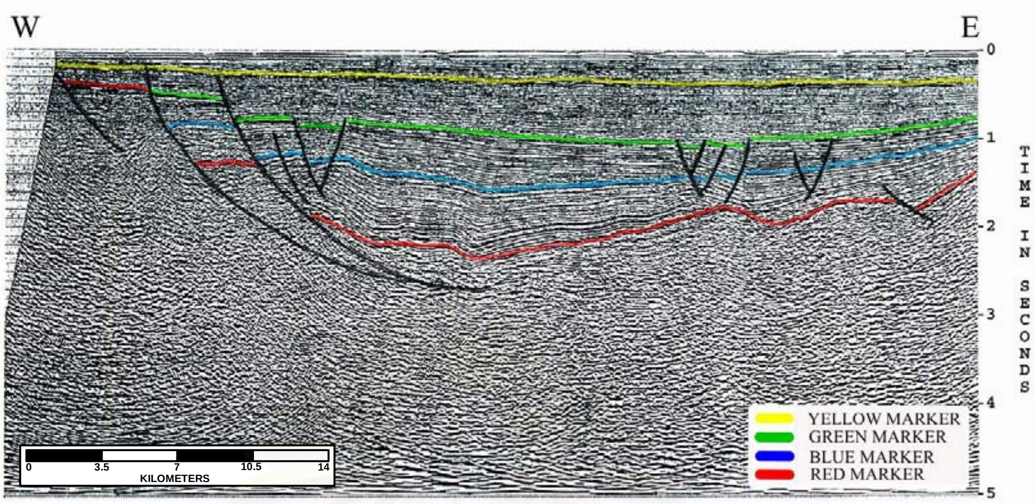


Figure 3.2 Interpreted seismic section of line POPL-16, showing the listric normal faults and intrabasinal structures within the basin.

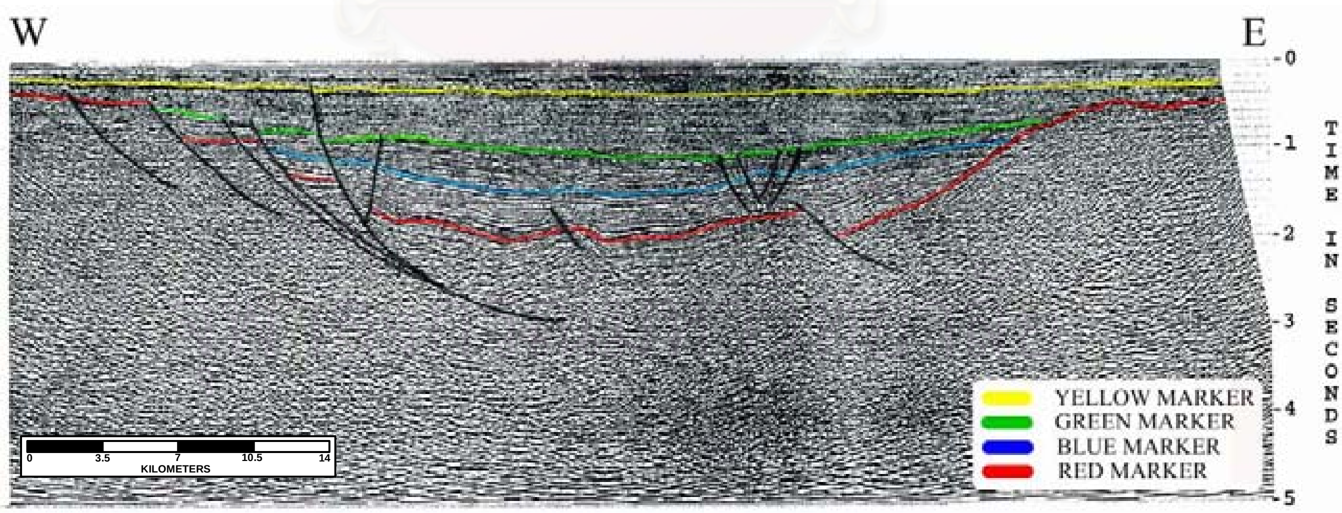


Figure 3.3 Interpreted seismic section of line POPL-09, showing the western boundary faults and intrabasinal structures within the basin.

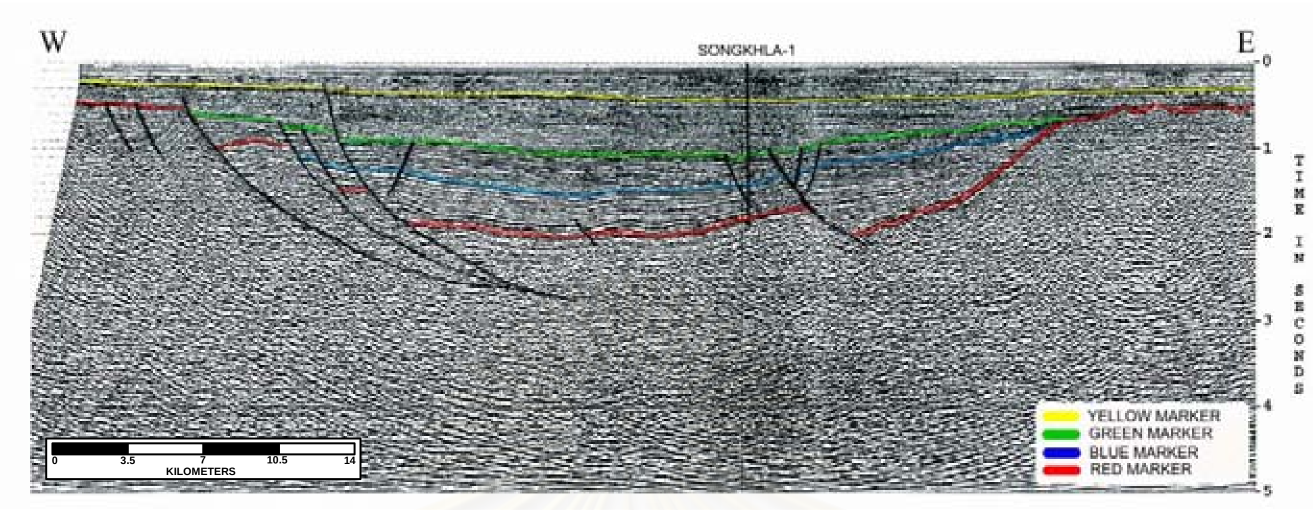


Figure 3.4 Interpreted seismic section of line POPL-41 across the Songkla-1 well, showing synthetic and antithetic faults.

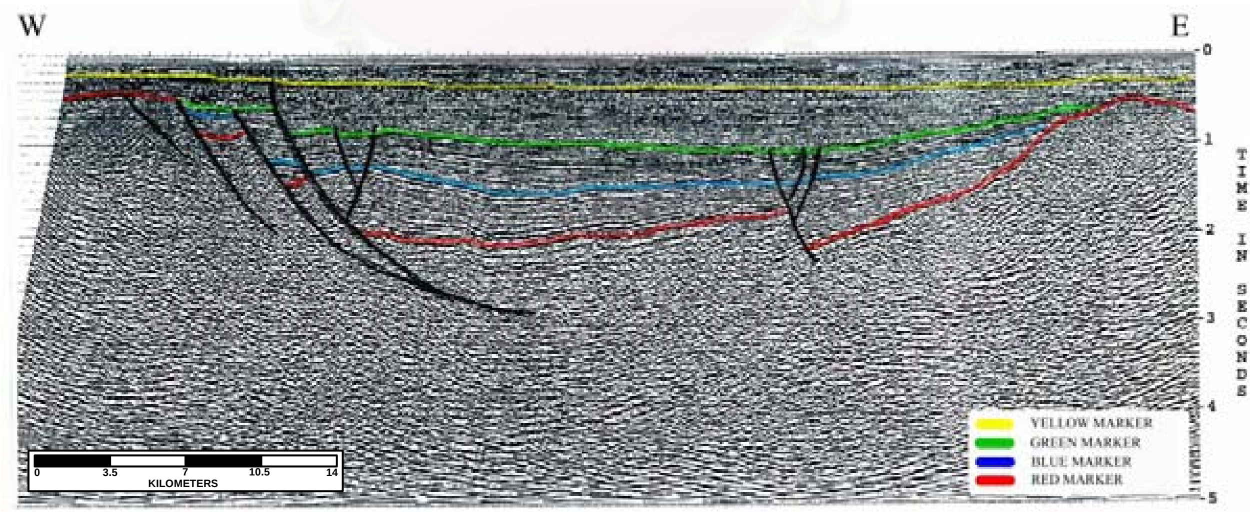


Figure 3.5 Interpreted seismic section of line POPL-12, showing the rollover anticline.

The lithology is reinterpreted from mud logs. The geophysical logs used in the study consist of 3 parameters such as gamma ray, resistivity, and sonic logs. The seismic data are used to correlate each depositional sequence throughout the basin.

The sedimentary thickness of Songkhla basin varies from 2,800 to over than 3,500 meters in the deeper part of the basin where basement is below 2.5 seconds in two-way time as seen in seismic section (Figure 3.2). Most well reached basement in which depth ranges from 2,800 to 3,200 meters beneath seabed, and the oldest Tertiary rocks may be ?Late Eocene. Nevertheless, in the central part in which may be the deepest of the basin is still undrilled.

Based on the subsurface geological information, the Tertiary sedimentary sequence in the Songkhla basin can be subdivided into 5 formations, namely SK-1, SK-2, SK-3, SK-4, and SK-5 in ascending order (Table 3.1). Detailed description of each formation will be discussed as follows.

SK-1 Formation

The lowest Tertiary stratigraphy unit of the Songkhla basin is SK-1 Formation that overlies unconformably on Pre-Tertiary basement and conformably underlying the SK-2 Formation. This formation has been penetrated in all wells of the Songkhla basin. The thickness of this formation in western part is thicker than in eastern part of the basin and also thicker on the south and thinning toward the north as wedge shaped geometry. The characteristics of the SK-1 Formation is summarized in Figure 3.6.

The SK-1 Formation is generally characterized by very pale gray to dark yellowish brown, fine to coarse grained or pebbly, poorly sorted sandstone with interbedded reddish brown to dark brown claystone or shale.

The beginning of the SK-1 Formation is clearly observed as appeared on logs and seismic reflection because of different lithologies from the Pre-Tertiary basement to

Table 3.1 The proposed stratigraphic classification of the Songkhla basin.

AGE		FORMATION		MARKER	LITHOLOGY	LITHOLOGICAL DESCRIPTION	ENVIRONMENT OF DEPOSITION
Holocene Pleistocene Pliocene		UNNAMED				Claystone or shale and sandstone	Intertidal / Marine
Miocene	Late	SK-5		Top of Middle Miocene (YELLOW)		Sandstone interbedded with claystone or shale and coal	Fluvial / Mangrove swamp / Coastal plain
Miocene	Middle	SK-4		Top of Early Miocene (GREEN)		Interbedded sandstone and claystone or shale	Fluvial
Miocene	Early	SK-3		Top of Oligocene (BLUE)		Sandstone interbedded with claystone or shale with minor limestone and coal	Fluvial / Lacustrine
Oligocene	Late	SK-2	SK-2C			Claystone or shale interbedded sandstone and limestone	Lacustrine / Fluvial
Oligocene	Late	SK-2	SK-2B			Predominantly claystone or shale interbedded sandstone and minor limestone	Lacustrine
Oligocene	Early	SK-2	SK-2A			Predominantly dark gray claystone or shale interbedded sandstone and minor limestone	Lacustrine
?Eocene	Late	SK-1		Top of Basement (RED)		Sandstone interbedded with varicoloured claystone or shale	Alluvial / Fluvial
Pre-Teriary		BASEMENT				Granite and low grade metamorphic rock	

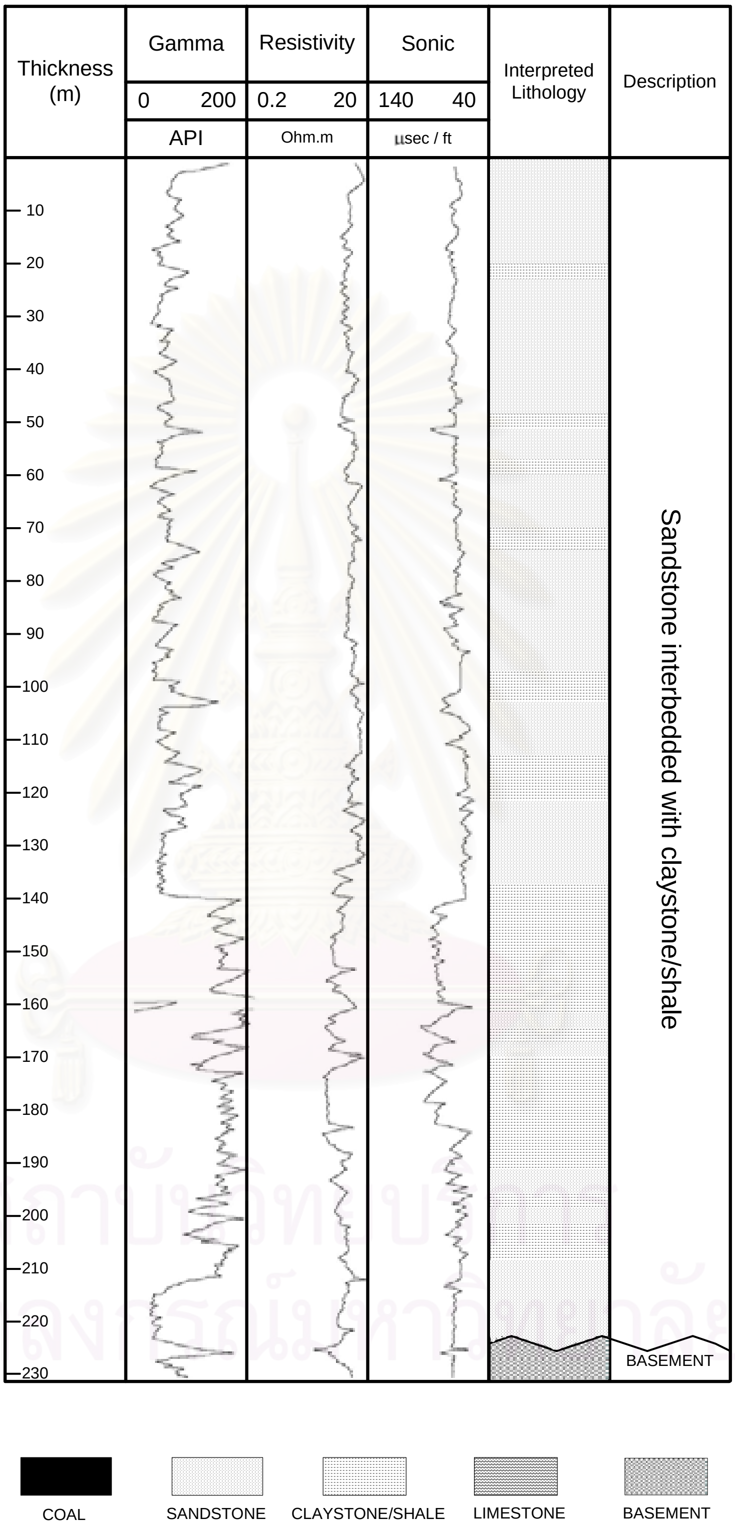


Figure 3.6 Lithological and petrophysical characteristics of the SK-1 Formation of Songkhla South-1 well.

sedimentary sequence and unconformity. In the lower part of the formation, the gamma ray is of high values that contain high clay content associated with floodplain. In contrast, in the upper part of the formation, the gamma ray shifts to low and curve shapes like a cylindrical shaped pattern indicating high sand content and fluvial environment which is composed of stacks of point-bar supported by lithology. Moreover, the seismic reflections are chaotic and free characteristics appeared on the western flank of basin along the major fault that is possibly indicated alluvial fan as shown on Figure 3.13. The formation is different lithology from SK-2 Formation and barren of palynomorphs so the formation may be older than Late Oligocene that is probable Late Eocene age.

The depositional environments of the formation are alluvial fan dominated on the west that is closed to the fault plane while fluvial environment associated floodplain condition occur far to the east away from the western fault block. Beside that, the reddish brown claystone or shale indicates the oxidizing environment.

SK-2 Formation

The SK-2 Formation, overlying conformably on the SK-1 Formation and underlying conformably the SK-3 Formation, is composed predominantly of dark gray organic claystone or shale. The boundary of this formation is marked by a dramatic formation change and supported by palynological and geophysical data. The lower boundary is defined by lithological change from dominant sandstone of the SK-1 Formation to dominant claystone or shale of the SK-2 Formation. The upper boundary of the formation is defined by lithological change from dark gray claystone or shale to varicolored claystone or shale of the overlying SK-3 Formation. The SK-2 Formation makes up significant large volume of sedimentary sequence in the Songkhla basin and its distribution is widespread throughout the basin with varying thickness. The thickness of the formation ranges approximately 600 to 1,200 meters and thinned toward the east edge of basin.

Based on lithology from mud logs and petrophysical logs, the SK-2 Formation can be subdivided into 3 members, SK-2A, SK-2B, and SK-2C in ascending order. Detailed lithostratigraphy of each member is summarized and presented in Figures 3.7, 3.8 and 3.9.

1. SK-2A Member

The SK-2A Member, the lowermost member of the SK-2 Formation, is generally characterized by highly carbonaceous, organic rich, grayish brown to dark gray claystone or shale interbedded with fine-grained sandstone and minor limestone.

From the petrophysical log, high gamma ray with some low gamma ray are presented in the member because of predominant claystone or shale containing high organic contents interbedded with sandstone. At the base of the member, the sonic log shows the funnel shaped pattern, which is a decreasing transit time with depth due to increasing of rock density.

2. SK-2B Member

The SK-2B Member, the middle member of the SK-2 Formation, is mainly composed of medium to light gray occasionally dark gray claystone or shale. There are some interbedded of light gray, fine to medium grained, well sorted sandstone throughout the member and limestone at bottom of the member.

At base of the member, the gamma ray and sonic log responses show low values indicating limestone. The gamma ray trend above limestone is also high and reflects series of coarsening upward and fining upward sequences that resulted from progradation of fan delta. The progradational sequences are made up of stacked parasequences of lacustrine and fan delta separated by flooding surfaces which may be cyclic of marine transgressive occurring in short period. The cycles of parasequences associate to rapid lake level fall, controlled by climatic changes. In this period, the sediment influx exceeded the rate of subsidence.

3. <u>SK-2C Member</u>

The uppermost member of the SK-2 Formation is the SK-2C Member. There are predominantly medium-light brown, medium gray, calcareous and carbonaceous claystone or shale interbedded with light gray, very fine-coarse sandstone and argillaceous limestone.

The gamma ray responses high value and the log curves are irregular pattern as saw-tooth that result from mixed claystone or shale and sand. These characters indicate lacustrine with minor fluvial influences.

The SK-2 Formation is mainly composed of lacustrine Oligocene sediments that supported by lithological and palynological data. There are abundant organic materials which dominated by freshwater algae, *Pediastrum sp*. indicating freshwater lacustrine environment. The miospores found in the formation such as *Florschuetzia trilobata* and *Magnastriatites howadi* indicate Middle Miocene to Oligocene age*, Lavigatosporites sp*. found in the SK-2 Formation indicates Late Oligocene, and *Pinuspollenite ssp.* indicate lacustrine environment (Achalabhuti, 1981 and Polachan, 1992).

The depositional environment of the SK-2 Formation is mainly lacustrine with minor fluvial influence. A freshwater, perennial lake occupied the Songkhla basin during the Oligocene. The predominance of dark claystone or shale, high organic content and rarely sandstone depositions indicate a lacustrine environment under reducing condition. In addition, the lithological association of claystone or shale interbedded sandstone indicates fluvial influence within lacustrine environment. Generally, the coarsening upward sequences deposited in deltaic environments that prograde into the center of the lacustrine basin, so that the stacked parasequences of lacustrine and fan delta occurred when a rate of sediment influx was higher than subsidence and related

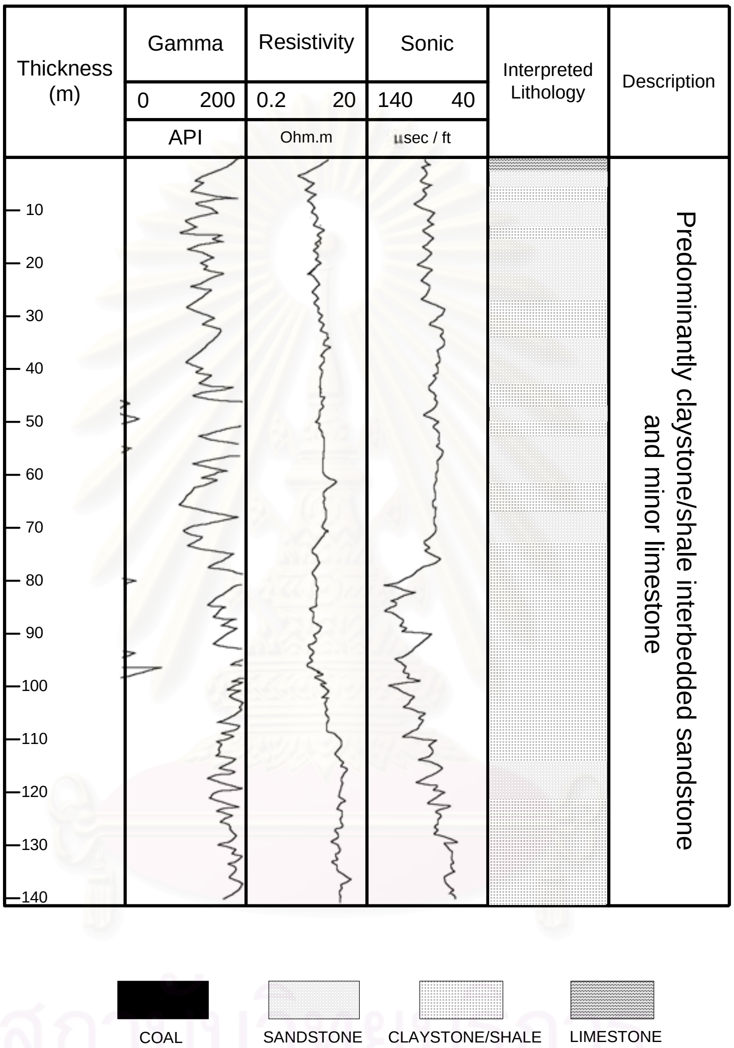


Figure 3.7 Lithological and petrophysical characteristics of the SK-2A Member of Songkhla-1 well.

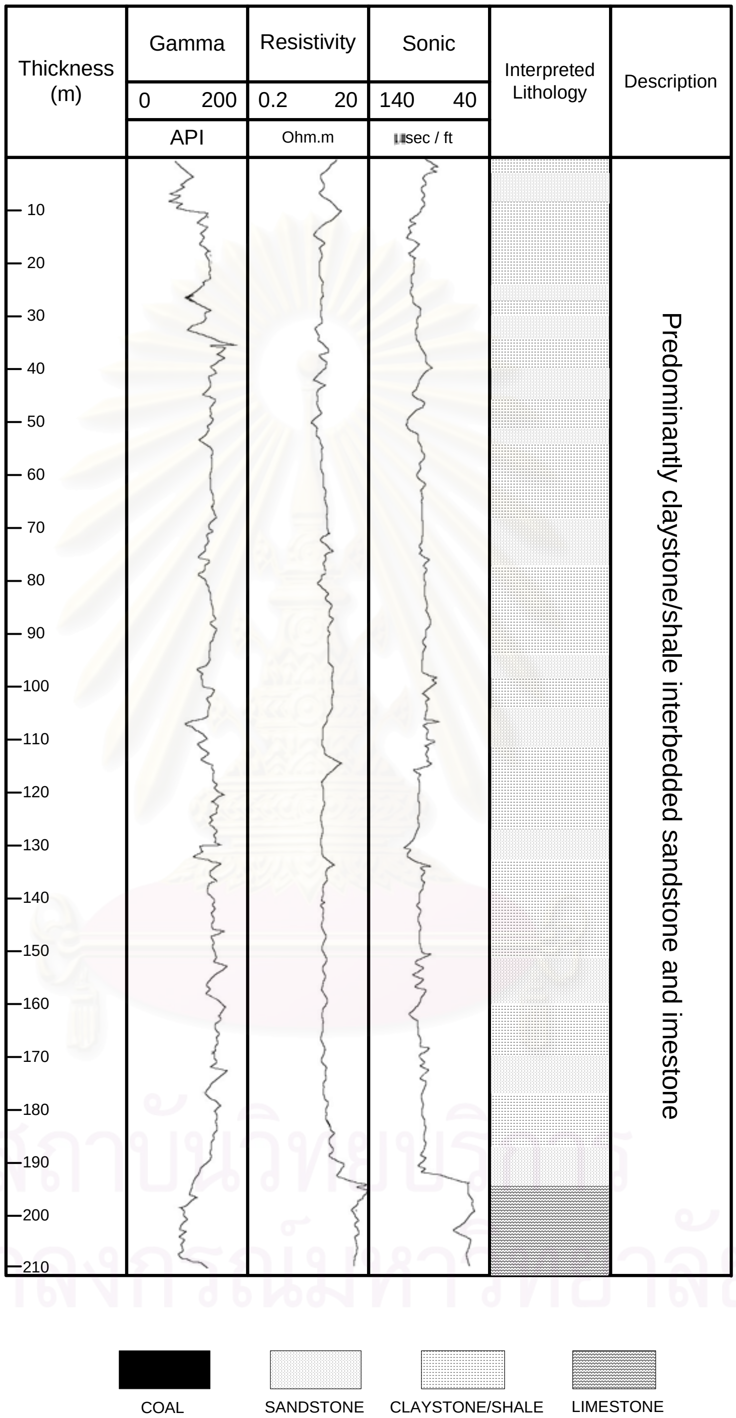


Figure 3.8 Lithological and petrophysical characteristics of the SK-2B Member of Songkhla-1 well.

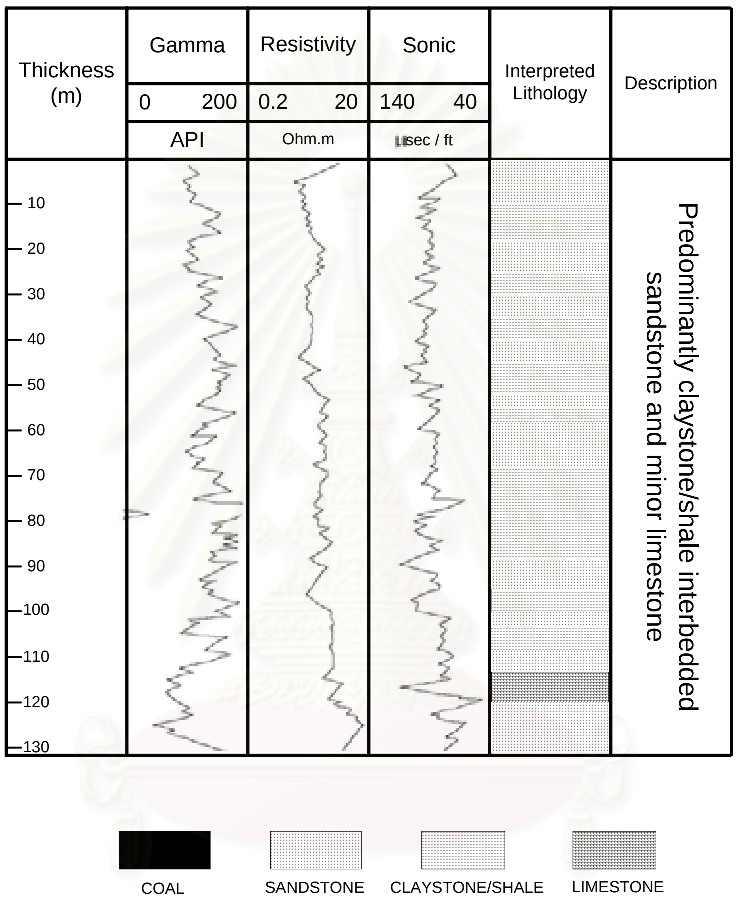


Figure 3.9 Lithological and petrophysical characteristics of the SK-2C Member of Songkhla South-1 well.

to a fall in lake level which indicates the climatic variations. The progradating deltaic sanndstone derived from lake margin in the north and east and transported into the basin along downslope. The flooding surfaces that may be marine transgressive separated each parasequence. The marine transgression that occurred in the short periods is indicated by cyclic of parasequences and kerogen type. From the petroleum geochemical study, the kerogen type of this formation containing kerogen types I/II/III. The environment is mainly continental deposits with marine influences because kerogen type II mostly derived from marine, deposited in reducing environment. An abundance of organic material, freshwater algae, *Pediastrum sp*. and *Pinuspollenite ssp*., indicates lacustrine environment.

<u>SK-3 Formation</u>

The SK-3 Formation, presented in Figure 3.10, overlies conformably on the SK-2 Formation and unconformably underlies the SK-4 Formation. The upper unconformity is defined in accordance with Top of Early Miocene marker in seismic stratigraphy correlation and is used as the upper boundary of SK-3 Formation throughout the basin. The Early Miocene unconformity is recognized from seismic and logs. No obvious lithological change is seen and palynological data is sparse because of the predominance of non-marine nature.

The lithology of this formation contains dominant series of interbedded fine to coarse, poorly sorted sandstone and varicolored claystone or shale which is predominantly yellowish brown to grayish brown. The claystone or shale become increasing calcareous with depth and minor thin limestone and coal.

The gamma ray log curves consists of cylindrical, funnel and bell shaped patterns, so the in the formation was probably occurred in fluvial environment which supported by sonic, resistivity logs, and seismic sections. The funnel profiles, coarsening upward sequence, presented in the lowermost of the formation. The cylindrical shaped pattern, in the middle of the formation, shows low gamma ray value that indicates sandstone sequence and occasionally with limestone supported low transit time values. Besides, the bell shaped patterns shown in the next upper of the formation indicated, that the fining upward sequence should occur and turned into coarsening upward to the end of formation. The Early Miocene Unconformity, at the top of the formation, shows abrupt change of log curves.

The SK-3 formation is Early Miocene in age because *Florschuetzia levipoli* is found in the formation. *Florschuetzia levipoli* are mainly found in the Early Miocene sediment (Achalabhuti, 1981 and Polachan, 1992).

The environment of deposition of the SK-3 Formation is a transitional environment from lacustrine to fluvial due to a little change of the lithology from The SK-2 to the SK-3 Formation. The coarsening upward sequences indicate delta. Whereas the fining upward sequence indicate migration of fluvial point bar. Additionally, the coal seams are considered to have swamp accumulation origin.

<u>SK-4 Formation</u>

The SK-4 Formation overlies unconformably on the SK-3 Formation and underlies unconformably the SK-5 Formation. The Middle Miocene unconformity is at the top of this formation which identified from a lithological change and supported by both seismic reflection and palynology. The characteristics of the SK-4 Formation is summarized in Figure 3.11.

The SK-4 Formation is composed of interbedded sandstone and varicolored claystone or shale. The claystone or shale is orangish red to reddish brown, yellow, white and green color. The sandstone are clear to translucent, a variable grain size from fine to medium and, poorly sorted.

The Middle Miocene Unconformity, the regional unconformity, occurs at the top of this formation that corresponds to clearly shown by log break. The gamma ray, resistivity, sonic curves look like saw-tooth throughout the formation. The gamma ray trends present the funnel, bell, and irregular patterns which results from coarsening upward, fining upward and mixed sandstone and claystone or shale respectively. The log shaped patterns indicate fluvial environment.

The palynomorph assemblege within the SK-4 Formation is characterized by *Echitricolpite spinosus* that indicates Middle/Late Miocene to recent and *Florschuetzia meridionalis* which is found in intra Middle Miocene to recent sediments (Highton et al, 1997). Thus, this formation is not older than Middle Miocene age (Achalabhuti, 1981 and Polachan, 1992). *Florschuetzia levipoli* and *Florschuetzia triobata* was found in the formation.

Based upon the lithological and log characteristics, the formation is predominantly fluvial environment.

SK-5 Formation

The SK-5 Formation is the uppermost unit of Tertiary sequence within the Songkhla basin. It overlies unconformably on the SK-4 Formation in which the Middle Miocene unconformity occurs. The characteristics of the SK-5 Formation are presented in Figure 3.12.

The lithology encountered in this formation comprises of interbedded fine to coarse, poorly sorted sandstone with yellow, orange brown soft dispersive claystone or shale with lignite beds.

The gamma ray log is only one log run trough the formation. The gamma ray trends are generally low and constant values. The gamma ray characters indicated mainly sandstone with occasionally claystone or shale and coal bed.

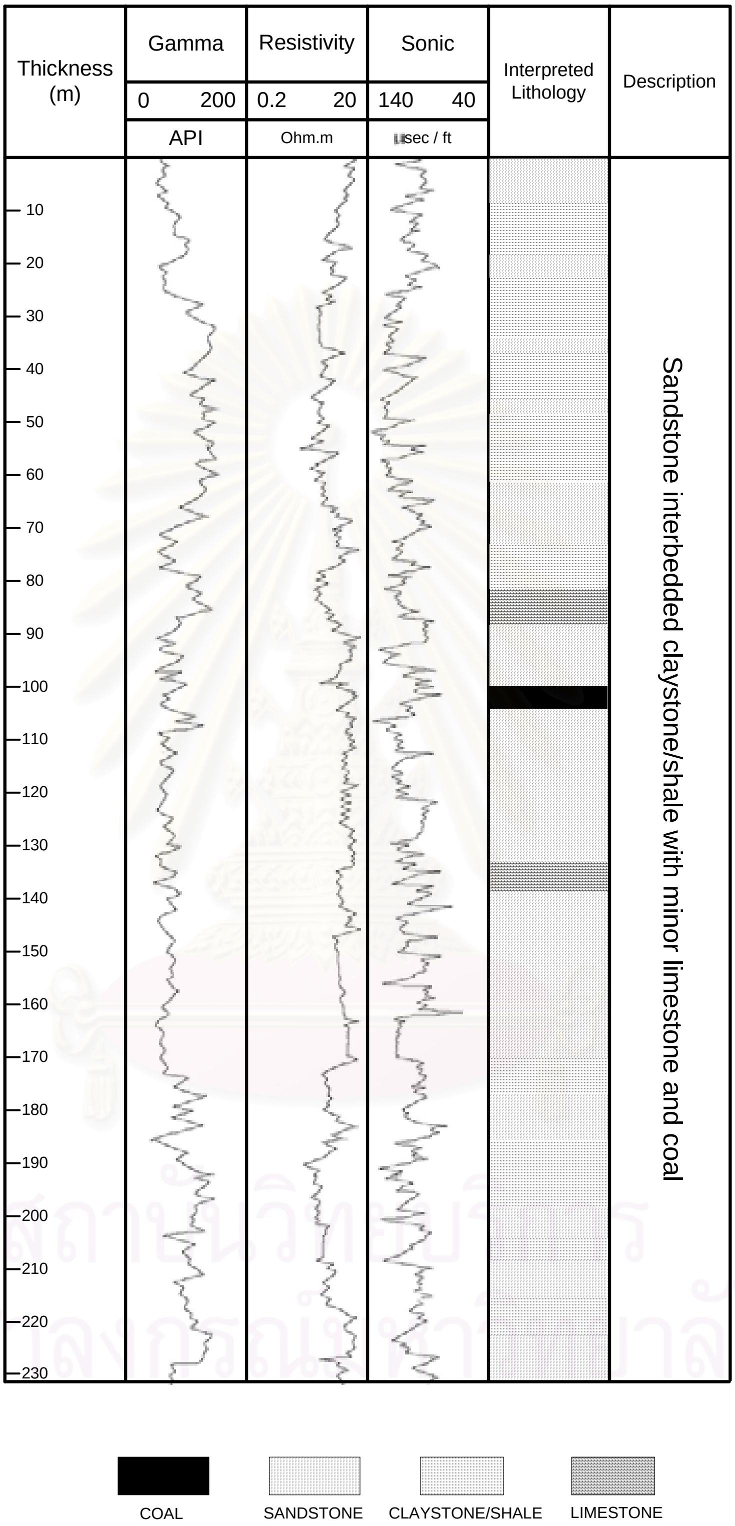


Figure 3.10 Lithological and petrophysical characteristics of the SK-3 Formation of Bua Ban-1 well.

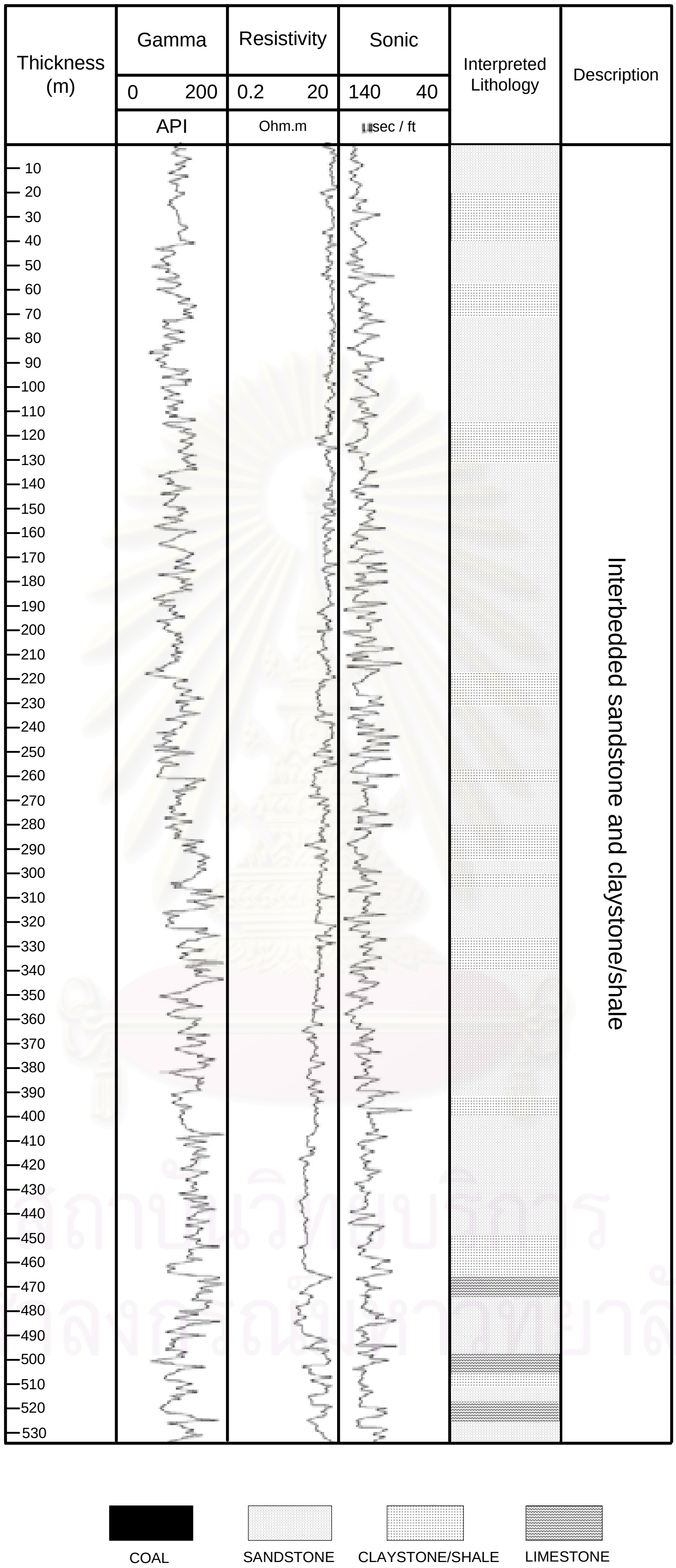


Figure 3.11 Lithological and petrophysical characteristics of the SK-4 Formation of Bua Ban-1 well.

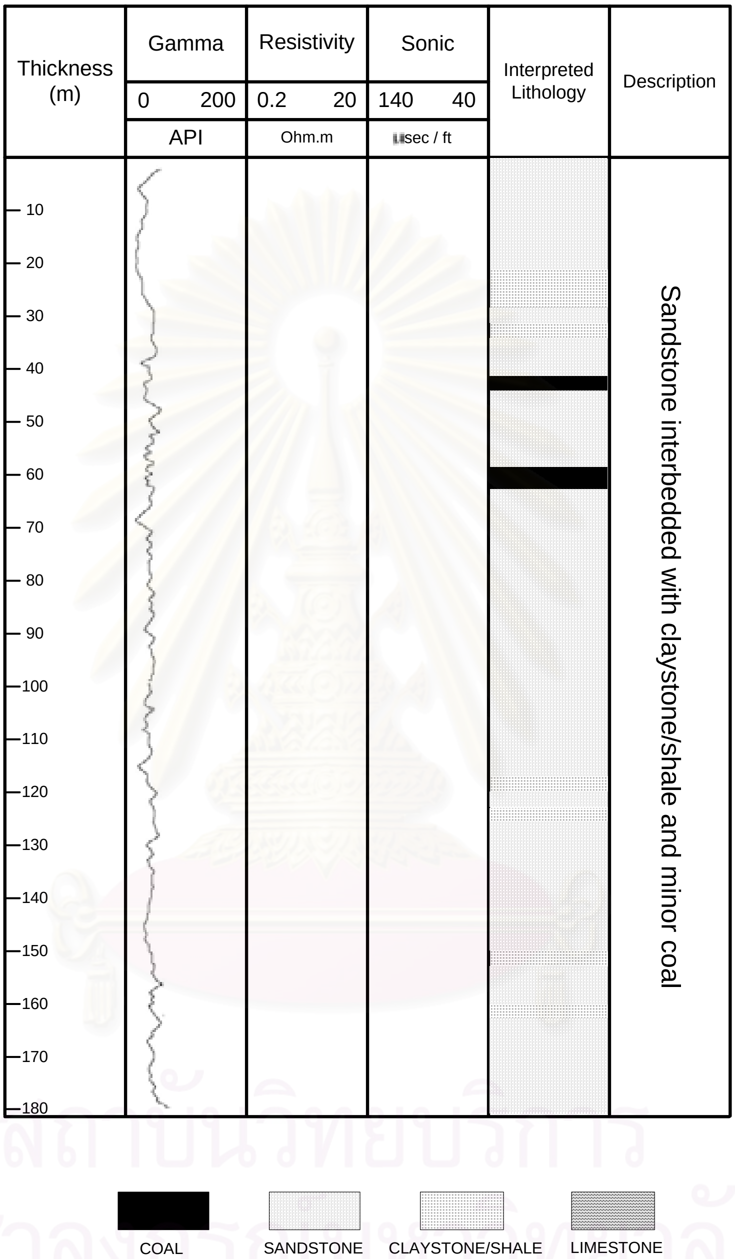


Figure 3.12 Lithological and petrophysical characteristics of the SK-5 Formation of Songkhla-1 well.

The SK-5 Formation consists of the Late Miocene sediment because *Stenochlaena laurifolia* indicating Late Miocene to Recent (Polachan, 1992) was found in the formation. Coal seams in the formation are considered to have a swamp accumulation origin. Based on the lithological characteristics, the depositional environments of the SK-5 Formation are fluvial, mangrove swamp and coastal plain.

Stratigraphic Marker

Stratigraphic markers on seismic sections have been choosen from biostratigraphic data, mud logs, and composite logs of exploration wells in the Songkhla basin as shown in Figure 3.14. Three of five wells are located in the seismic lines. The Songkhla–1 well, in the eastern flank of the basin, is located in the seismic line POPL-41 at the shot point 969 (Figure 3.4). The Bua Ban-1 well and Benjarong-1 well, in the western flank of the basin, are located in the seismic line P-835 at the shot point 448 and the seismic line P-837 at the shot point 809 respectively. Four stratigraphic markers have been identified as shown in Figure 3.13 and 3.14 and more detail of each stratigraphic marker is described as follows.

1. Top of Basement Marker

Top of Basement Marker or Red Marker represents the basement lying under the Tertiary to recent succession. The base Tertiary reflection is generally very strong peak and marks a major unconformity. This marker is obvious reflection in the northern part of the basin but some reflections in the southern part are ambiguous.

2. Top of Oligocene Marker

Top of Oligocene Marker or Blue Marker is identified by top of couple of clear and parallel reflections. The reflections between Red and Blue markers are divided into two parts. The upper part is characterized by strong, parallel, continuous reflections, high amplitude and low frequency. These reflection characteristics indicate source rock

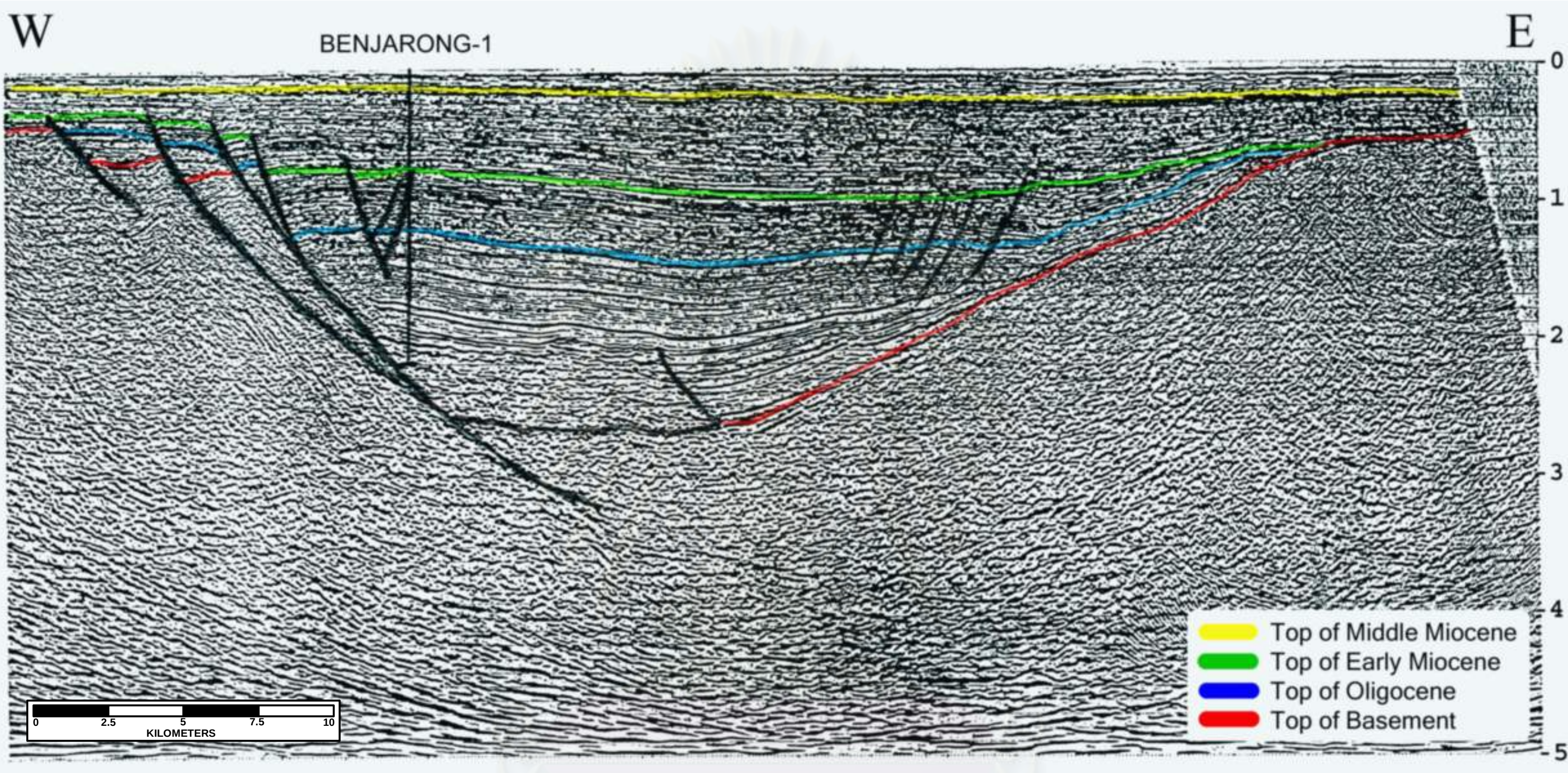


Figure 3. 13 Interpreted seismic section of line P-837, showing seismic markers across the Benjarong-1 well at shot point 809.

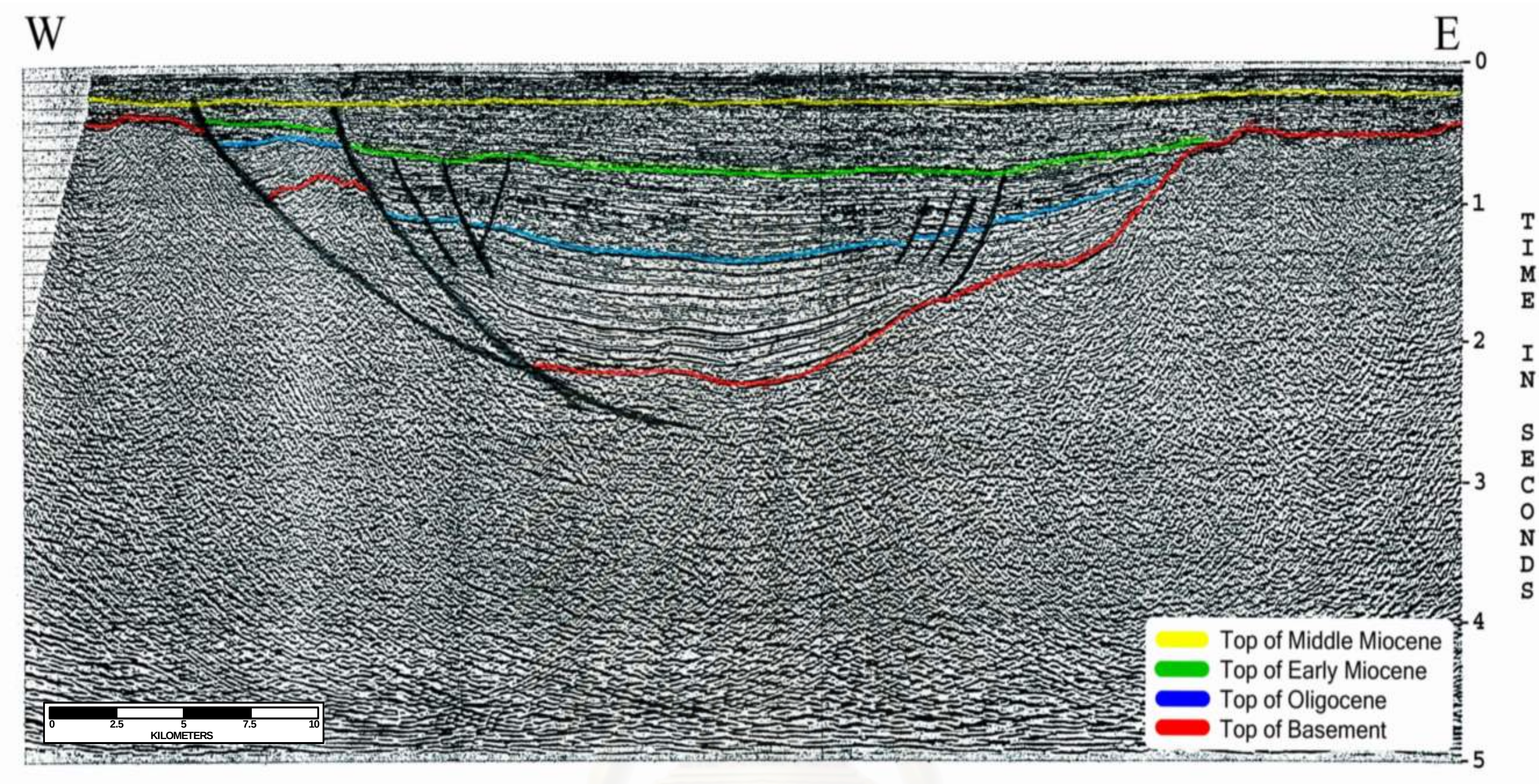


Figure 3.14 Interpreted seismic section of line POPL-28, showing the seismic markers.

horizon. The reflection characteristics of the lower part are identified as free reflections and chaotic reflections appear at the flank of basin. The reflections generally truncated to eastern flank of basin.

3. Top of Early Miocene Marker

Top of Early Miocene Marker or Green Marker is picked by clear, strong and continuous reflections. This section between Blue and Green Markers can be divided into two parts, upper and lower parts. The upper part is very clear, parallel, continuous reflection throughout the basin. In contrast, the lower part is ambiguous, subparallel, low-moderate continuous reflections. The truncations generally occur at the eastern flank of basin.

4. Top of Middle Miocene Marker

Top of Middle Miocene Marker is indicated by Yellow Marker. At the marker, reflections are generally very strong peak and are continuous throughout the basin. This marker is recognized as regional unconformity. The section from Blue Marker to Yellow Marker is characterized by faint, parallel, discontinuous reflections.

The correlation of logs can conduct regional environment, make cross sections and map. The marker beds, log patterns such as coarsening upward and fining upward sequences, biostratigraphic data and seismic sections are used to correlate the Songkhla basin. A long distance correlation of the Songkhla basin is illustrated in Figure 3.15. The Songkhla-1, Bua Ban-1, Songkhla South-1, Songkhla Southwest-1 and Bejarong-1 wells represent a N-S and E-W cross section through the basin.

Evolution of the Songkhla Basin

The Songkhla basin is N-S trending half-graben which was initiated in the ?Late Eocene. Generally the sediment fills within the basin are mostly continental sediments including alluvial, fluvial and lacustrine sequences with occasionally marine transgression influences in short periods. The evolution of the Songkhla basin is divided into three phases as follows.

1. ?Late Eocene to Early Miocene

Pre-rift folding and uplift of Pre-Tertiary accreted basement terrances from the Cretaceous to the Eocene (Jardine, 1997). Since ?Late Eocene, the basement was eroded and initial rifting created the Songkhla basin as a small narrow, elongated basin associated with N-S extensional faults. The major normal faults that appeared in the western flank of basin is high displacement with rapid extension and deepening controlled the basin geometry as a half-graben and basin sedimentation. Besides, the set of small displacement faults occurred in the north (Figure 3.16). The rock unit, SK-1 and SK-2 Formation, is thickening westward as a wedge shape indicating the half-graben depocenter was in the west so that the western part was more subsidence than other parts of basin. The alluvial fan formed along the fault margin of the western flank of the basin and deposited in the deeper part of the basin. In the Oligocene age, the lacustrine claystone or shale were deposited during time of rapid subsided and low sediment input. The major fault was still extension with syn-deposition because the hanging wall deformed as a rollover anticline with some subsidiary faults, synthetic and antithetic faults (Figures 3.4 & 3.5). The small scale fault sets occurred in along the eastern flank of basin. By the end of Oligocene time, the displacement of major and small scale faults were low but small scale fault sets were still densely situated in the northern and eastern parts of basin (Figure 3.17).

2. Early Miocene to Middle Miocene

In this period, the major fault was low displacement but basin still extended in the E-W direction. The basin formed a narrow and elongated N-S trending basin in which the depocenter was in the north (Figure 3.18) so that the subsidence in the north was more than the south. The sediment thickness is more uniform but is thinner than the previous one. A change in both climatic and tectonic in Early Miocene resulted in a transition from lacustrine to fluvial environment. The synthetic and antithetic faults and rollover anticline that were affected by syn-depositional tectonic movement still appeared as shown on Figure 3.5. By the end of Early Miocene time, some minor crustral movements resulted in local unconformity so the most small-scale faults ceased at or near the local unconformity (Figure 3.2). During Middle Miocene time, the basin still continually extended in E-W direction which controlled by major faults. The small-scale faults were rare. The thickness is uniform throughout the basin and the basin became more developed northward. By the end of Middle Miocene, most major faults in the west disappeared (Figure 3.19) and a regional unconformity occurred widespread throughout the Gulf of Thailand including Songkhla basin. Resulted from tectonic and/or climatic changes, the extension decreased dramatically and the major normal faults of the basin ceased at or near the unconformity.

3. Late Miocene to Recent

From Late Miocene to present, basin subsidence continued and driven by quiescent thermal subsidence. The sediment accumulations above the unconformity are fairly uniform thickness. Fine-grained sand, claystone or shale and lignite deposited in the basin. The fluvial, mangrove swamp and coastal plain environments are predominant with more marine influences.

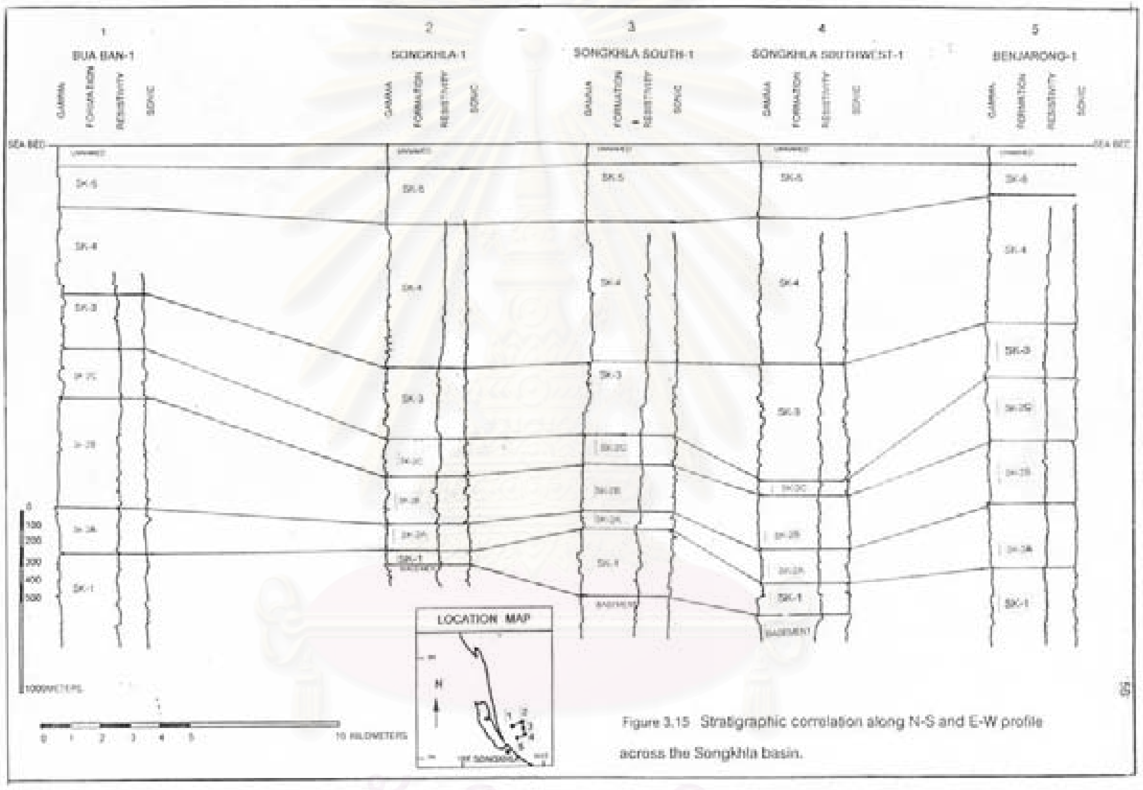


Figure 3.15 Stratigraphic correlation along N-S and E-W profile across the Songkhla basin.

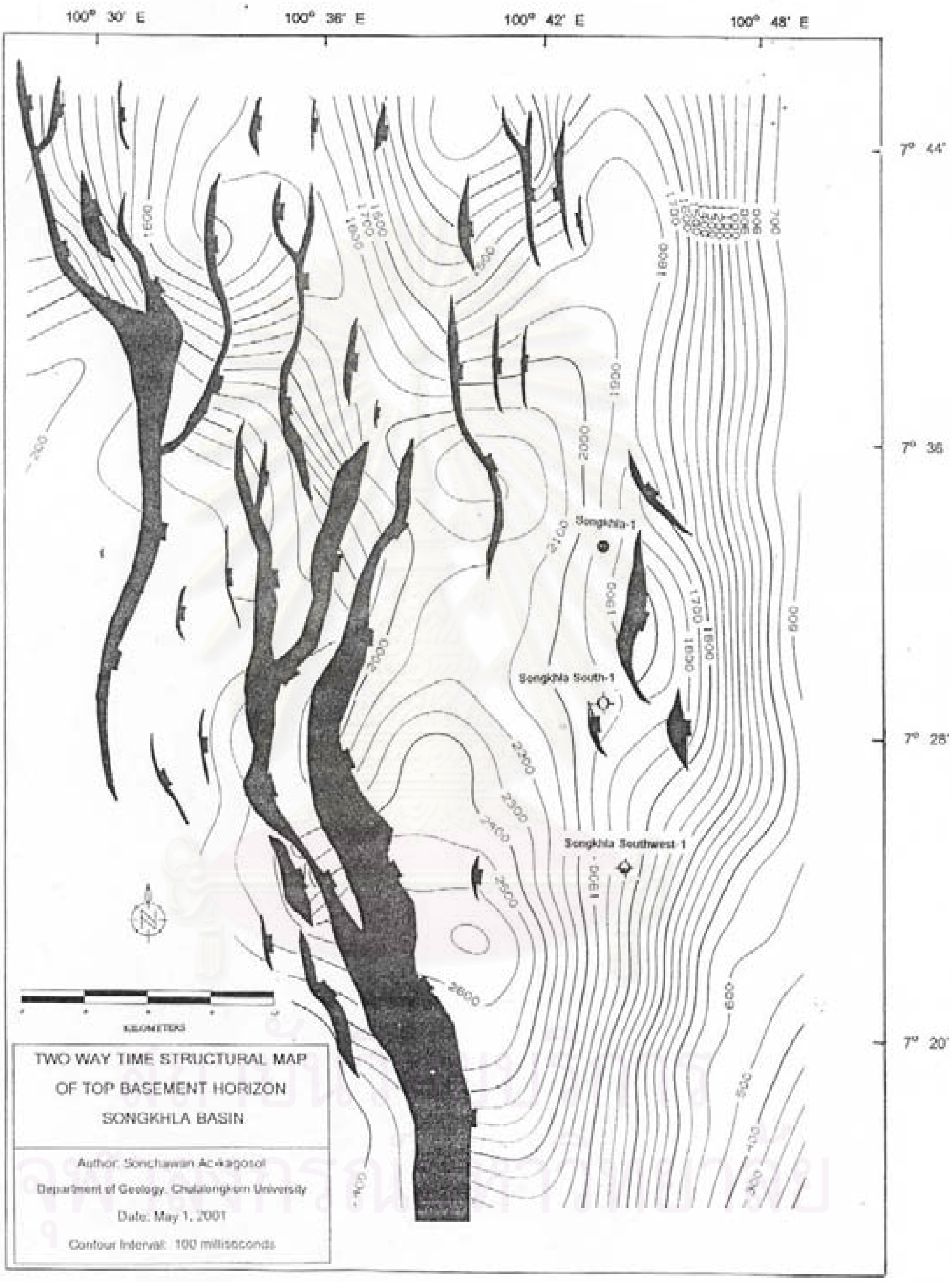


Figure 3.16 The TWT structural map of Top Basement Horizon of the Songkhla basin.

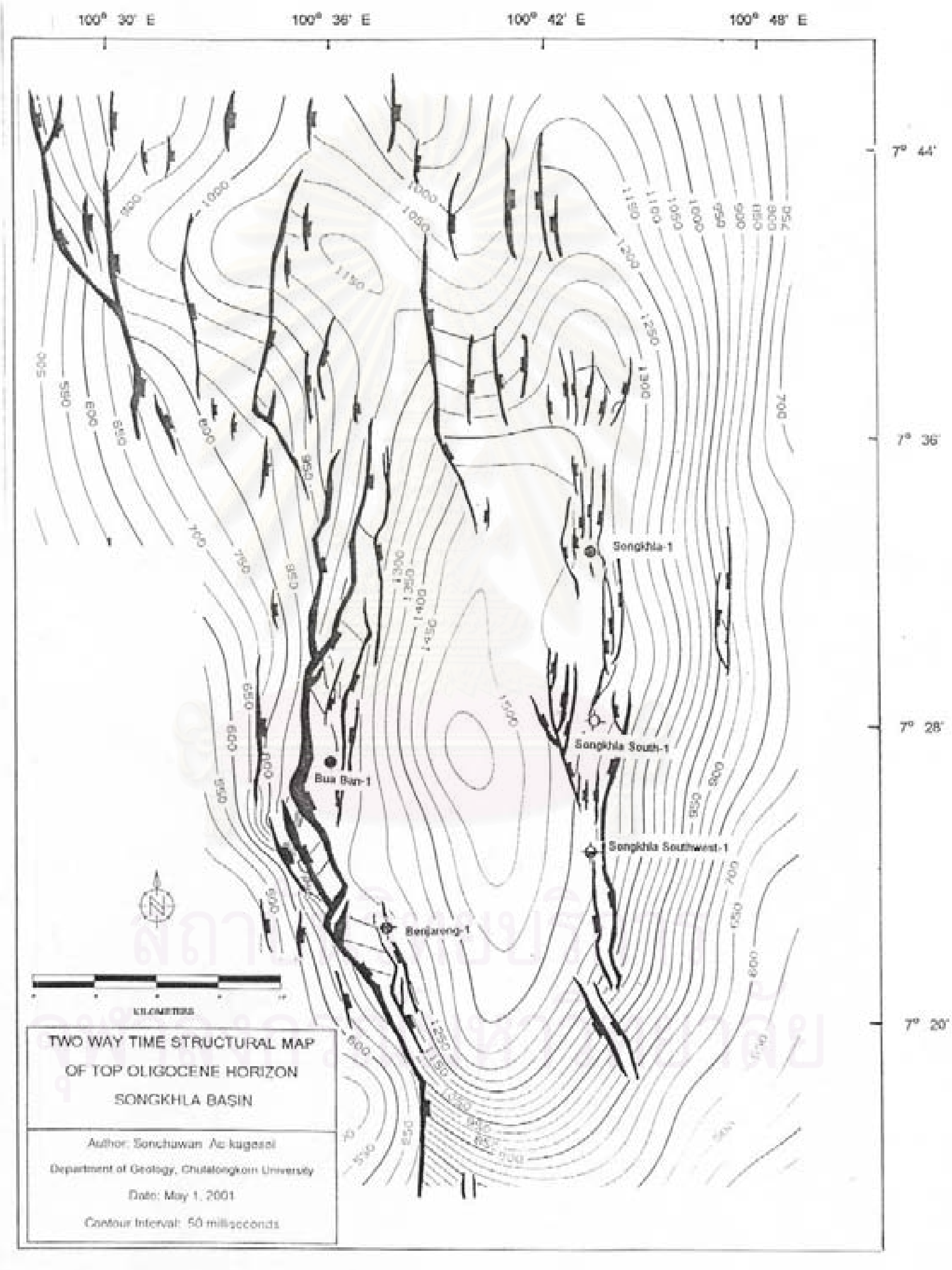


Figure 3.17 The TWT structural map of Top Oligocene Horizon of the Songkhla Basin.

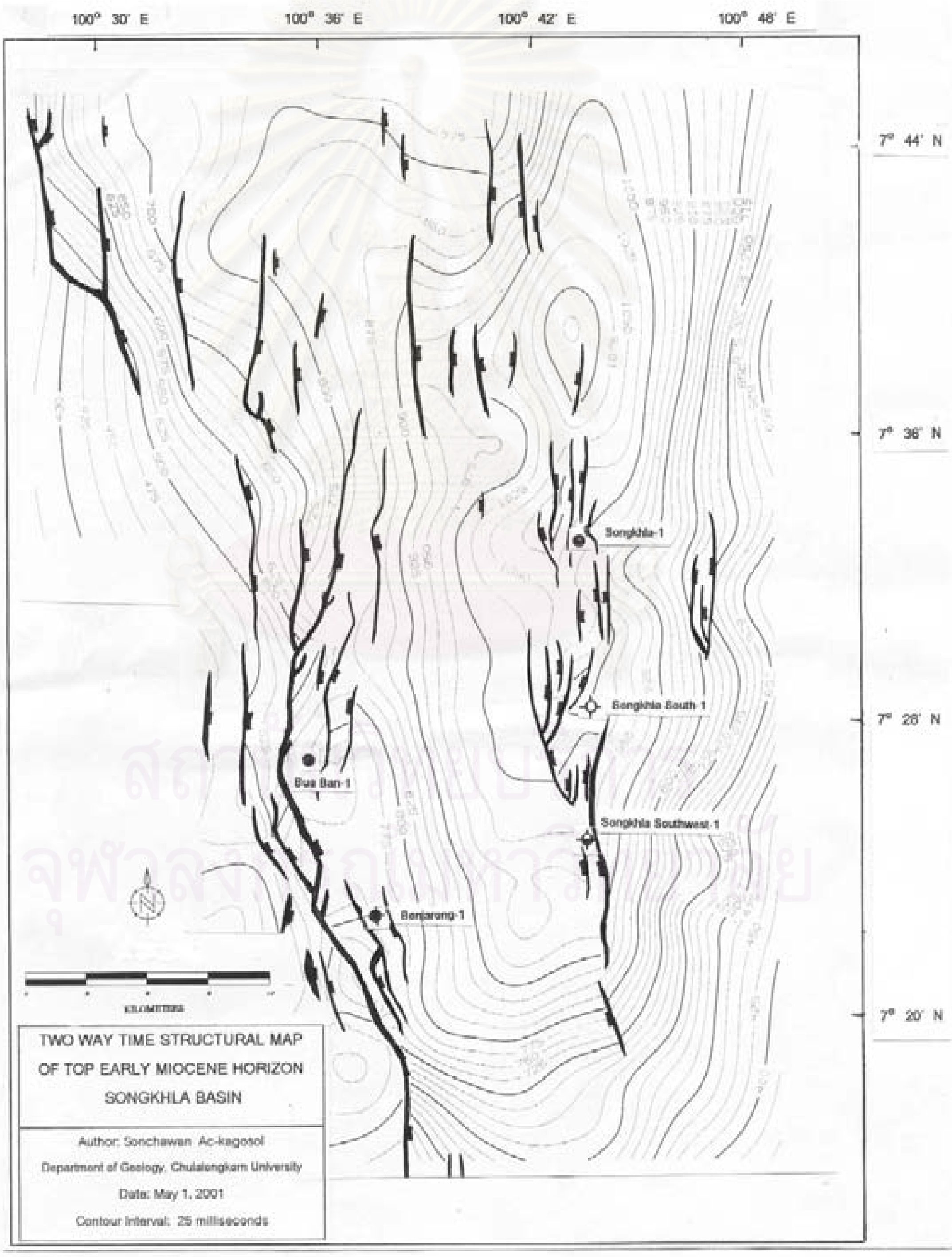


Figure 3.18 The TWT structural map of Top Early Miocene Horizon of the Songkhla Basin.

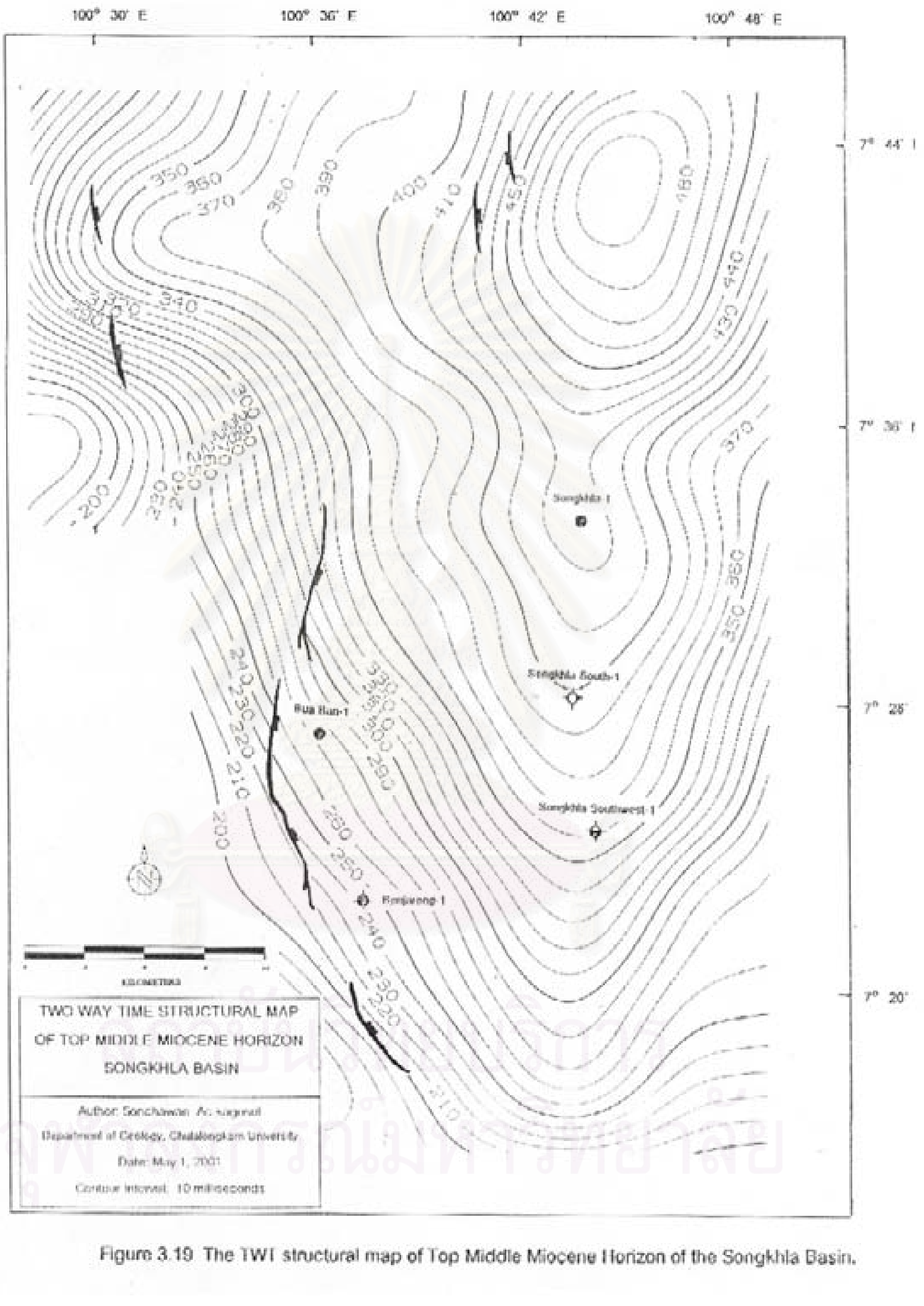


Figure 3.19 The TWT structural map of Top Middle Miocene Horizon of the Songkhla Basin.

CHAPTER IV

PETROLEUM GEOLOGY

Petroleum geology is one aspect of petroleum exploration and production. Moreover, petroleum geology concerns about generation, migration and accumulation of hydrocarbon. The hydrocarbon accumulation will occur in good conditions such as organic rich source rocks are large enough to generate the oil and/or gas and must have been heated sufficiently to yield their petroleum. The reservoir must have good porosity and permeability for containing the expelled hydrocarbon and must be sealed by an impermeable cap rock to prevent the upward escape of petroleum to the earth's surface. In addition, source rock, reservoir, and seal must be arranged in such a way as to trap the petroleum.

The hydrocarbon in Songkhla basin has been discovered in the Tertiary succession. Two of five wells, Songkhla-1 and Bua Ban-1 wells, found oil. They are proven to be oil bearing in the Early Oligocene sandstone. The Songkhla-1 well successfully flowed 30 °API oil at rate 1,500 BOPD while the Bua Ban-1 well flowed 29 °API oil at rate 768 BOPD. Thus, petroleum geology of the basin is very important for understanding of petroleum generation, migration and accumulation that can help to decrease the uncertainty in prediction of petroleum filled traps. It should be noted that the identifying of source rock and hydrocarbon potential of each source rock in time and space relate to the information of geologic evolution of the basin.

The petroleum geology of the Songkhla basin is described as follows.

Source Rock

For identifying petroleum source rock, rock cuttings and sidewall core samples were collected from Songkhla-1, Bua Ban-1, Songkhla South-1, Songkhla Southwest-1 and Benjarong-1 wells. The petroleum geochemistry was analyzed for organic content, kerogen type and thermal maturity by total organic carbon, Rock-Eval pyrolysis and vitrinite reflectance respectively and were studied by Core Laboratories International. TOC and vitrinite reflectance were analyzed on all wells. All of petroleum geochemical studies were replotted and reinterpreted. Unfortunately, Rock-Eval pyrolysis was analyzed only four wells because almost all Total organic carbon or TOC of Songkhla South-1 well are less than 1 wt.% which are non-source rock.

The primary source rock sequences in the Songkhla basin are generally dark gray claystone or shale of SK-2A Member and SK-1 Formation. Source rock mainly deposited in lacustrine and fluvial environments. The kerogen types are type I, II, and III because the organic matter derived from aquatic and terrestrial materials which can produce oil and/or gas reserves. However, source rock are immature in the shallow part of basin while in the deeper part of the basin they are early mature to mature source rock.

1. Organic Richness

The first requirement in the recognition of petroleum source rock is quantity of organic matter or organic richness. TOC is used to measure and identify source unit. In general, source rocks should be at least 1 wt.% TOC while rock with TOC less than 0.5 wt.% are non-source.

In Songkhla-1, Bua Ban-1, Songkhla South-1, Songkhla Southwest-1 and Benjarong-1 wells, the organic richness for each formation has been shown in Figure 4.1. As a whole, the organic richness of each well is only considered fair to good with almost 70% of all TOC determinations falling between 0.5 and 2 wt.%. In addition, approximately 20% of all TOC determinations is considered to have good to very good organic richness with TOC falling above 2 wt.% which is dominant in deeper part of the basin. Except the Songkhla South-1, only one well contains non-source rock because most TOC determinations are less than 1 wt.%. It should be mentioned that the highest TOC value is up to 5.26 wt.% occurring in SK-2A at the Benjarong-1 well. The distribution of organic matter in the Songkhla basin is influenced by depositional setting especially high total organic content are in the lacustrine environment. Consequently, the possible source rock unit in the Songkhla basin is generally dark gray claystone or shale of SK-2B, SK-2A Member and SK-1 Formation due to the average TOC of these units are 1.13, 1.63 and 1.21 wt.% that are greater than 1 wt.%. Most organic rich interval are located in both of western and eastern flank of basin where they may exceed 850 meters in thickness. Nevertheless, the total organic content may increase toward the basin center where lake is the deepest portion.

2. Type of Organic Matter

Kerogen is the portion of the organic matter in the sedimentary rock which is insoluble in ordinary organic solvents. The different kinds of kerogen in the basin are important aspect in predicting oil and/or gas occurrences. The organic geochemical classification of kerogen is divided into three types. A Van Krevelen diagram, expressed in atomic H/C and O/C ratio or Hydrogen Index and Oxygen Index, determines type of organic matter. The Hydrogen Index and Oxygen Index cross plots of Songkhla-1, Songkhla Southwest-1 and Benjarong-1 wells are shown in Figure 4.2. In the Songkhla basin, kerogen types, I, II and III, are really mixtures. In Songkhla-1 and Benjarong-1 wells, the kerogen types are generally type II and III but some kerogens of Benjarong-1 well are type I. Furthermore, kerogen type of Songkhla Southwest-1 is mainly type I with occasionally type II. Oligocene sediment, SK-2B and SK-2A, consists of type I and II so that the environment of deposition is lacustrine with occasionally marine transgression confirmed with parasequences. Nevertheless, the SK-1 Formation is composed of type I and III deposited in fluvio-lalustrine. The difference of kerogen type affects to the hydrocarbon production. Kerogen type I generally consists of algal material that is a very good oil source. Kerogen type II has a relatively high hydrogen content like type I but generated less significant amount of hydrocarbon. Kerogen type III mainly consisting of terrestrial higher land plants transported to the central of the basin that are lacustrine gives gas source and little potential for hydrocarbon generation. In summary,

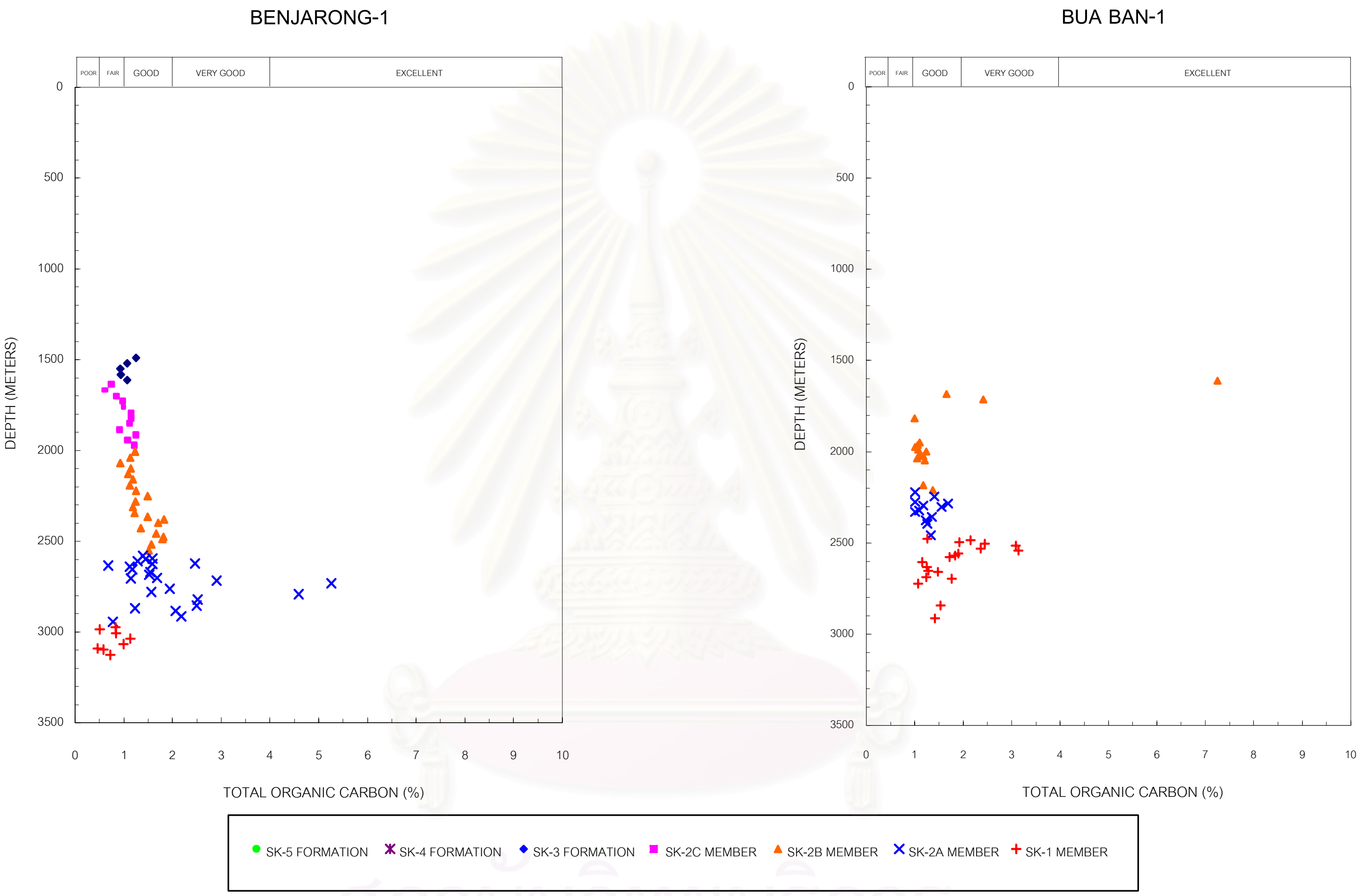


Figure 4.1) Plots of total organic carbon versus depth for each well.

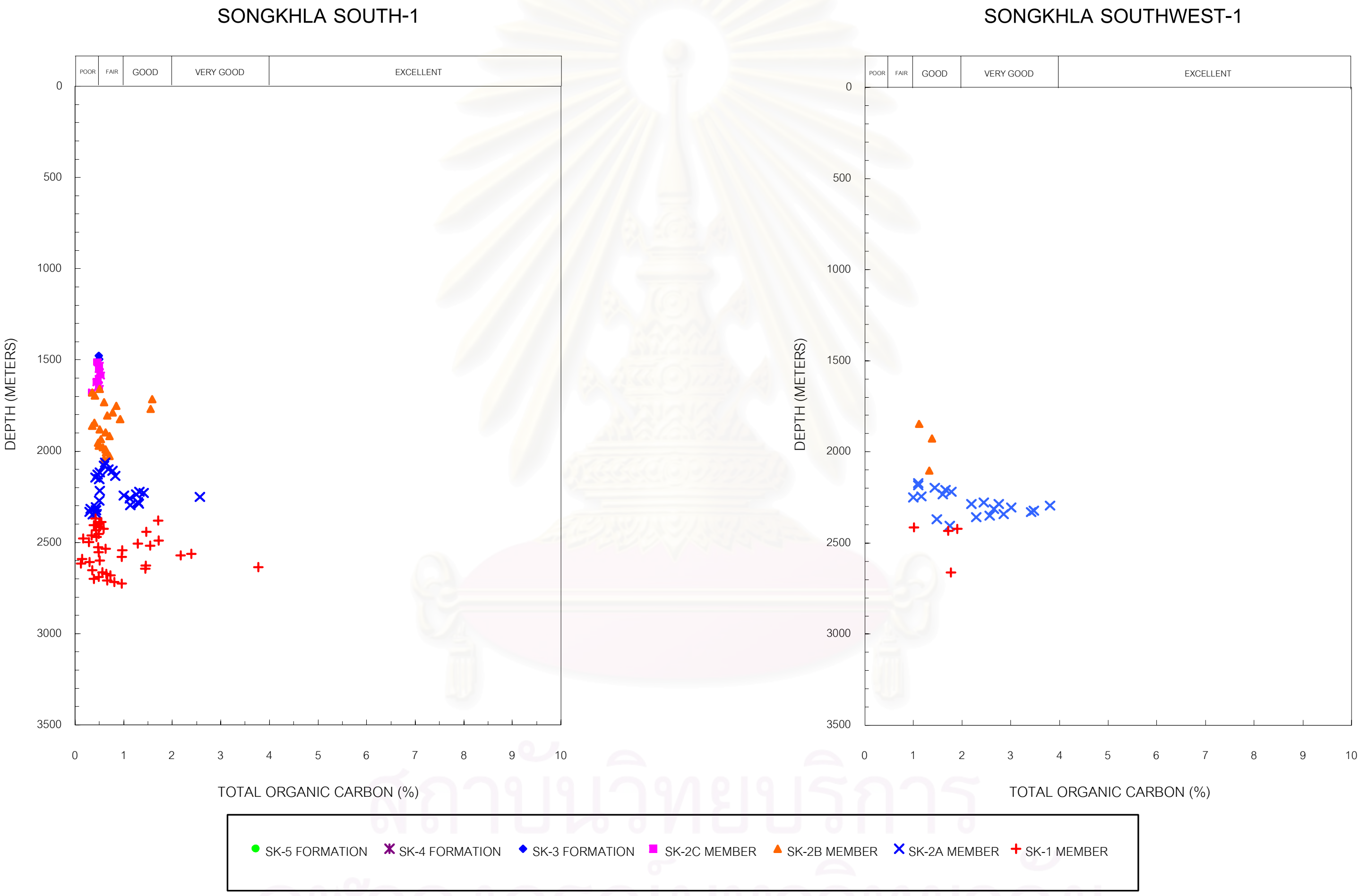


Figure 4.1 (cont.) Plots of total organic carbon versus depth for each well.

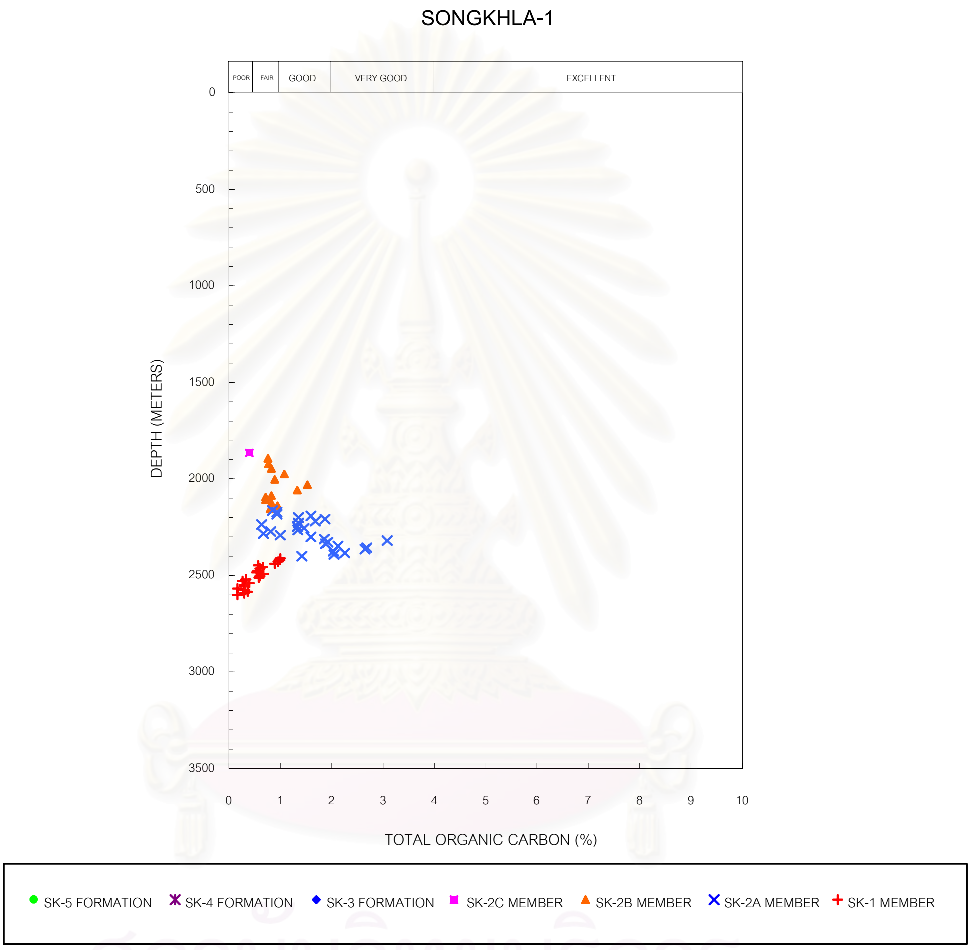


Figure 4.1 (cont.) Plots of total organic carbon versus depth for each well.

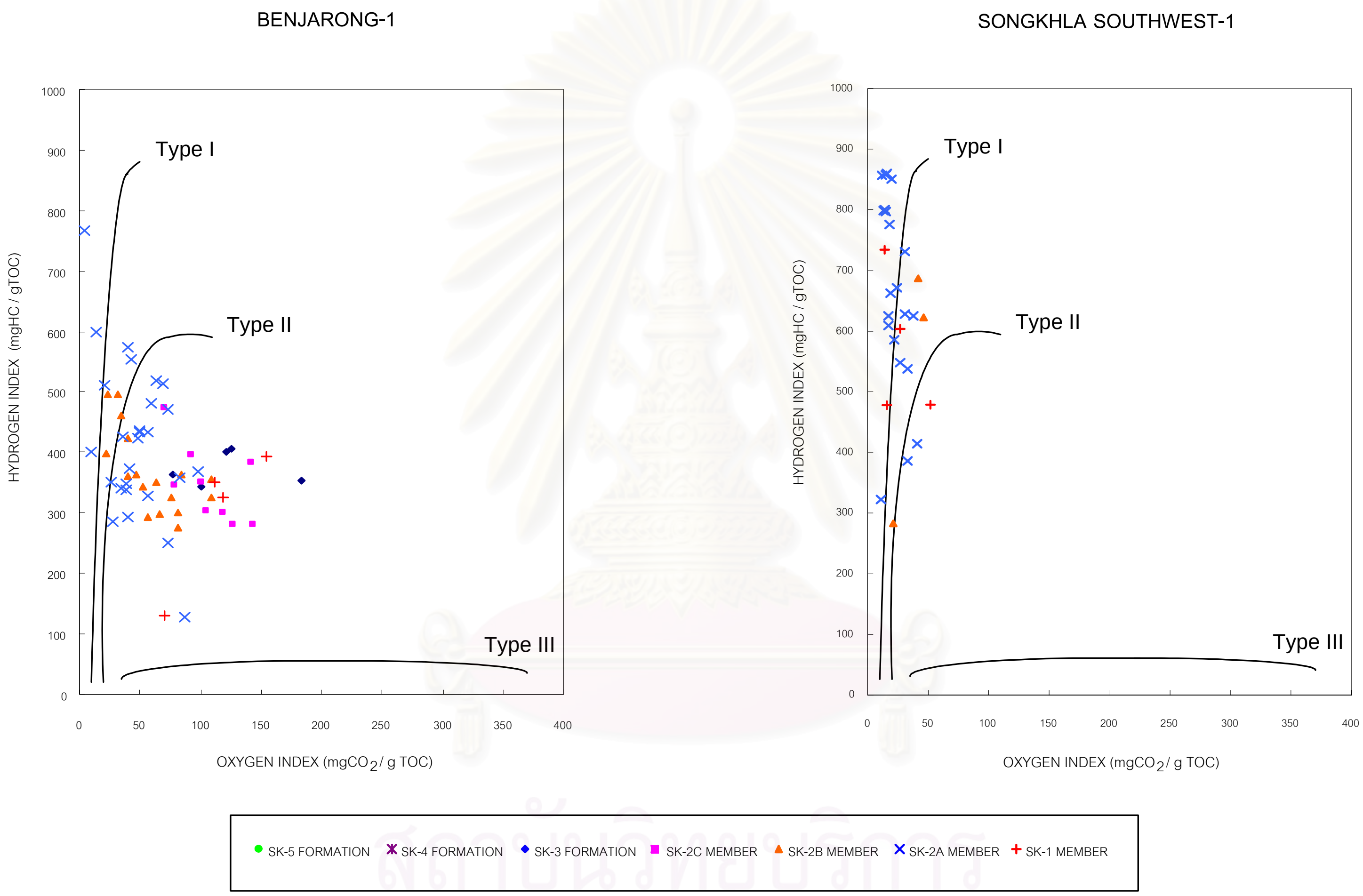


Figure 4.2 Plots of hydrogen index versus oxygen index for each well.

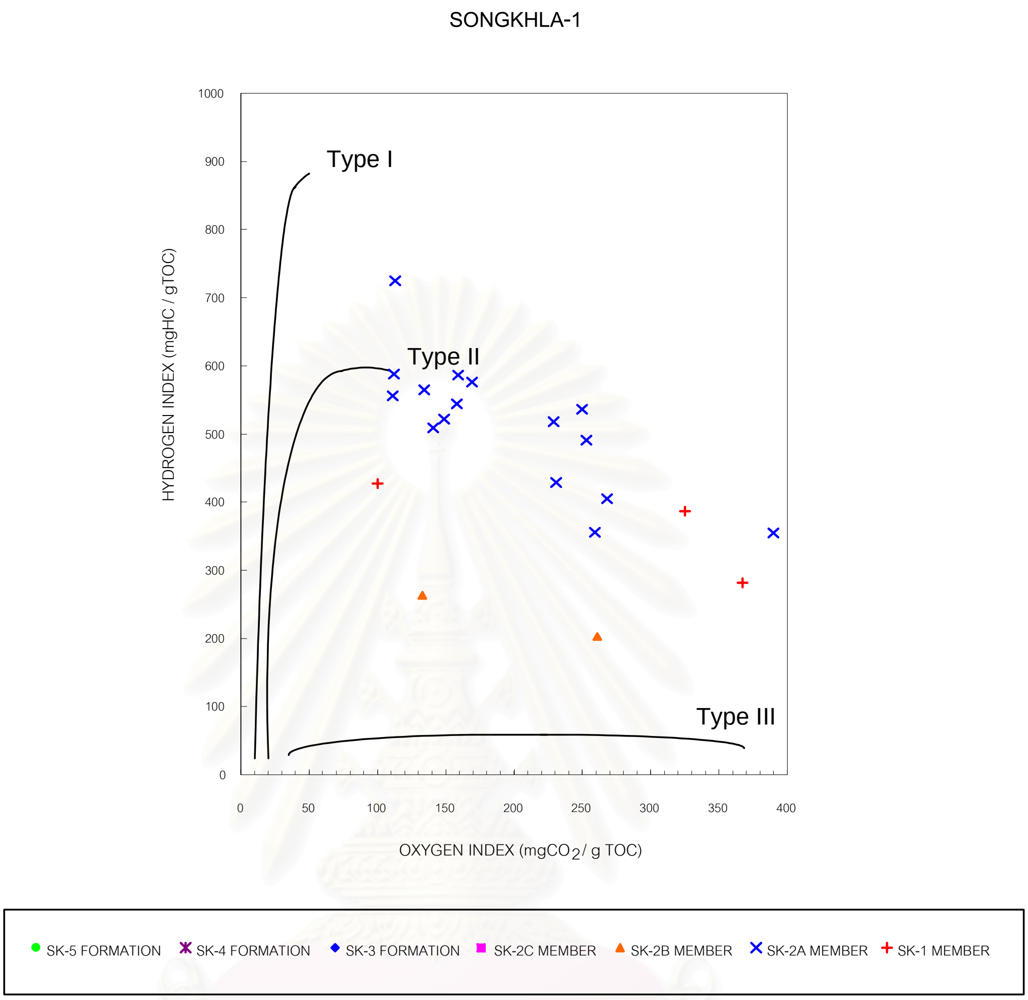


Figure 4.2 (cont.) Plots of hydrogen index versus oxygen index for each well.

kerogen type of the Songkhla basin suggests that organic matters maybe prime oil prone source rock and/or gas source rock in the Oligocene sediment.

3. Thermal Maturity

Thermal evolution of source rock changes many physical and chemical properties of the organic matter. The maturation is analyzed by optical and physiochemical analysis of kerogen such as vitrinite reflectance and pyrolysis. The source rock is considered to be immature or diagenesis if it has never generated petroleum, mature or catagenesis if it is generating petroleum now and the overmature or metagenesis if it has gone beyond the generation of liquid and can only generate gas.

Vitrinite reflectance (Ro) is the most widely used for indicator of source rock maturity. Generally, oil generation referred to oil window occurs for vitrinite reflectance values between 0.6 and 2 %. Vitrinite reflectance profiles from wells increase regularly with increasing stratigraphic depth as shown in Figure 4.3. The maturity of source rock in each well, Ro, varies from immature in shallow portions to early mature in deeper portions. Accordingly, the oil generation of Songkhla basins should occur approximately 2,000 meters.

From Songkhla-1 well, vitrinite reflectance values range from 0.2 to 0.93 that indicate the well section to be immature to mature for hydrocarbon generation. The hydrocarbon significant generation occurs below 1,900 meters. Within the SK-2A Member and SK-1 Formation, source rock is mature to generate hydrocarbon now due to the Ro exceeds 0.6 %. From the results of drilling of the Songkhla-1 well discovered oil in SK-2A Member, which is 30 °API in this formation so that the Ro value makes clear to confirm hydrocarbon generation.

The maturation of Songkhla South-1 and Songkhla Southwest-1 wells generally ranges immature to marginal mature from shallow to deeper portions. Almost Ro values are less than 0.5 % throughout both sections but some parts of the SK-1 Formation are more than 0.6 %. Even though the early mature is in SK-1 Formation but no hydrocarbon generate because these wells located in eastern flank of basin that is low subsidence and low heated insufficiently to yield hydrocarbon.

From the Bua Ban-1 well, the vitrinite reflectance values range from 0.41 to 1.32 that are immature to mature. Below 1,800 meters, the maturity is early mature and the mature source rock is below 2,800 meters. As the results of drilling of Bua Ban-1 well, oil is discovered in the SK-2A Member where the member yields enough heated. From Benjarong-1 wells, the vitrinite reflectance values range from 0.22 to 0.74. Most source rocks are immature to early mature with occasionally mature.

The pyrolysis method, transformation ratio and peak temperature (Tmax) is also used to judge maturation level. The transformation ratio or S1/(S1+S2) which is the ratio of hydrocarbon already to generate to the total generation potential plotted against depth, the transformation ratio will generally show a gradual increase as the source rock mature. From transformation ratio plot, the immature/mature boundary is at about 0.1 and the mature/overmature boundary is at about 0.4.

Transformation ratio of Songkhla-1, Bua Ban-1 and Benjarong-1 wells shown in Figure 4.4 is mostly greater than 0.1 in SK-2A Member and SK-1 Formation indicating oil generation potential; however all transformation ratio of Songkhla Southwest-1 well are less than 0.1 that confirms a source rock of this well cannot generate hydrocarbon.

Tmax is the temperature recorded at the maximum point of hydrocarbon generation during the pyrolysis. The onset of maturity marks at 435°C and overmaturity marks at 470°C. From Songkhla-1, Bua Ban-1 and Songkhla Southwest-1 wells, almost of Tmax determinations of those wells are immature in shallow portions to mature in deeper portions of basin as illustrated in Figure 4.5. Tmax of SK-2B Member generally ranges 420 – 440°C that is immature to early mature source rock. The SK-2A Member and SK-1 Formation are early mature to mature source rock that comprise 430 – 445 $^{\circ}$C.

Tmax of source rock in the basin are in ranges because of the different kerogen type of source rocks which occurred in fluvio-lacustrine. Tmax values of SK-2A Member and SK-1 Formation in the western flank of basin are higher than in the eastern flank of basin so that the opportunity of hydrocarbon generation may mainly occur in western basin.

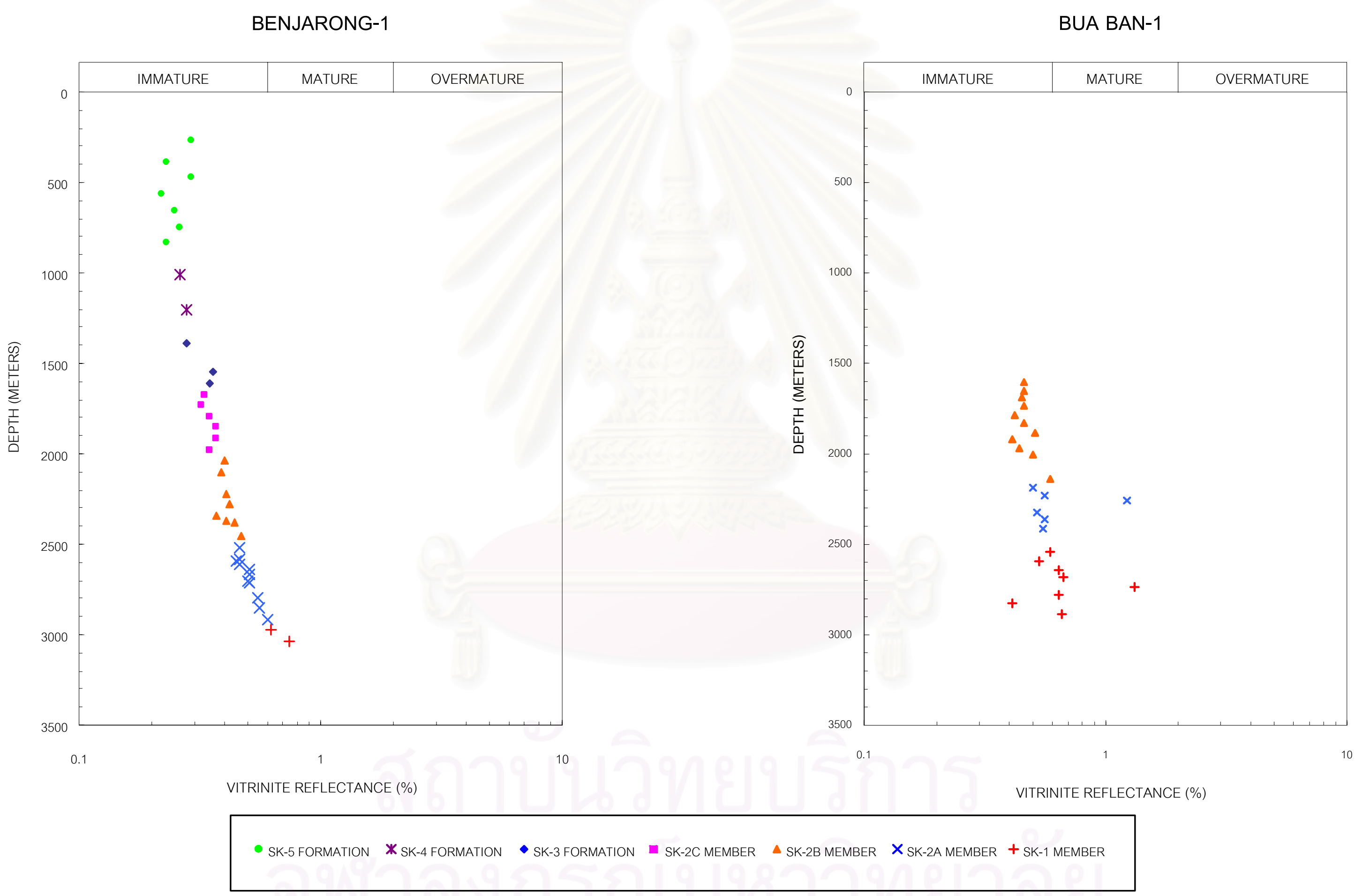
In summary, the thermal maturity of source rock of the Songkhla basin ranges from immature to mature source rock that indicated by vitrinite reflectance with transformation ratio and Tmax. The immature source rock generally locates in shallow parts of basin especially above SK-2A Member; however the early mature to mature source rock are SK-2A Member and SK-1 Formation where average depth is below 2,000 meters. The mainly mature source rock is in the deeper part of the western flank of basin. Nevertheless, the central part of the basin fortunately occurs as mature source rock.

4. Generation Potential

Generation potential can be achieved by using pyrolysis. The S1+S2 is an evaluation of the genetic potential whereas S1 represents the fraction of the original genetic potential that has been effectively transformed into hydrocarbon and S2 represents the other fraction of the genetic potential. The S1+S2 that is greater than 2.5 mg HC/g rock is considered to be the potential source rock.

The generation potential indicates fair to excellent for hydrocarbon generation in organic rich samples as shown in Figure 4.6. The high values of organic richness and generation potential indicate that significant oil and/or gas generation can be expected from fair to very good source rock within the peak of thermal maturity. From Songkhla-1, Bua Ban-1, Songkhla Southwest-1, and Benjarong-1 wells, the generation potential mostly presents in SK-2A Member and SK-1 Formation containing 9.58 mg HC/g rock average S1+S2. All of them indicate fair to excellent generation potential. Additionally, the transformation ratio, Ro and Tmax show that the SK-2A Member and SK-1 Formation are mature source rock effectively transformed into hydrocarbon generation. As the

Figure 4.3 Plots of vitrinite reflectance versus depth for each well.



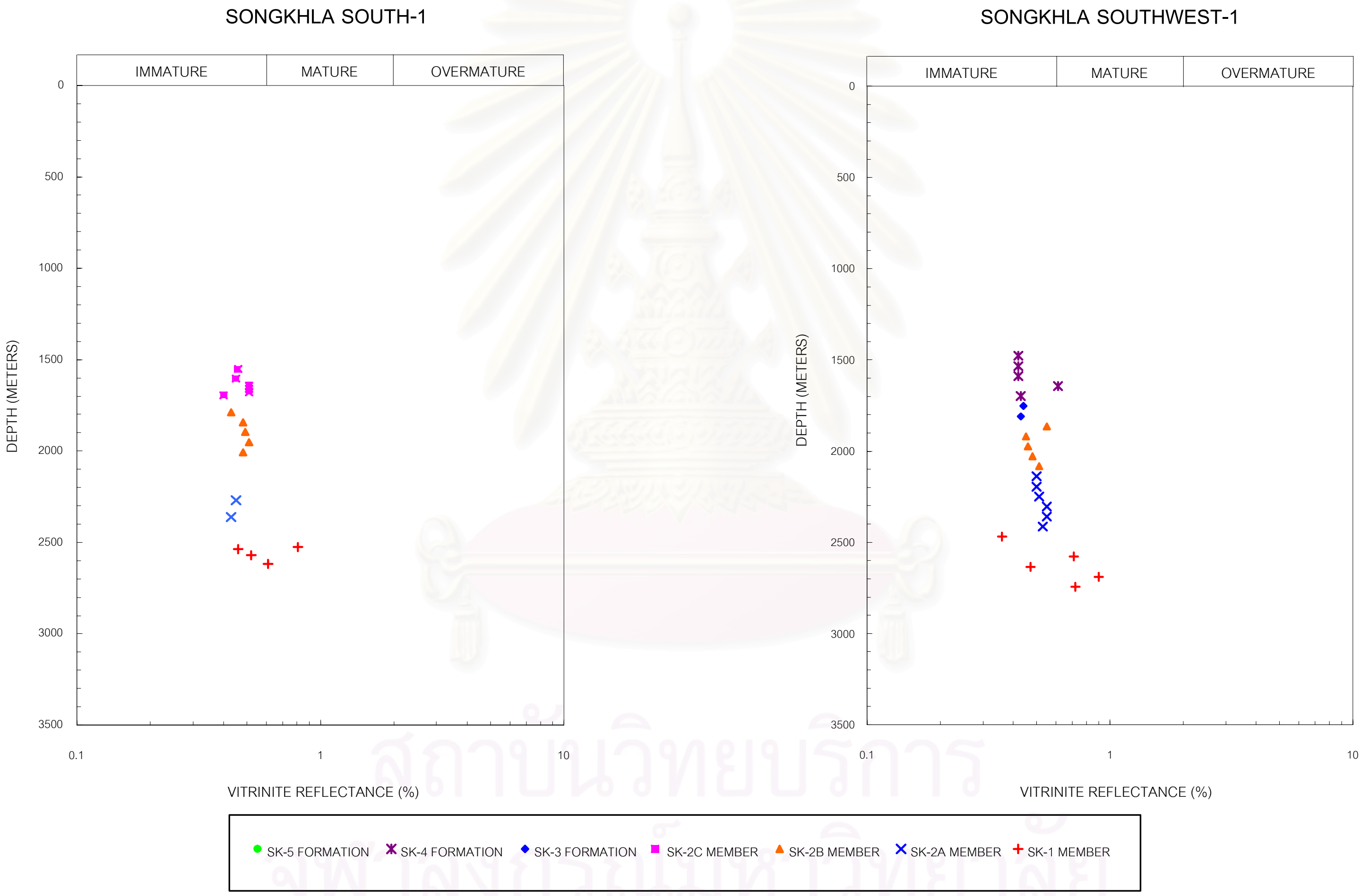


Figure 4.3 (cont.) Plots of vitrinite reflectance versus depth for each well.

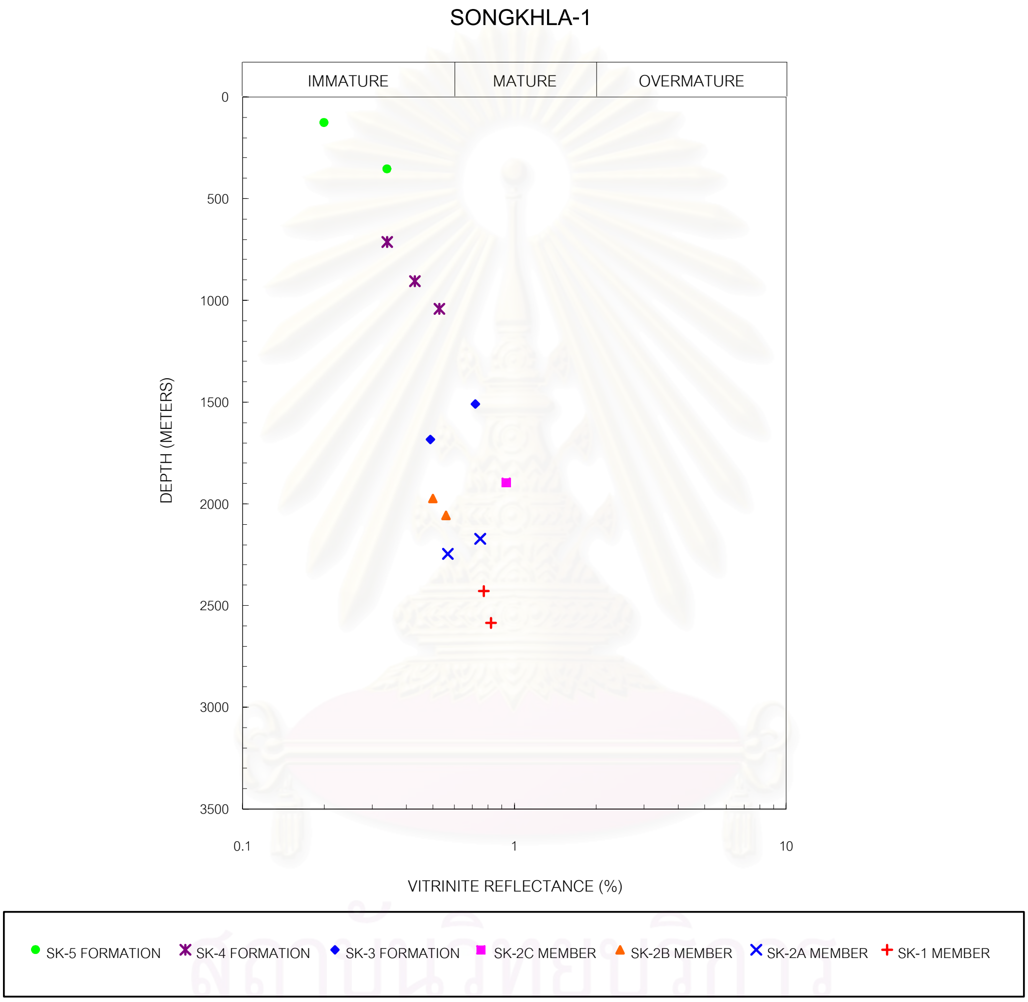


Figure 4.3 (cont.) Plots of vitrinite reflectance versus depth for each well.

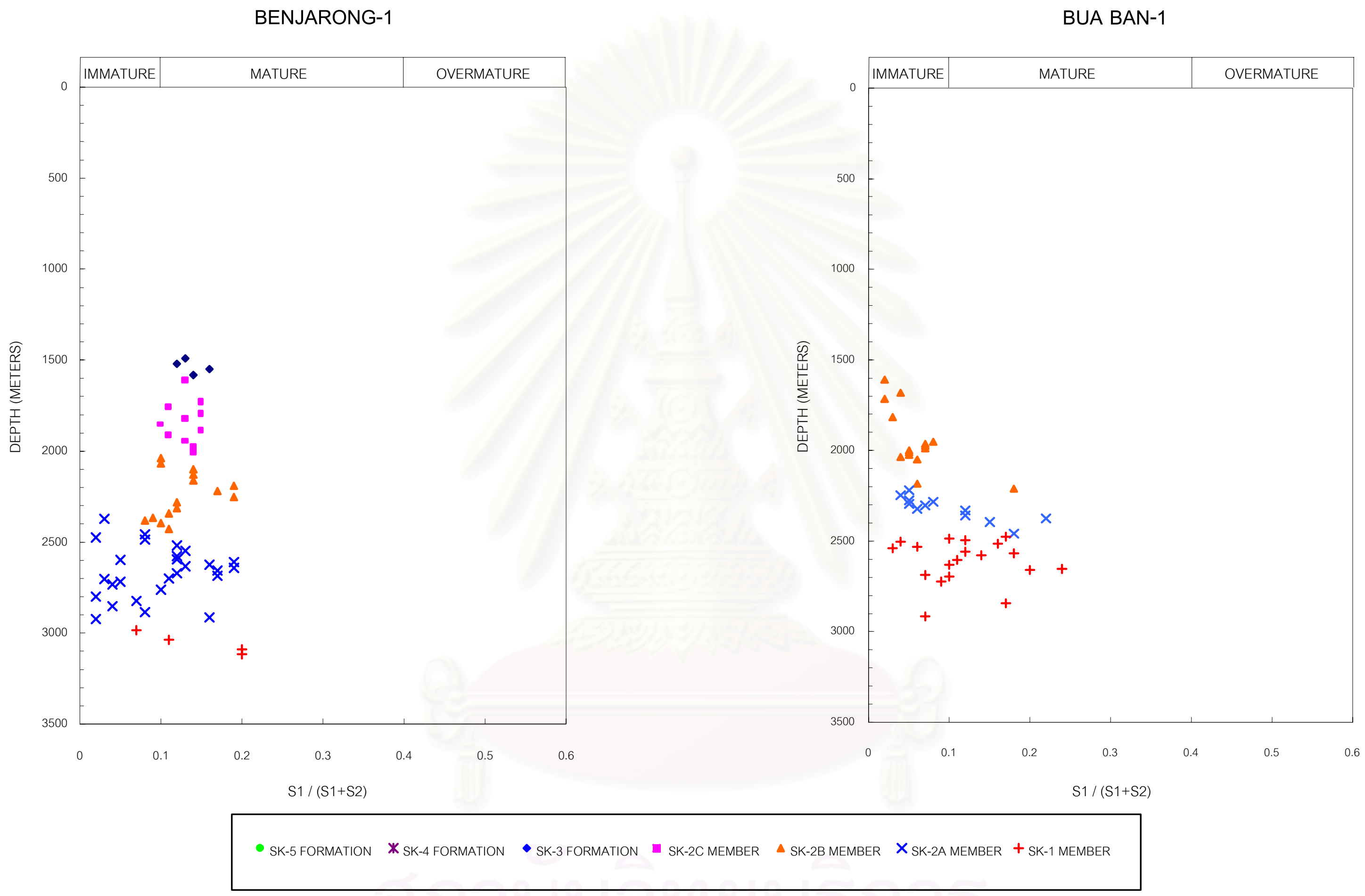


Figure 4.4 Plots of transformation ratio versus depth for each well.

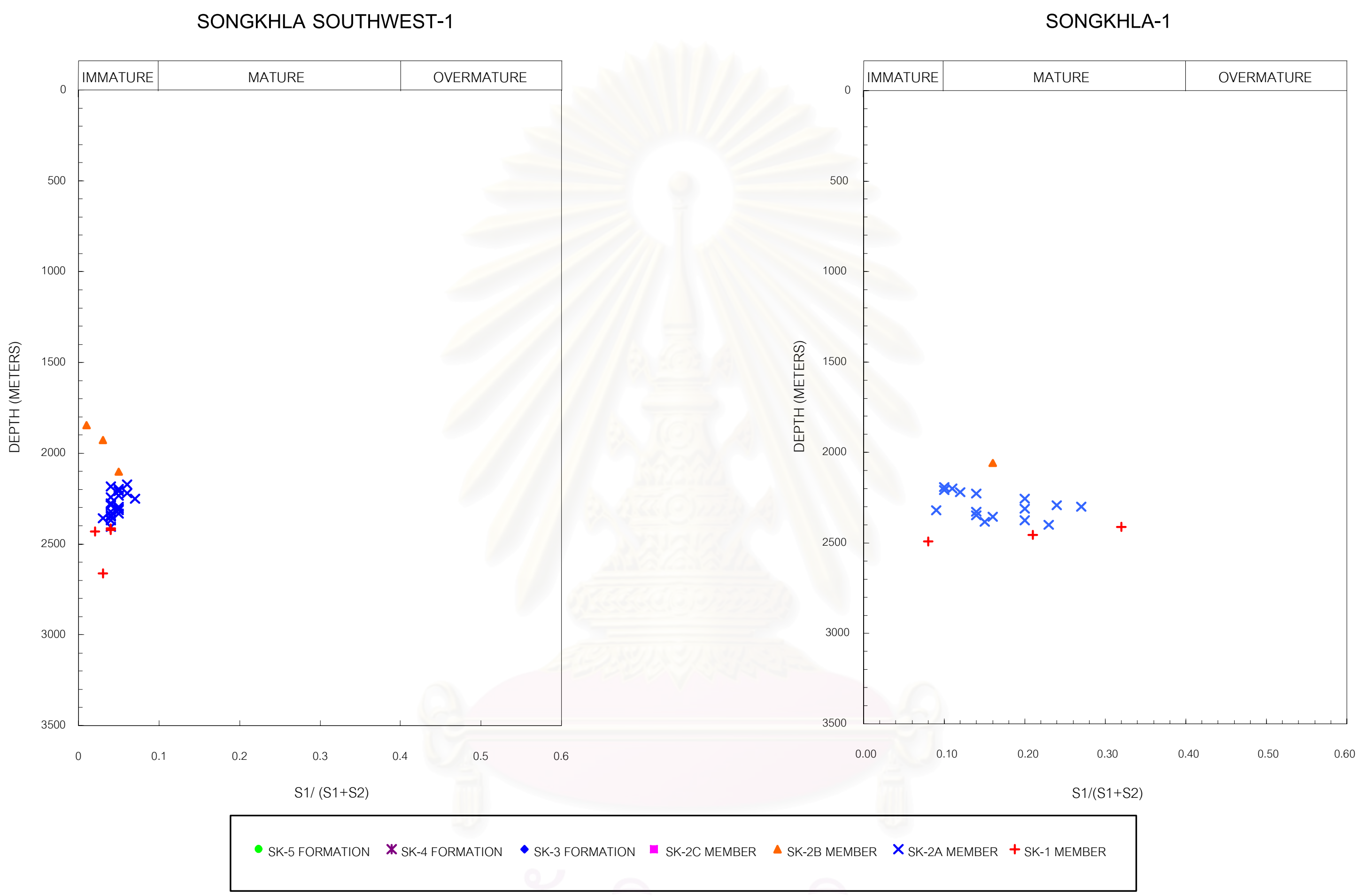


Figure 4.4 (cont.) Plots of transformation ratio versus depth for each well.

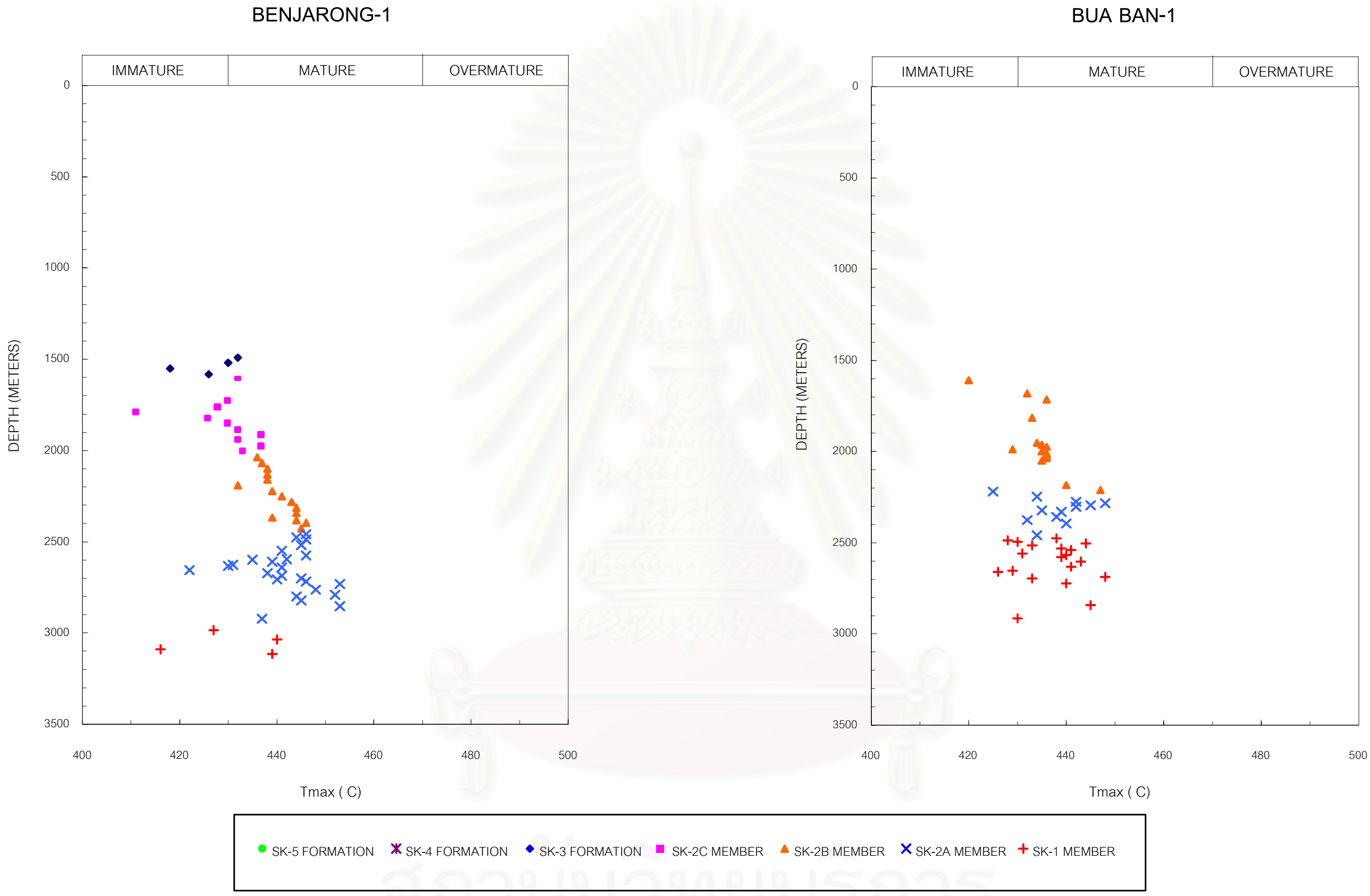


Figure 4.5 Plot of Tmax versus depth for each well.

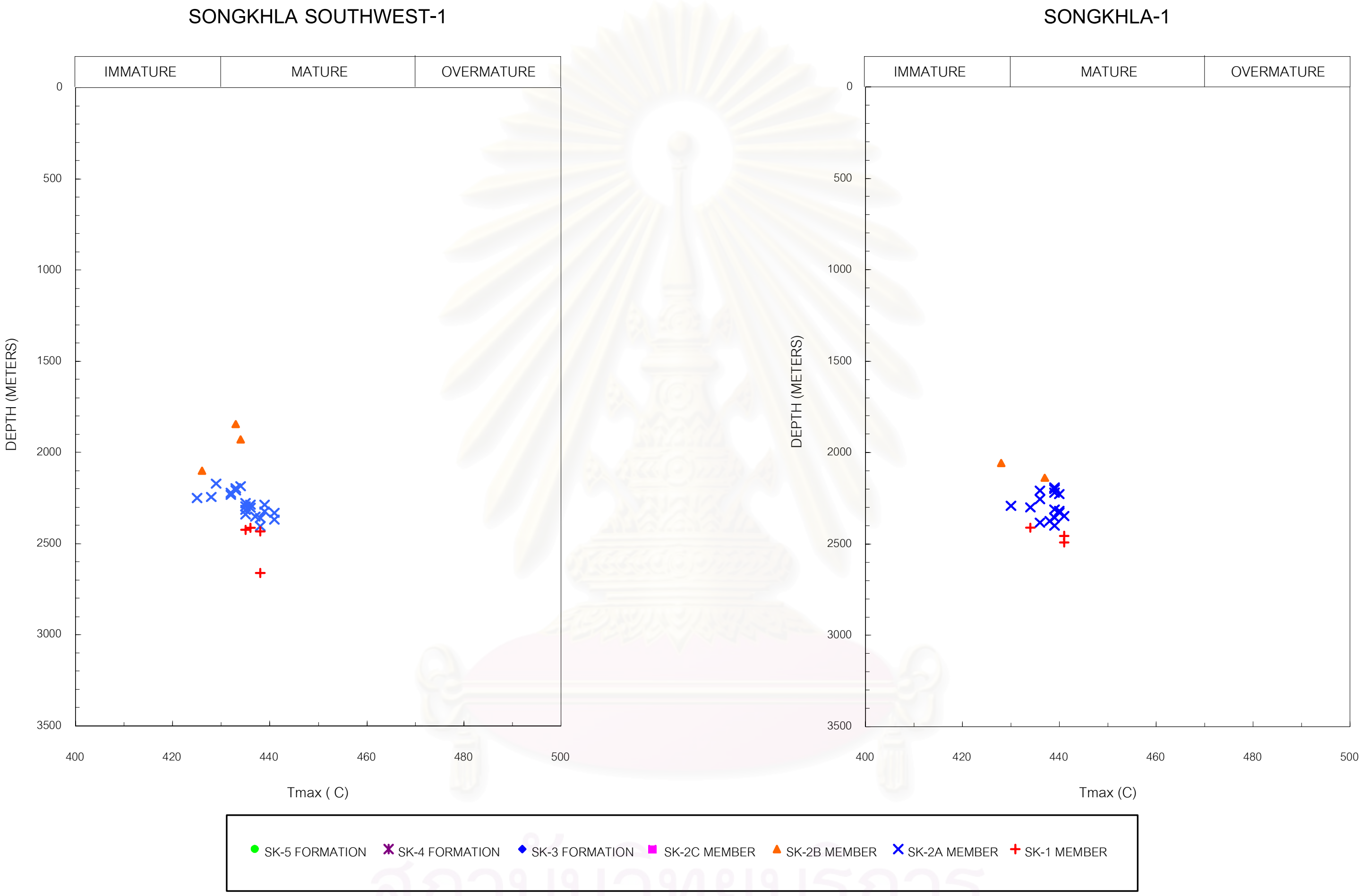


Figure 4.5 (cont.) Plot of Tmax versus depth for each well.

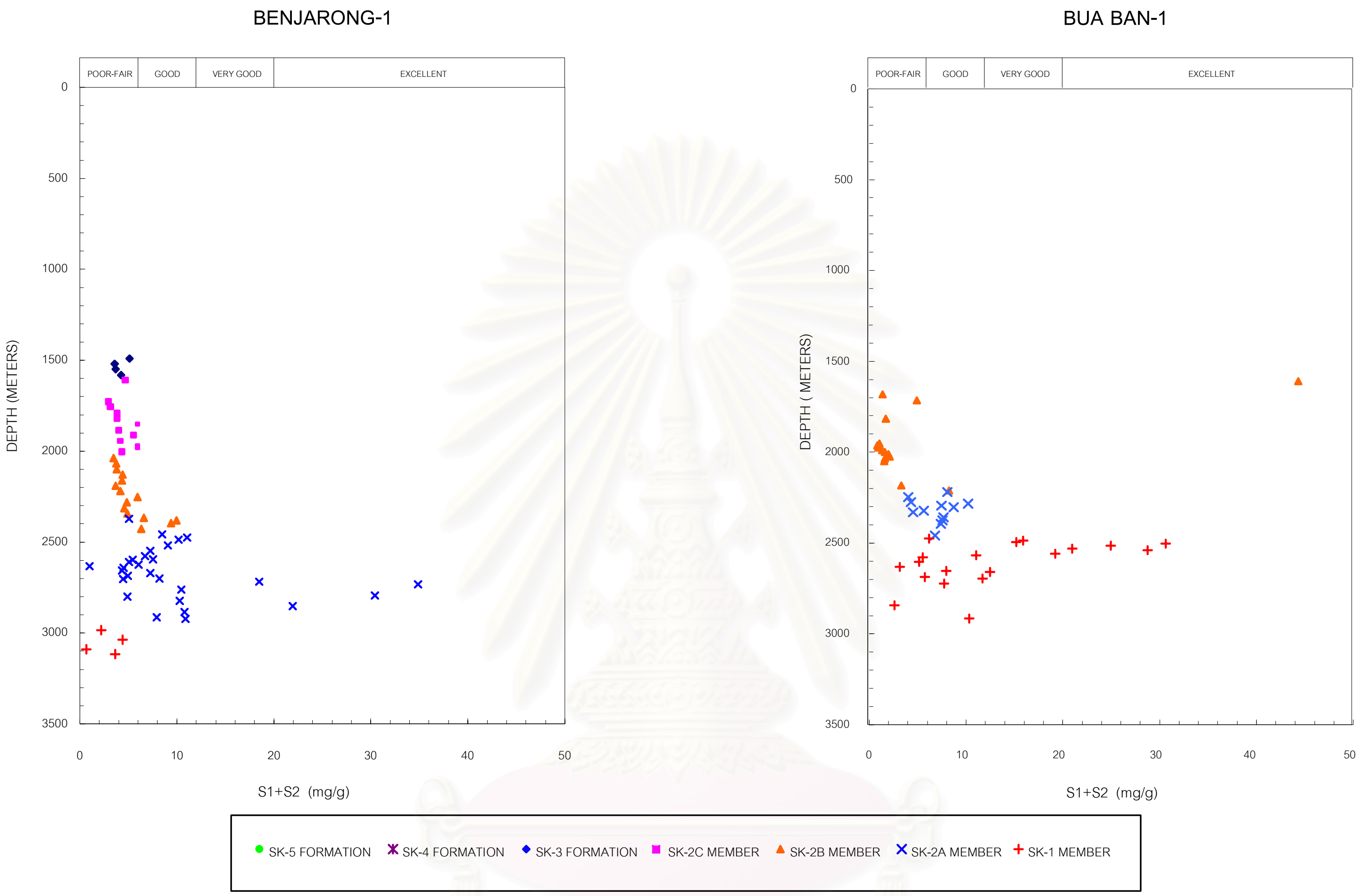


Figure 4.6 Plots of hydrocarbon generation potential versus depth for each well.

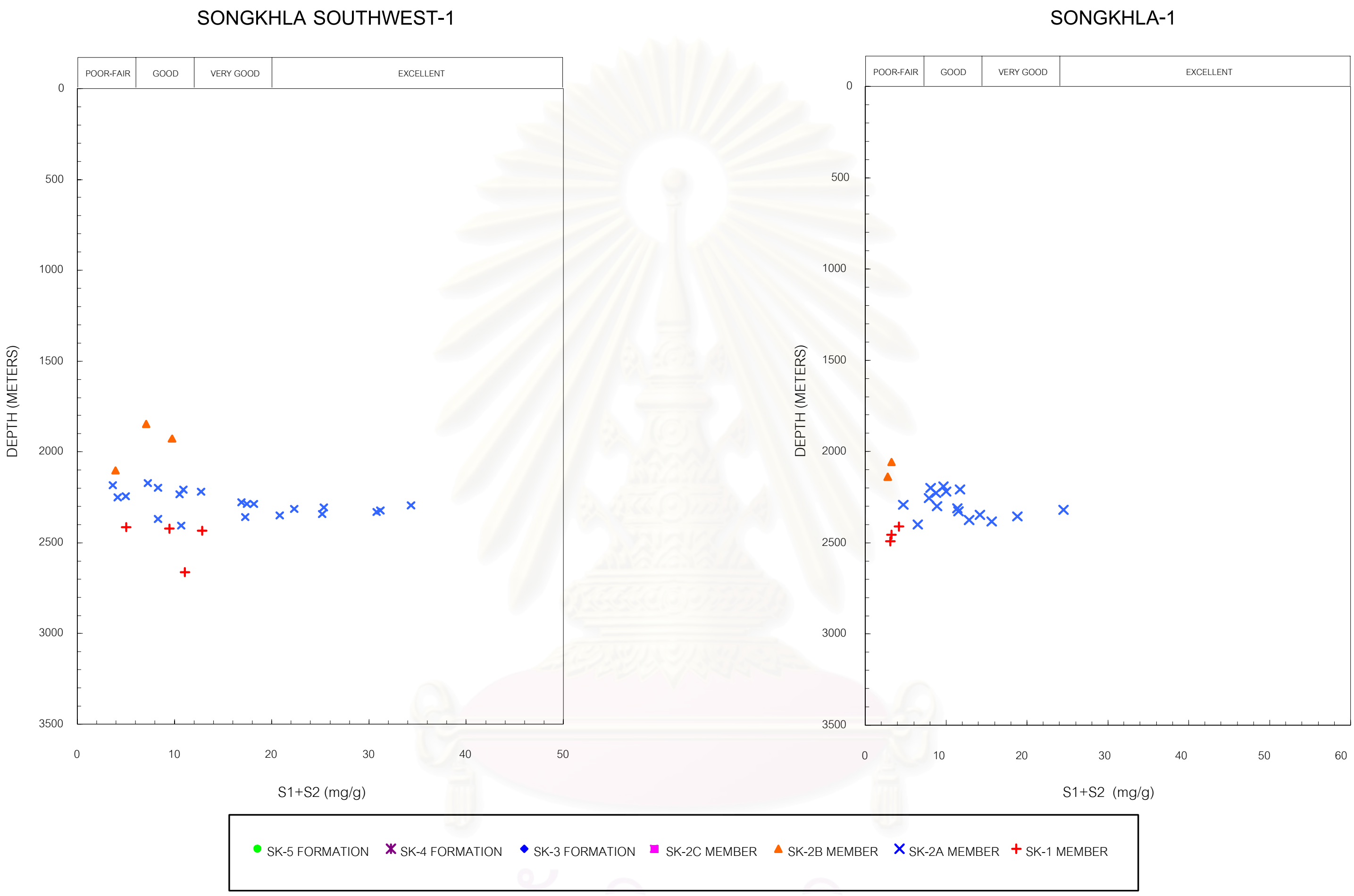


Figure 4.6 (cont.) Plots of hydrocarbon generation potential versus depth for each well.

result, the opportunity of generation potential in the Songkhla basin is SK-2A Member and SK-1 Formation.

5. Source Rock Volumetric

Source rock of the Songkhla basin is predominant in SK-2A Member and SK-1 Formation, which are mature source rock units. The mature source rock area and volume that calculated by CPS-3 are approximately 570 km^2 and 300 km^3 respectively.

CPS-3 is an application program of Schlumberger. Volumetric operation is one operation in CPS-3 which can calculate the volume of a modeled enclosure bounded on the top by surface, on bottom by a reference plane and on the size by polygon or interesting area (Figure 4.7a & b). To calculate volumes, CPS-3 uses an integration method that follows surface curvature within a grid cell. CPS-3 assumes input surface as a thickness on isopach grid, but CPS-3 does not calculate the thickness between two input surface (top and base) automatically. Before volumetric calculation, the thickness or isopach is calculated by multisurface operation that is one operation of CPS-3.

Generally, vitrinite reflectance of mature source rocks should be at least 0.6% Ro. The SK-2A Member and SK-1 Formation where average depth is deeper than 2,000 meters beneath the seabed are mainly mature source rock of the basin. From Songkhla-1, Benjarong-1, Bua Ban-1 and Songkhla Southwest-1 wells, the generation potential of mature source rock is approximately 9.58 mg oil/g rock and 9.58 kg oil/ton rock resulted from pyrolysis and illustrated in Table 4.1.

Where: oil density = 0.88 g/cm^3

rock density = 2.3 g/cm^3

Thus, Oil 0.88 g, Volume = 1 cm^3 = 10^{-6} m^3

Oil 9.58 kg, Volume = $(10^{-6} x\ 9.58\ x 10^3) / 0.88$ = $1.09x10^{-2}$ m^3

Rock 2.3 g, Volume = 1 cm^3 = 10^{-6} m^3

Rock 1000 kg, Volume = $(10^{-6} x1000x10^{3}) / 2.3 = 4.35x10^{-1}$ m^3

So that, Rock $4.35 x10^{-1} m^3$ contain oil = 1.09×10^{-2} m^3

Rock 1 km^3 contain oil = 25×10^{6} m^3

The generation potential of mature source rock is 25×10^{6} m^3oil/ km^3rock

From the CPS-3, the volume of mature source rock of the Songkhla basin is approximately 300 km^3. Therefore, the volume of generation potential is

$25 \times 10^{6} \times 300$ = 7.5×10^{9} m^3oil

For more appropriate volumetric unit,

m^3oil converts to MMbbl by multiplying of 6.2897×10^{-6}.

Thus, the volume of generation potential is 47170 MMbbl or 47 Bbbl

Generated oil in the Songkhla basin is 0.86 mg oil/g rock or 0.86 kg oil/ton rock

Thus, Oil 0.88 g, Volume = 1 cm^3 = 10^{-6} m^3

Oil 0.86 kg, Volume = $(10^{-6} x 0.86 x10^{3}) / 0.88 = 9.77x10^{-4}$ m^3

So that, Rock $4.35 x10^{-1} m^3$ contain oil = 9.77×10^{-4} m^3

Rock 1 km^3 contain oil = 2.25×10^{6} m^3

The generated oil of mature source rock is 2.25×10^{6} m^3oil/ km^3rock

From the CPS-3, the volume of mature source rock of the Songkhla basin is approximately 300 km^3. Therefore, the volume of generation potential is

$2.25 \times 10^{6} \times 300$ = 0.68×10^{9} m^3oil

For more appropriate volumetric unit,

m^3oil converts to MMbbl by multiplying of 6.2897×10^{-6}.

Thus, the volume of generation potential is 4280 MMbbl or 4.3 Bbbl

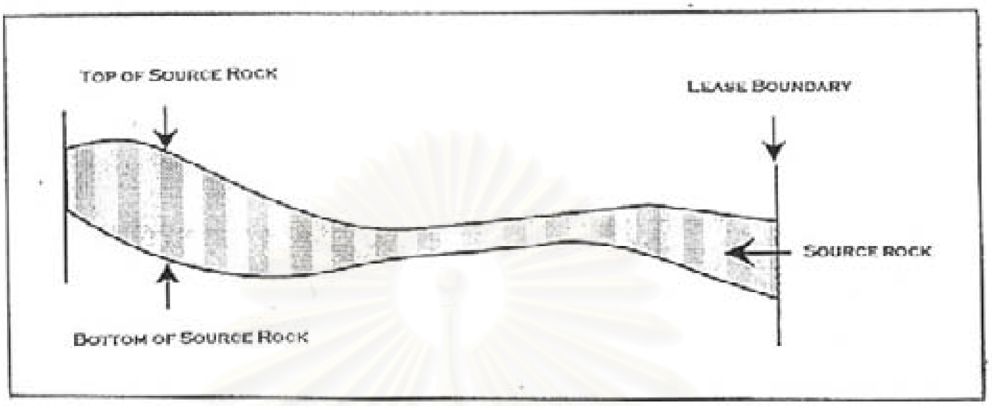


Figure 4.7a Idealized two-dimension of source rock volumetric.

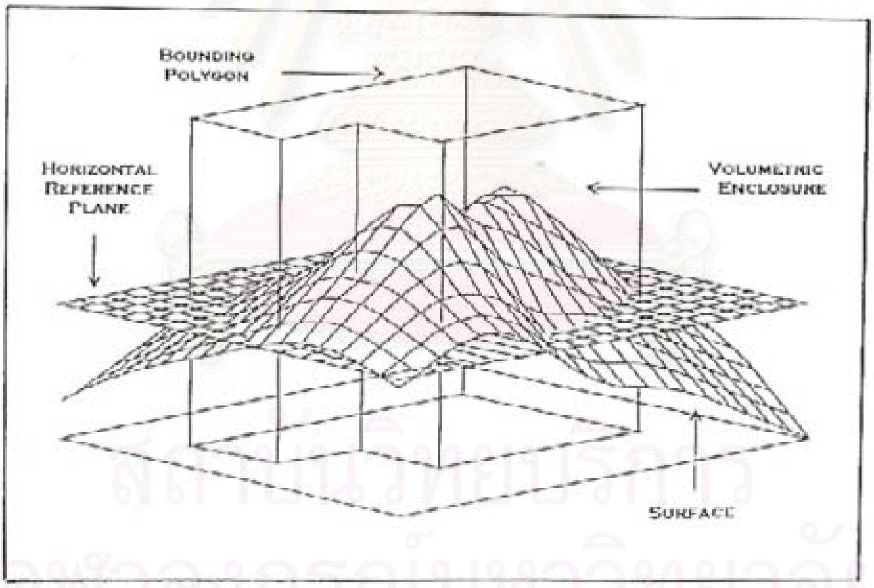


Figure 4.7b Idealized three-dimension volumetric enclosure

Table 4.1 A summary of hydrocarbon generation and generation potential of mature source rock by averaged of SK-2A Member and SK-1 Formation for Songkhla-1, Bua Ban-1, Songkhla Southwest-1 and Benjarong-1 wells.

WELL	S1 AVERAGE mg oil/g rock	S1+S2 AVERAGE mg oil/g rock
Songkhla-1	1.00	6.50
Bua Ban-1	0.97	9.35
Songkhla Southwest-1	0.63	14.70
Benjarong-1	0.85	7.77
AVERAGE	0.86	9.58

Table 4.2 Correlation of TTI with important stages of oil generation and preservation (Waples, 1980).

Stage	TTI
Onset of oil generation	15
Peak of oil generation	75
End of oil generation	160
Upper TTI limit for occurrence of oil with API gravity $< 40^{\circ}$	~500
Upper TTI limit for occurrence of oil with API gravity $< 50^{\circ}$	~1,000
Upper TTI limit for occurrence of wet gas	~1,500
Last known occurrence of dry gas	65,000

In summary, the volume of petroleum generation potential is approximately 47 billion barrels (Bbbl) and the maximum oil generation that generated from source rock within the basin is 4.3 Bbbl. If the expelled oil in the basin are 10% of mature source rock, the expelled oil are approximately 430 million barrels (MMbbl). In addition, about 10% of all expelled oil are trapped so that the oil reserves of the Songkhla basin are 43 MMbbl. From the annual report 1994 of the Department of Mineral Resource, the possible reserves of the Songkhla basin are 48 MMbbl of oil and 7 billion cubic feet of gas.

6. Migration

The Songkhla basin is small, the amount of generated and migrated oil is rather limited. The movement of hydrocarbon from mature source rock into the reservoir rock is in the early phase of migration. Due to the fact that, the S1 that measured hydrocarbon naturally presented in rock is to low values while S2 which measured hydrocarbon generated by pyrolysis is very high values. The average transformation ratio of SK-2A Member and SK-1 Formation is about 0.1 so that source rocks are early mature to mature and begin to move from source bed in to reservoir rock. The majority of oil generation maybe migrated toward the flank of basin. The long distance lateral migration is probably unlikely because no significant unconformity occurred in source section and sandstones were discontinuous. The vertical migration along fault plane during reactivation period was likely.

7. Geothermal Gradient

The geothermal gradient of each well is estimated by the bottom-hole temperatures (BHT) that obtained from wireline logs. In many wells, a single bottom-hole temperature is recorded by using a maximum-reading thermometer. The BHT is recorded after drilling and circulation operations have stopped and before thermal equilibrium between formation and wellbore fluid is reached so that the recorded temperature is usually lower than the true formation temperature. The Horner plot is used to correct the recorded temperature to the true formation temperature. The equation of the Horner technique is

$$T_F \quad = \quad T_L + K \log \Delta t / (t_c + \Delta t)$$

Where T_F is true formation temperature ($^{\circ}$C), T_L is maximum recorded temperature. K constant value equals to 1. The t_c, circulation time in hours, is time interval between time at depth cut to circulation stopped which obtained from well log heading. Δt, time since circulation stopped in hours, results from the different of time logger on bottom temperature measurement (BTM) and time circulation stopped, and both of these are obtained from well log heading. Whenever the circulation time (t_c) increases, the temperature of well will be cooled in contrast the time since circulation stopped (Δt) increases the temperature of well will increase too.

This equation is applied by plotting by semi-logarithmic grid. In x-axis, $\Delta t / (t_c + \Delta t)$ is plotted on logarithmic scale. In y-axis, T_L is plotted on a linear scale. T_F is read as the intersection of the line with the y-axis for x=1. The true formation temperature of each well except the Songkhla-1 well which does not consist of time depth cut data is calculated and shown in Tables 4.3 a, b, c, d and Figure 4.8.

The geothermal gradient of each well in the Songkhla basin is calculated as following:

$$\text{Geothermal Gradient} = \frac{\text{True formation temperature} - \text{Surface temperature @ sea floor}}{\text{Depth logger} - \text{Height above datum}}$$

Where the surface temperature at sea floor is 16 $^{\circ}$C or 60 $^{\circ}$F (Premier, 1997). The datum of geothermal gradient is sea floor or ground level so the height above datum that equals the sum of elevation of Kelly Bushing (K.B.) and Ground Level (G.L.) obtained from well log heading.

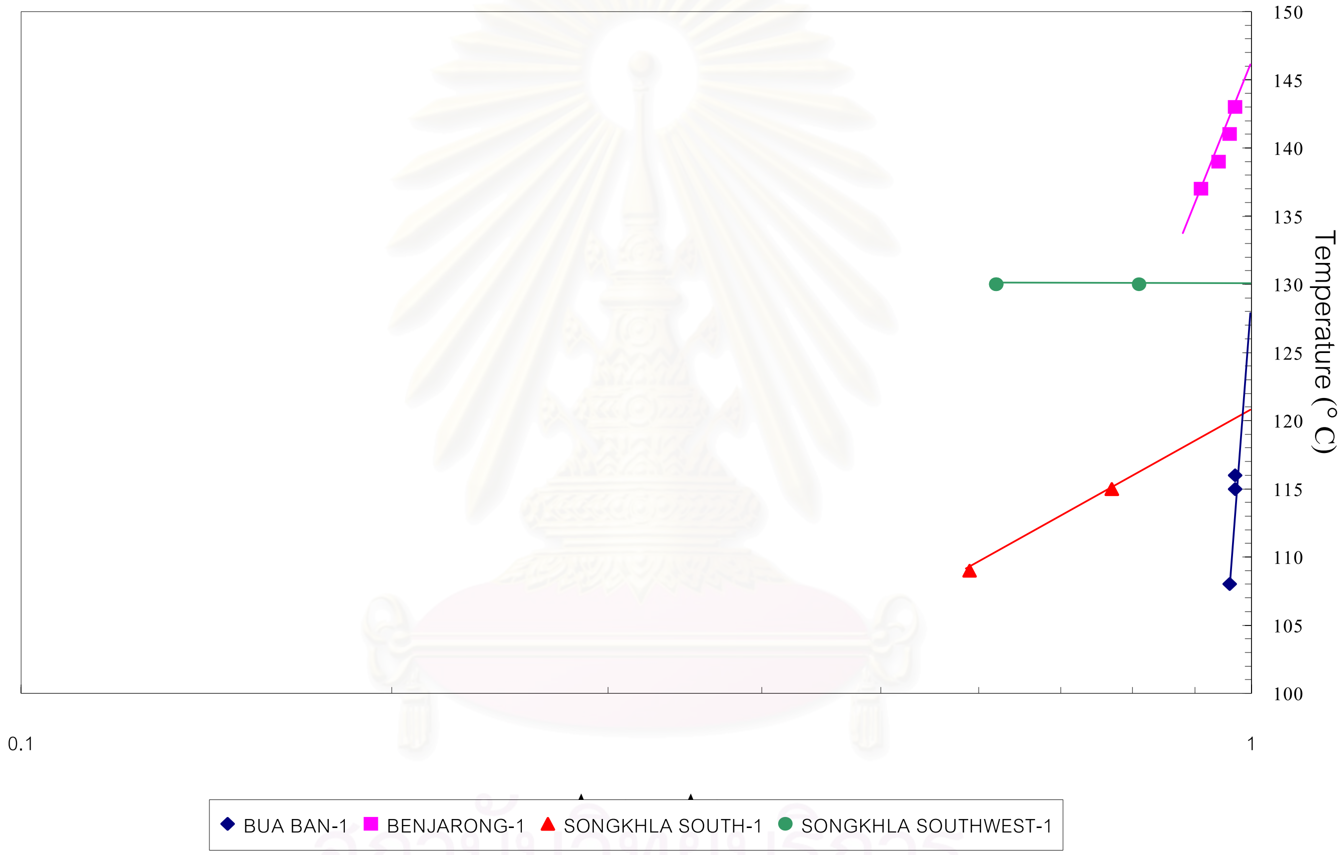


Figure 4.8 True formation temperature of each well within the Songkhla basin.

Table 4.3a The calculation of geothermal gradient using the bottom-hole temperature of the Bua Ban-1 Well.

Depth of measurement = 3010 m. Elevation of K.B. = 25 m. G.L. = -18.7 m.

Time depth cut = 13 : 20 11/3/1990

Time circulation stopped = 14 : 00 11/3/1990

Time circulation = 0.40 hr

Log Name	Time logger on BTM	Δt (hr.)	$\Delta t / (t_c + \Delta t)$	T_L (^oC)
DLL-MSFL-SLS-AMS	22:42 11/3/1990	8.42	0.96	108
LDL-CNL-NGL-AMS	04:18 12/3/1990	14.18	0.97	115
NGT	04:18 12/3/1990	14.18	0.97	116

T_F = 128 ^oC @ 3010 m.

Geothermal Gradient = 3.8 ^oC/ 100 m.

Table 4.3b The calculation of geothermal gradient using the bottom-hole temperature of the Benjarong-1 Well.

Depth of measurement = 3180 m. Elevation of K.B. = 30.5 m. G.L. = -18.9 m.

Time depth cut = 06 : 40 21/5/1996

Time circulation stopped = 07 : 50 21/5/1996

Time circulation = 1.1 hr

Log Name	Time logger on BTM	Δt (hr.)	$\Delta t / (t_c + \Delta t)$	T_L (^oC)
AIT-LSS-GR-AMS	19:20 21/5/1996	11.30	0.91	137
LDL-CNL-EPT-NGS-AMS	00:20 22/5/1996	16.30	0.94	139
OBDT-AIT-BHC-GR-AMS	09:50 22/5/1996	26.00	0.96	141
SEISMIC CHECKSHOT	17:25 22/51996	33.35	0.97	143

T_F = 145 ^oC @ 3180 m.

Geothermal Gradient = 4.1 ^oC/ 100 m.

Table 4.3c The calculation of geothermal gradient using the bottom-hole temperature of the Songkhla South-1 Well.

Depth of measurement = 2780 m. Elevation of K.B. = 26 m. G.L. = -24.1 m.

Time depth cut = 01 :30 8/6/1990

Time circulation stopped = 06 : 00 8/6/1990

Time circulation = 4.30 hr

Log Name	Time logger on BTM	Δt (hr.)	$\Delta t / (t_c + \Delta t)$	T_L (°C)
DLL-MSFL-SLS-GR-SP-CAL	12:05 8/6/1990	6.05	0.59	109
LDL-CNL-NGS-PCD-EPT-AMS	20:32 8/6/1990	14.32	0.77	115
NGT	20:32 8/6/1990	14.32	0.77	115

T_F = 121 °C @ 2780 m.

Geothermal Gradient = 3.9 °C/ 100 m.

Table 4.3d The calculation of geothermal gradient using the bottom-hole temperature of the Songkhla Southwest-1 Well.

Depth of measurement = 2810 m. Elevation of K.B. = 24.7 m. G.L. = -22.6 m.

Time depth cut = 23 : 30 12/6/1990

Time circulation stopped = 11 :45 12/6/1990

Time circulation = 12.15 hr.

Log Name	Time logger on BTM	Δt (hr.)	$\Delta t / (t_c + \Delta t)$	T_L (°C)
NGT	08:00 12/6/1990	20.15	0.62	130
LDL-CNL-NGS	08:00 12/6/1990	20.15	0.62	130
VSP	22.30 14/6/1990	54.45	0.81	130

T_F = 130 °C @ 2810 m.

Geothermal Gradient = 4.1 °C/ 100 m.

The geothermal gradients within the basin range from 3.8 to 4.1 °C per 100 meters. While the geothermal gradients of the Gulf of Thailand studied by Lekuthai (1992) range approximately 3.5 – 7.40 °C per 100 meters where surface temperature is 27 °C or 80 °F.

The potential source rock in the Songkhla basin are the SK-2A Member and SK-1 Formation, ?Late Eocene – Early Oligocene in age, and average geothermal gradient is 4 °C/100 meters.

8. Lopatin's Method

Lopatin's method is one of useful applications for petroleum exploration by commonly used of Time Temperature Index or TTI. Lopatin believes that two factors, time and temperature, are important in oil generation and destruction. The effects of both time and temperature could be considered in calculating the thermal maturity of organic material in sediment. The time temperature index of maturity is developed to model, which could predict the thermal conditions under which hydrocarbon could be generated and preserved. These two factors are interchangeable: high temperature acting for a shot time while a low temperature acting over a long time. The rate of the chemical reactions involved in thermal maturation of organic matter appears to double with every 10°C rise in temperature.

The total maturation or TTI of sediment is given by the sum of the maturities acquired in each interval. Thus

$$TTI = \sum_{n\,min}^{n\,max} (\Delta T_n)(r^n)$$

Where n is index values, n max and n min are the n-values of highest and lowest temperature intervals encountered. ΔT_n is the length of time in million years spent by sediment in temperature interval n. r^n is temperature factor where r is 2 (Waples, 1980).

The values of Lopatin's time temperature index of maturation correlating with important stages of oil generation and preservation are shown in Table 4.2. Thus, the present day TTI values could be used for finding preserved accumulations of hydrocarbon in suspected reservoir, answering of the time of generation and whether or not the thermal maturity necessary for hydrocarbon generation.

The time and temperature relate to kerogen maturity which based on a burial history curve. The burial depth is plotted against geologic time for a particular region. Figure 4.9, 4.10 and 4.11 show a geologic model having 8 horizons (Top of basement, SK-1, SK-2A, SK-2C, SK-3, SK-4, and SK-5) The possible of calculation of present day TTI values for geologic model is given in Tables 4.4, 4.5 and 4.6.

Figure 4.9 shows a geologic model of seismic line P-835 and Bua Ban-1 well in which TTI values of 15 has been located on SK-1 formation. The onset of oil generation has occurred since 13 million years. The first oil generation of Songkhla Southwest-1 well has occurred since 9 million years. In summary, the western flank of basin generated oil before eastern flank of basin because the rate of subsidence of western flank is more than the eastern flank.

All of generated oil maybe preserved in reservoir. Oil generation occurred from 13 to 9 million years before present while the structural trap in the basin created during subsidence lasting 35 to 10 million years before present. The structural trap occurred long before oil generation, the possibility is high because these local traps could have captured this oil. It is more likely that these traps were formed long before the oil migrated into the reservoir.

Lopatin's method must be used with caution because it assumes that geothermal gradient has been constant through time, which is seldom likely to be true. The constant geothermal gradient can roughly indicate mature formation such as SK-1 Formation shown in Figures 4.9 and 4.11 yields heat enough to generate hydrocarbon, but SK-2A Member which is identified by vitrinite reflectance is early mature-mature to

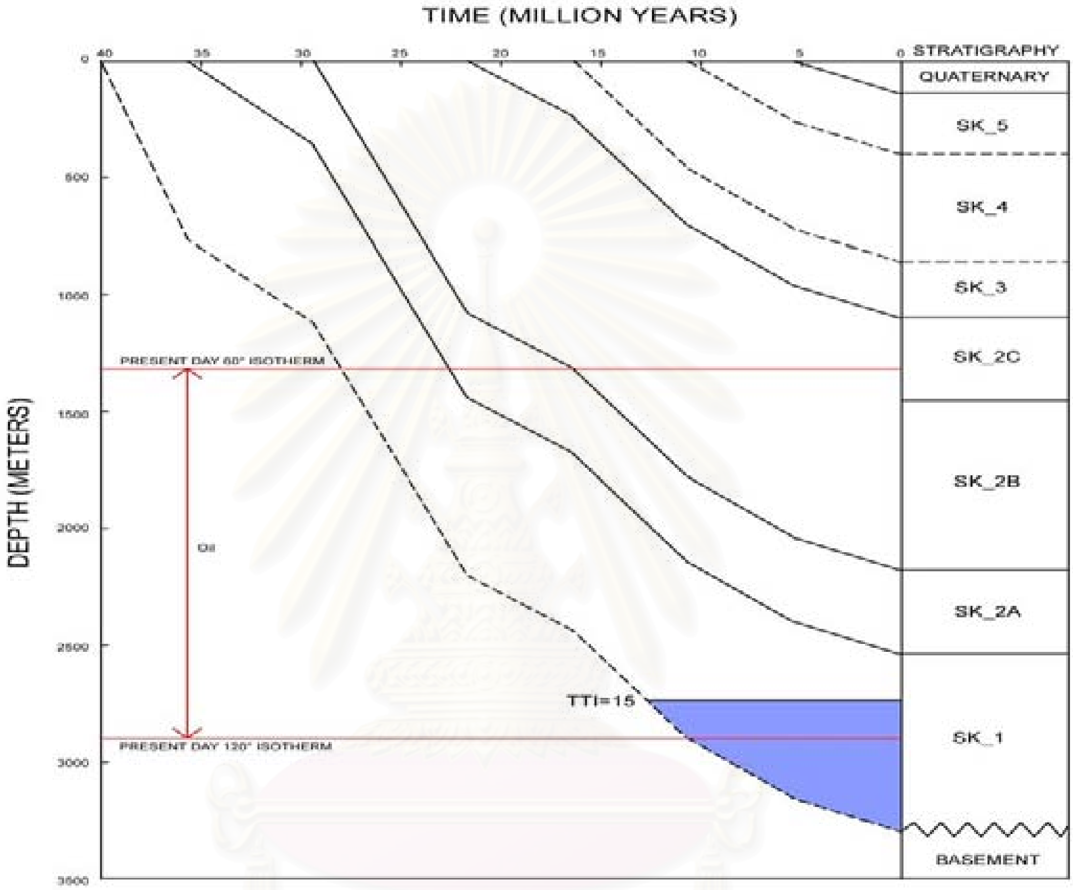


Figure 4.9 Burial history graph of the Songkhla basin at Bua Ban-1 well.

Table 4.4 Calculating of present TTI values of Bua Ban-1 well at shot point on seismic line no. P835.

Temperature ($^{\circ}$ C)	r^n	Δ t (my)	TTI	Total TTI
Top of Basement				
16-20	2^{-9}	1.0	0.002	0.002
20-30	2^{-8}	1.0	0.004	0.006
30-40	2^{-7}	1.5	0.012	0.018
40-50	2^{-6}	1.5	0.023	0.041
50-60	2^{-5}	4.0	0.125	0.166
60-70	2^{-4}	3.0	0.188	0.354
70-80	2^{-3}	2.0	0.250	0.604
80-90	2^{-2}	2.0	0.500	1.104
90-100	2^{-1}	2.0	0.100	2.104
100-110	2^{0}	5.0	5.000	7.104
110-120	2^{1}	3.0	6.000	13.104
120-130	2^{2}	3.0	12.000	25.104
130-140	2^{3}	6.5	52.000	77.104
140-150	2^{4}	4.5	72.000	149.104
Top of SK-1				
16-20	2^{-9}	3.5	0.004	0.007
20-30	2^{-8}	5.0	0.020	0.027
30-40	2^{-7}	2.0	0.016	0.043
40-50	2^{-6}	2.5	0.039	0.082
50-60	2^{-5}	1.5	0.047	0.129
60-70	2^{-4}	3.0	0.156	0.315
70-80	2^{-3}	4.0	0.500	0.815
80-90	2^{-2}	3.0	0.375	1.565
90-100	2^{-1}	4.5	2.250	3.815
100-110	2^{0}	6.5	6.500	10.315
Top of SK-2A				
16-20	2^{-9}	1.0	0.002	0.002
20-30	2^{-8}	2.0	0.007	0.007
30-40	2^{-7}	2.7	0.021	0.028
40-50	2^{-6}	2.0	0.031	0.059
50-60	2^{-5}	5.0	0.156	0.215
60-70	2^{-4}	3.3	0.206	0.421
70-80	2^{-3}	3.3	0.413	0.834
80-90	2^{-2}	5.0	1.250	2.334
90-100	2^{-1}	5.0	2.500	4.834

Table 4.4 (cont.) Calculating of present TTI values of Bua Ban-1 Well at shot point on seismic line no. P835.

Temperature (^{o} C)	r^n	Δ t (my)	TTI	Total TTI
Top of SK-2C				
16-20	2^{-9}	3.0	0.006	0.006
20-30	2^{-8}	4.0	0.015	0.021
30-40	2^{-7}	2.5	0.021	0.042
40-50	2^{-6}	5.0	0.078	0.120
50-60	2^{-5}	7.0	0.219	0.339
Top of SK-3				
16-20	2^{-9}	1.1	0.002	0.002
20-30	2^{-8}	3.2	0.013	0.015
30-40	2^{-7}	5.0	0.039	0.054
40-50	2^{-6}	7.0	0.109	0.163
Top of SK-4				
16-20	2^{-9}	3.2	0.006	0.006
20-30	2^{-8}	7.0	0.027	0.033
Top of SK-5				
16-20	2^{-9}	4.7	0.009	0.009
20-30	2^{-8}	0.5	0.002	0.011

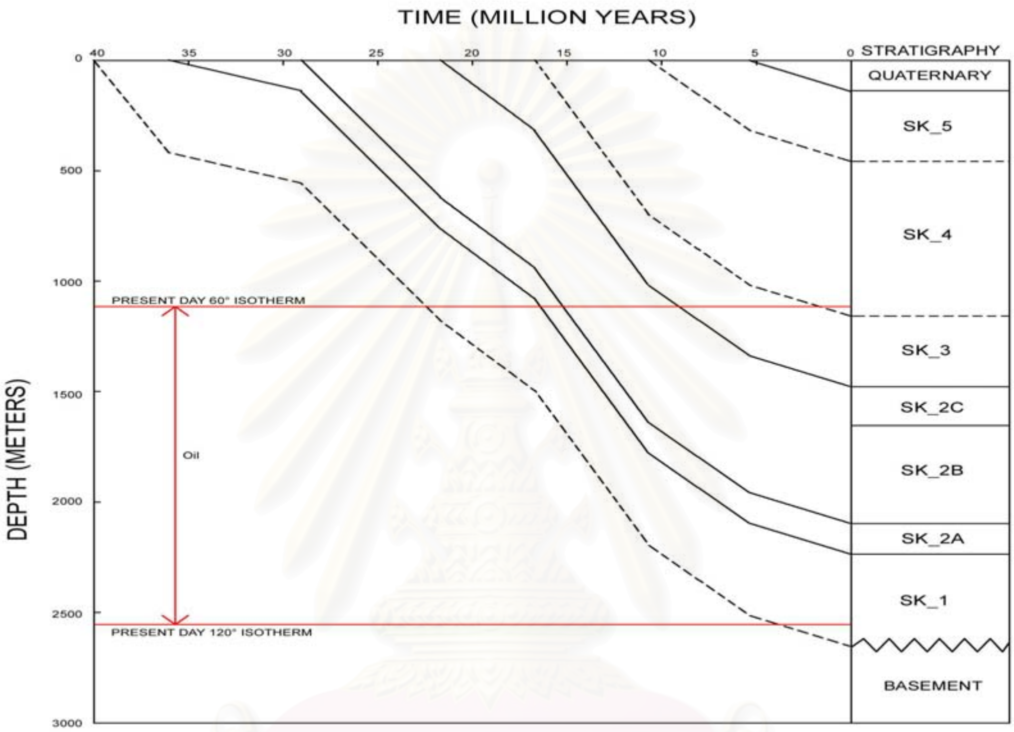


Figure 4.10 Burial history graph of the Songkhla basin at Songkhla South-1 well.

Table 4.5 Calculating of present TTI values of Songkhla South-1 well.

Temperature (°C)	r^n	Δt (my)	TTI	Total TTI
Top of Basement				
16-20	2^{-9}	1.0	0.003	0.003
20-30	2^{-8}	3.0	0.012	0.015
30-40	2^{-7}	7.0	0.054	0.069
40-50	2^{-6}	4.0	0.063	0.132
50-60	2^{-5}	3.5	0.109	0.241
60-70	2^{-4}	3.0	0.188	0.429
70-80	2^{-3}	3.0	0.375	0.804
80-90	2^{-2}	2.0	0.500	1.304
90-100	2^{-1}	2.0	1.000	2.304
100-110	2^{0}	3.0	3.000	5.304
110-120	2^{1}	3.5	7.000	12.304
120-130	2^{2}	5.0	40.000	52.304
Top of SK-1				
16-20	2^{-9}	3.0	0.006	0.006
20-30	2^{-8}	4.0	0.019	0.025
30-40	2^{-7}	3.0	0.023	0.048
40-50	2^{-6}	3.0	0.047	0.095
50-60	2^{-5}	4.0	0.125	0.220
60-70	2^{-4}	2.0	0.125	0.345
70-80	2^{-3}	2.0	0.250	0.595
80-90	2^{-2}	2.5	0.625	1.220
90-100	2^{-1}	5.0	2.500	3.470
100-110	2^{0}	6.0	6.000	9.470
Top of SK-2A				
16-20	2^{-9}	1.0	0.002	0.002
20-30	2^{-8}	2.0	0.008	0.010
30-40	2^{-7}	3.3	0.026	0.036
40-50	2^{-6}	3.0	0.047	0.083
50-60	2^{-5}	3.0	0.078	0.161
60-70	2^{-4}	2.0	0.125	0.286
70-80	2^{-3}	2.0	0.250	0.536
80-90	2^{-2}	3.0	0.750	1.286
90-100	2^{-1}	3.0	1.500	2.786
100-110	2^{0}	7.0	7.000	9.786

Table 4.5 (cont.) Calculating of present TTI values of Songkhla South-1 well.

Temperature (°C)	r^n	Δt (my)	TTI	Total TTI
Top of SK-2C				
16-20	2^{-9}	1.5	0.003	0.003
20-30	2^{-8}	4.0	0.016	0.018
30-40	2^{-7}	2.0	0.016	0.034
40-50	2^{-6}	1.5	0.023	0.057
50-60	2^{-5}	3.0	0.094	0.151
60-70	2^{-4}	4.5	0.281	0.432
70-80	2^{-3}	5.0	0.625	1.057
Top of SK-3				
16-20	2^{-9}	0.8	0.002	0.002
20-30	2^{-8}	3.0	0.012	0.014
30-40	2^{-7}	2.0	0.016	0.030
40-50	2^{-6}	3.0	0.047	0.077
50-60	2^{-5}	8.0	0.250	0.327
50-60	2^{-4}	0.5	0.031	0.358
Top of SK-4				
16-20	2^{-9}	1.6	0.003	0.003
20-30	2^{-8}	8.0	0.031	0.034
30-40	2^{-7}	0.8	0.006	0.040
Top of SK-5				
16-20	2^{-9}	5.2	0.010	0.010

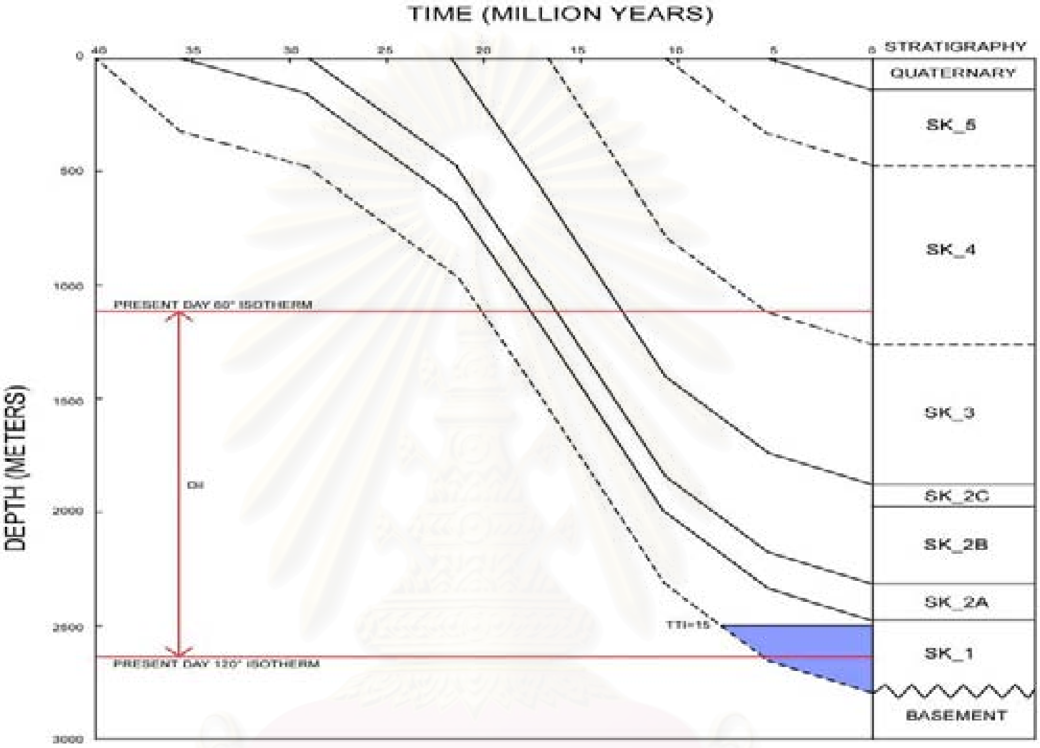


Figure 4.11 Burial history graph of the Songkhla basin at Songkhla Southwest -1 well.

Table 4.6 Calculating of present TTI values of Songkhla Southwest-1 well.

Temperature (^{o} C)	r^n	Δ t (my)	TTI	Total TTI
Top of Basement				
16-20	2^{-9}	2.0	0.004	0.004
20-30	2^{-8}	5.0	0.020	0.024
30-40	2^{-7}	5.0	0.040	0.064
40-50	2^{-6}	4.0	0.063	0.127
50-60	2^{-5}	3.0	0.094	0.221
60-70	2^{-4}	2.0	0.125	0.346
70-80	2^{-3}	1.5	0.188	0.534
80-90	2^{-2}	1.0	0.250	0.784
90-100	2^{-1}	1.0	0.500	1.284
100-110	2^{0}	1.0	1.000	2.284
110-120	2^{1}	4.0	8.000	10.284
120-130	2^{2}	5.5	22.000	32.284
130-140	2^{3}	5.0	32.000	64.284
Top of SK-1				
16-20	2^{-9}	4.0	0.007	0.007
20-30	2^{-8}	6.0	0.023	0.030
30-40	2^{-7}	4.0	0.031	0.061
40-50	2^{-6}	3.0	0.047	0.108
50-60	2^{-5}	2.0	0.063	0.171
60-70	2^{-4}	2.0	0.125	0.296
70-80	2^{-3}	1.0	0.125	0.421
80-90	2^{-2}	1.5	0.375	0.796
90-100	2^{-1}	3.0	1.500	2.296
100-110	2^{0}	4.0	4.000	6.296
110-120	2^{1}	5.0	5.000	11.296
Top of SK-2A				
16-20	2^{-9}	1.0	0.002	0.002
20-30	2^{-8}	3.5	0.014	0.016
30-40	2^{-7}	3.5	0.027	0.043
40-50	2^{-6}	2.0	0.031	0.075
50-60	2^{-5}	2.5	0.078	0.152
60-70	2^{-4}	1.5	0.094	0.246
70-80	2^{-3}	1.0	0.125	0.371
80-90	2^{-2}	1.5	0.375	0.746
90-100	2^{-1}	2.5	1.250	1.996
100-110	2^{0}	3.5	3.500	5.496
110-120	2^{1}	7.0	14.000	19.496

Table 4.6 (cont.) Calculating of present TTI values of Songkhla Southwest-1 well.

Temperature (°C)	r^n	Δ t (my)	TTI	Total TTI
Top of SK-2C				
16-20	2^{-9}	0.5	0.001	0.001
20-30	2^{-8}	2.0	0.008	0.009
30-40	2^{-7}	2.0	0.016	0.025
40-50	2^{-6}	1.5	0.023	0.048
50-60	2^{-5}	2.0	0.063	0.111
60-70	2^{-4}	2.0	0.125	0.236
70-80	2^{-3}	4.0	1.333	1.566
80-90	2^{-2}	64.0	1.500	3.066
90-100	2^{-1}	1.5	0.750	3.816
Top of SK-3				
16-20	2^{-9}	3.0	0.001	0.001
20-30	2^{-8}	2.0	0.008	0.009
30-40	2^{-7}	2.0	0.016	0.025
40-50	2^{-6}	2.0	0.031	0.056
50-60	2^{-5}	4.0	0.124	0.180
60-70	2^{-4}	6.0	0.375	0.555
Top of SK-4				
16-20	2^{-9}	1.4	0.003	0.003
20-30	2^{-8}	5.0	0.002	0.005
30-40	2^{-7}	4.0	0.031	0.036
Top of SK-5				
16-20	2^{-9}	5.2	0.010	0.010

generate hydrocarbon. Burial curves must also be used carefully especially present day depth of formation and other factors such as compaction, uplift, subsidence and sedimentation balance one another; however the geologic reconstruction is based on the best information available that represents the best guess.

Reservoir

Generally, the reservoirs of the Songkhla basin are sandstone rock in the SK-1, SK-2 and SK-3 Formation. Most of sandstone reservoirs are alluvial fan, Oligocene prograding sandstone sequence consists of stacked parasequences of lacustrine and fan delta facies and Miocene fluvial sandstone. The deltaic sandstone are thin but laterally extensive while the fluvial sandstone are more restricted. Thus, sandstone in lacustrine sequence are quite interesting in the Songkhla basin because they are fair quality reservoir with fair porosity, commonly in range 11-13% whereas porosity of sandstone in SK-3 Formation is less than 10% (Premier, 1990). The Pre-Tertiary basement are mainly granite and metamorphic rock in which rare fractures occurred in. Therefore, they could not possess possible reservoir potential.

Seal

SK-2 Formation is the most effective hydrocarbon seals due to the lacustrine claystone or shale source rock in the basin interbedded with sandstone and acting as source and seal at the same time. Moreover, the floodplain claystone or shale could be appropriate seals in the basin. In Kra and Chumphon basin, claystone with thickness greater than 30 ft. commonly provide good seal capacity in the lacustrine sequence (Pradidtan and Dook, 1992). Whereas interbedded thin claystones about 10 to 20 ft. thick are proved to be effective seals in the Phitsanulok basin (Knox and Wakefield, 1983). Therefore, good and better sealing claystone are generally deposited in the deeper part of the basin because the thickness of claystone is greater than 30 ft. It should be noted that claystone are thick enough to prevent the upward escape of hydrocarbon. Besides, fault planes are likely to be sealed by smearing of these claystone or shale.

Trap

Traps of the Songkhla basin may be formed either structural or stratigraphic traps. Firstly, The structural traps are prime targets for exploration because they are easy to locate by geophysical exploration technique. The types of structural traps are fault trap, and rollover anticline that are mainly in the western flank of the basin (Figure 3.5). They are situated in or nearby kitchen areas where migration and seal are good. Hydrocarbon may be trapped in the rollover anticline above fault plane and in reservoir sealed beneath the plane. A major trap occurs in the western flank of the basin. Although the structural traps are rare in the eastern flank of basin, the small tilted faults can capture the petroleum, only as long as they are in the path of migration. Moreover, all of structural traps have been formed since Oligocene age (approximately 35 Ma.) before oil generated out from source rock (approximately 13 Ma.)

Secondly, the stratigraphic traps are also possible which relate to sediment deposition and erosion such as facies changes and unconformity. The stratigraphic traps of the basin may occur in the Oligocene age due to a sand body embedded in and sealed by shales in the progradational sequence and this trap might appear in the eastern part of the basin.

Finally, the relationship of structural and stratigraphic traps becomes to combination traps. The combination traps associated with oil accumulations where traps may be formed along the faults or folds and plugged on the facies changes or unconformity.

Petroleum Potential of the Songkhla Basin

Hydrocarbon discovered within the Songkhla basin is in the Tertiary succession. Most of source rocks that are organic rich claystone or shale in SK-2 and SK-1 Formations are good quality source rock. The source rock materials consist of Type I/II/III kerogens that indicate the organic matter were from algal and terrestrial plants deposited in lacustrine and fluvial environments. The mixing of organic matter types causes variability in generation of oil and/or gas prone.

Potential source rock in lower part of the SK-2 and SK-1 Formations are early mature to mature source rock depending on depth of source rock. The top of oil generation of the basin is at 2,000 meters. The volume of petroleum generation potential is approximately 47 Bbbl and the maximum generated oil within the basin is 4.3 Bbbl. From preliminary assessment, oil accumulation is approximately 43 MMbbl. Therefore, the volume of oil accumulation is a quite interesting. However, the upper part of SK-2 Formation may be mature if buried deep enough in the center of the basin. Therefore, the kitchen area is in the lower part of basin especially the western flank of the basin. Some exploration wells particularly in the eastern flank of basin due to source rock are mainly immature and/or petroleum generated in the kitchen area may not be migrated into this area.

The potential reservoir of the Songkhla basin are alluvial fan, progradation sandstone, and fluvial that are SK-1, SK-2 and SK-3 Formations. There are fair quality sandstone reservoirs for hydrocarbon accumulation. The petroleum is discovered in some parts of formations because of the discontinuous of sequences and path of migration.

Good and better sealing claystone deposited in the deeper part of the basin because the thickness is thick enough to seal hydrocarbon. Additionally, fault planes are likely to sealed smearing of these claystone. Thus, seal is considered to be a low risk.

The possibility of petroleum potential in Pre-Tertiary basement both source rock and reservoir rock is difficult because Pre-Tertiary basement are mainly granite and metamorphic rock that are not good reservoir and with rare fractures due to few faults cut into the basement.

The Songkhla basin is the structural control basin developed by listric normal faults. The petroleum, generated and accumulated in the basin, may be trapped by listric normal growth faults creating rollover anticline, synthetic and antithetic faults. They are situated in or nearby kitchen areas where migration and seal are good. The rollover anticline appearing in the western flank of basin is an important structural trap in which hydrocarbon accumulated. The synthetic and antithetic faults divided traps into several small traps that yield low preserved potential. The listric normal faults developed during the sedimentation on the down thrown side and ceased at the Middle Miocene time. Thus, the structural traps possibly trap hydrocarbon that generated since 13 Ma. before present. Otherwise, the stratigraphic traps is promising especially in the Oligocene sediments that parasequences occurred in.

Accordingly, the potential area is in the western flank of basin where source rocks are good and have been heated sufficiently to yield hydrocarbon. There are fair porosities within reservoir rock which contain the expelled oil and seal is effectively good because thickness of seal is large enough to prevent hydrocarbon escape. In addition, hydrocarbon may migrate and accumulate in structural traps which are rollover anticline appearing along fault plane. Although, no commercial hydrocarbon was discovered in the Songkhla basin from exploration of Premier Oil Limited since wells drilled far from kitchen area, migration was short distances and well suited on separated structures. However, the information of the quality and maturity of source rock, reservoir and structural traps suggests that the Songkhla basin will be needed more information on better seismic data and advanced seismic program which might be pointed out about an economic quantity.

CHAPTER V

CONCLUSION

The Songkhla basin is located in the southwestern part of the Gulf of Thailand. The basin is a north-south trending half graben that controlled by listric normal faults in the west and onlap onto the Ko Kra Ridge in the east. The basin formed since Early Tertiary as the result of collision of Indian and Eurasian plates that associated with right lateral movement on the NW-SE trending, Three Pagoda fault, and left lateral movement on the NE-SW trending, Ranong and Klong Marui faults.

The Tertiary sedimentary sequence in the Songkhla basin is almost entirely non-marine sediments of alluvial, fluvial and lacustrine deposits with occasionally marine transgression. The maximum thickness of accumulation is approximately 3,500 meters. The stratigraphy of the Tertiary sequence is subdivided into 5 formations, namely SK-1, SK-2, SK-3, SK-4, and SK-5 in ascending order. The lowermost formation is SK-1 Formation overlying unconformably on the Pre-Tertiary basement rock that are granite and metamorphic rock. This formation consists of sandstone interbedded with reddish brown claystone or shale deposited in alluvial and fluvial environments. The SK-2 Formation overlies conformably on the SK-1 Formation. This formation mainly consists of dominant organic rich claystone or shale of lacustrine environment and can be subdivided into 3 members: SK-2A, SK-2B, and SK-2C Member in ascending order. The SK-2A Member, lowermost member of the SK-2 Formation, is composed of dominant dark gray organic-rich claystone or shale interbedded with sandstone and limestone. The middle member of the SK-2 Formation is the SK-2B Member which contains stacked parasequences of deltaic lacustrine environments by which marine transgressions may occur in short periods. It is characterized by claystone or shale interbedded with sandstone and limestone. The uppermost member of the SK-2 Formation is the SK-2C Member that consists of predominant claystone or shale interbedded with sandstone and minor limestone. The SK-3 Formation where deposited in transitional environment from lacustrine to fluvial environment, overlying on the SK-2

Formation, comprises sandstone and claystone or shale with minor limestone and coal. The SK-4 Formation, overlying a local unconformity, contains sandstone interbedded with claystone or shale and minor limestone. These sediments are interpreted as fluvial origin. The SK-5 Formation overlies unconformably the SK-4 Formation as on Middle Miocene Unconformity and is characterized by sandstone and claystone or shale and minor coal where deposited in fluvial, coastal plain and mangrove swamp. Generally, the geometry of SK-1 and SK-2 Formation also shows the westward thickening in the basin whereas other formations are uniform throughout the study area.

The basin developed since ?Late Eocene time related to tectonic activity. The east-west rifting was rapidly extension and high rates of sedimentation. The lacustrine environment of deposition was dominant in the area from Oligocene to Early Miocene time. Sandstone deposition was controlled by delta and river. A change in both climatic and tectonic in Early Miocene resulted in a transition from lacustrine to fluvial environment. By the end of Early Miocene time, some minor crustral movement resulted in a local unconformity. The perennial lake ceased and became fluvial environment in the Middle Miocene. By the end of Middle Miocene time, the tectonic changes resulted in a widespread regional unconformity. The extension decreased drastically and the cessation of listric fault occurred at or near the unconformity. Late Miocene time, the basin continued subsidence by thermal subsidence. The fluvial, coastal plain and mangrove swamp with marine influences prevailed and has continued until recent time.

The geochemical study of source rock in the Songkhla basin shows that the high quality source rocks occur within dark organic rich claystone or shale of the SK-1 and SK-2 Formation. The Oligocene sediments are good source rocks with the total TOC ranging from 0.5 to 2 wt.%. This organic claystone or shale are early mature to mature enough to generate oil and the top of oil generation is at 2,000 meters beneath seabed.

The volumes of generation potential of source rock and generated oil are approximately 47 and 4.3 Bbbl respectively. From preliminary assessment, oil accumulation within the basin is about 43 MMbbl. The oil has generated since 13 Ma. during which the structural traps have been in place throughout the period of generation. The migration from source rock in to reservoir rock is in early phase that oil generation possibly migrates toward the flank of basin. The sandstone of SK-2 Formation is fair reservoir that interbedded with claystone or shale acting as seal at the same time. Besides that, sandstone in the SK-1 Formation and the Miocene fluvial sandstone in SK-3 Formation, are quite interesting reservoir. Seals are thick claystone or shale in lacustrine sequence and fault planes are likely to be sealed by smearing of these claystone or shale. The petroleum is mainly accumulated in the structural traps and/or possibly accumulated in stratigraphic traps. The structural traps mainly occur in the western flank of basin and hydrocarbon may be trapped in the rollover anticline that is near the kitchen area. The tilted fault blocks divided traps into several small traps.

Accordingly, the potential area is in the western flank of basin in which source rock, reservoir rock and seal arranged to trap hydrocarbon in structural trap. Some commercial hydrocarbon will be possibly found in the Songkhla basin. Therefore, the study of petroleum geology and petroleum potential of the Songkhla basin can be served for understanding of the basin and is useful for oil exploration to investigate in its potential in the future.

REFERENCES

Achalabhuti, C., and Oudom-Ugsorn, P. 1978. Petroleum Potential in the Gulf of Thailand. Jour. Geol. Soc. Thailand 3 : 1-12.

Achalabhuti, C. 1980. Geology and Hydrocarbon Potential of the Gulf of Thailand. Workshop on Geology and Hydrocarbon Potential of the South China Sea and Possibilities of Joint Research and Development, pp. 1-22. Honolulu, Hawaii.

Achalabhuti, C. 1981. Natural Gas Deposits of Gulf of Thailand. In Halbouty, M. T.(ed.), Energy Resources of the Pacific Region, pp. 155-160. Oklahoma: AAPG.

Alderson, A., Holmes, N. A., and Murphy, C. 1994. A Summary of the Biostratigraphy and Biofacies for the Tertiary Sequence, Gulf of Thailand. Proceedings of the International Symposium on: Stratigraphic Correlation of Southeast Asia, pp. 292-295. Bangkok, Thailand.

Bal, A. A., Burgisser, H. M., Harris, D. K., Herber, M. A., Rigby, S. M., Winkler, F. J. and Thumprasertwong, S. 1992. The Tertiary Phitsanulok Lacustrine Basin, Thailand. Proceedings of the Conference on Development Geology for Thailand into the Year 2000, pp.408-429. Chulalongkorn University.

Barker, C. 1974. Pyrolysis Techniques for Source-Rock Evaluation. AAPG. Bull. 58: 2349-2361.

Bhuthuang, H. 1990. Subsurface Geology of some Upper Cenozoic Sediments in the Upper Gulf of Thailand with Special Reference to Off-Shore Hua Hin Basin. Master's Thesis, Department of Geology, Graduate School, Chulalongkorn University.

Bj∅rlykke, K. 1989. Sedimentology and Petroleum Geology. Berlin: Springer Verlag.

Bidston, B. J., and Daniel, J. S. 1992. Oil from the Ancient Lakes of Thailand. National Conference on "Geological Resources of Thailand: Potential for Future Development", pp. 584-599. Department of Mineral Resources, Bangkok, Thailand.

Bottomley, J. 1991. Oligocene Lacustrine Sediments of the Songkhla basin. Jour.Geol.Soc. Thailand 1 : 32-38.

Boulter, C. A. 1989. Four Dimensional Analysis of Geological Maps. Chichester: John Wiley & Son.

Bunopas, S., and Vella, P. 1983. Opening of the Gulf of Thailand-Rifting of Continental Southeast Asia, and late Cenozoic Tectonics. Jour. Geol. Soc. Thailand 6: 1-12.

Bunopas, S. 1994. Regional Stratigraphy, Paleogeographic and Tectonic Events of Thailand and Continental Southeast Asia. Proceedings of the International Symposium on: Stratigraphic Correlation of Southeast Asia, pp. 2-24. Bangkok, Thailand.

Burri, P. 1989. Hydrocarbon Potential of Tertiary Intermontane Basins in Thailand. In Thanasuthipitak, T. and Ounchanum, P. (eds.), International Symposium on Intermontane Basins: Geology&Resources, pp. 3-12. Chiang Mai University, Thailand.

Burton, C. K., and Bignell, J. D. 1969. Cretaceous-Tertiary Events in Southeast Asia. Geol. Soc. Amer. Bull. 80: 681-688.

Chaisilboon, B. 1997. Basin Modeling of Hua Hin South Basin Block B3/32, Gulf of Thailand. Master's thesis, Petroleum Geology, Science, University of Aberdeen, Scotland, UK.

Champeny, J. D. 1987. Petroleum Potential in the Far East. In Halbouty, M. T. (ed.), Energy Resources of the Pacific Region, pp. 189-194. Oklahoma: AAPG.

Chaodamrong, P., Janmaha, S., Ukakimapan, Y., Prадidtan, S., and Saeleow, N. 1983. A Review of the Tertiary Sedimentary Rocks of Thailand. Proceedings of the Workshop on Stratigraphic Correlation of Thailand and Malaysia, pp. 159-187. Haad Yai, Thailand.

Chinbunchorn, N., Pradidtan, S., and Sattayarak, S. 1989. Petroleum Potential of Tertiary Intermontane Basins in Thailand. In Thanasuthipitak, T. and Ounchanum, P. (eds.), International Symposium on Intermontane Basins: Geology&Resources, pp. 29-42. Chiang Mai University, Thailand.

Conybeare, C. E. B. 1979. Lithostratigraphic Analysis of Sedimentary Basins. London: Academic Press.

Dheeradilok, P., Wongwanich, T., Tansathien, W., and Chaodumrong, P. 1992. An Introduction to Geology of Thailand. National Conference on "Geological

Resources of Thailand: Potential for Future Development", pp. 737-752. Department of Mineral Resources, Bangkok, Thailand.

DMR. 1989. Annual Report 1989 Petroleum Activities in Thailand. Bangkok: Department of Mineral Resources.

DMR. 1994. Annual Report 1989 Petroleum Activities in Thailand. Bangkok: Department of Mineral Resources.

DMR. 1999. Annual Report 1999 Petroleum Activities in Thailand. Bangkok: Department of Mineral Resources.

Dyk, K. 1961. Geophysical Surveys. In Moody, G. B. (ed.), Petroleum Exploration Handbook, pp.11-1 - 11-43. New York: McGraw Hill.

Emery, K. O., and Nino, H. 1963. Sediment of the Gulf of Thailand and Adjacent Continental Shelf. Geol. Soc. Amer. Bull. 74: 541-554.

Erdman, J. G. 1975. Geochemical Formation of Oil. In Fischer, A. G., and Judson, S. (eds.), Petroleum and Global Tectonics, pp. 226-248. New Jersey: Princeton University Press.

Fischer, A. G. 1975. Origin and Growth of Basins. In Fischer, A. G., and Judson, S. (eds.), Petroleum and Global Tectonics, pp. 47-79. New Jersey: Princeton University Press.

Flint, S., Stewart, D. J., Hyde, T., Cevers, E. C. A., and Riessen, E. D. V. 1988. Aspect of Reservoir Geology and Production Behavior of Sirikit Oil Field, Thailand: and Integrated Study Using Well and 3-D Seismic Data. AAPG. Bull. 72: 1254-1269.

Gonecome, Y. 1998. The Implications of Basin Modeling for Petroleum Exploration of Kra and Western Basins, Northern Part of the Gulf of Thailand. Master's Thesis, Petroleum Geoscience, Science, Universiti Brunei Darussalam.

Harding, T. P., and Lowell, J. D. 1979. Structural Styles, their Plate-Tectonic Habitats, and Hydrocarbon Traps in Petroleum Provinces. AAPG. Bull. 63: 1016-1058.

Harding, T.P. 1985. Seismic Characteristics and Identification of Negative Flower Structures, Positive Flower Structures, and Positive Structure Inversion. AAPG. Bull. 69: 582-600.

Hington, P.J.C., Racey, A., Wakefield, M.I., Carmichael, A.J., and Glendinning, N.R.W. 1997. Quantitative Biostratigraphy: An Example from Neogene of the Gulf of

Thailand. The International Conference on Stratigraphy and Tectonic Evolution of Southeast Asia and the South Pacific, pp. 563-585. Bangkok, Thailand.

Ingersoll, R.V., and Busby, C.J. 1995. Tectonics of Sedimentary Basins. In Busby, C.J., and Ingersoll, R.V. (eds.), Tectonics of Sedimentary Basins, pp.1-52. Massachuchetts: Blackwell Science.

Jardine, E. 1997. Dual Petroleum Systems Govering the Profilic Pattani Basin, Offshore Thailand. The International Conference on Stratigraphy and Tectonic Evolution of Southeast Asia and the South Pacific, pp. 525-534. Bangkok, Thailand.

Katz, B. J., Pheifer, R. N., and Schunk, D. J. 1988. Interpretation of Discontinuous Vitrinite Reflectance Profiles. AAPG. Bull. 72: 1254-1269.

Katz, B. J. 1995. Petroleum Source Rocks-an Introductory Overview. In Katz, B. J. (ed.), Petroleum Source Rocks, pp.1-8. Germany: Springer-Verlag Berlin Heidelberg.

Kinsman, D. J. J. 1975. Rift Valley Basins and Sedimentary History of Trailing Continental Margins. In Fischer, A. G., and Judson, S. (eds.), Petroleum and Global Tectonics, pp. 83-126. New Jersey: Princeton University Press.

Klein, G. D. 1995. Strike-Slip Basins. In Busby, C.J., and Ingersoll, R.V. (eds.), Tectonics of Sedimentary Basins, pp. 459-478. Massachuchetts: Blackwell Science.

Klemme, H. D. 1975. Geothermal Gradients, Heat Flow and Hydrocarbon Recovery. In Fischer, A. G., and Judson, S. (eds.), Petroleum and Global Tectonics, pp. 251-304. New Jersey: Princeton University Press.

Knox, G. J. and Wakefield, L. L. 1983. An Introduction to the Geology of the Phitsanulok Basin. Conference on Geology and Mineral Resources of Thailand, pp. 1-8. Department of Mineral Resources, Bangkok, Thailand.

Kosuwan, T. 1995. Evolution of Sedimentary Deposition and Assessment of Petroleum Potential of the Wichian Buri sub-basin, Changwat Phetchabun. Master's Thesis, Department of Geology, Graduate School, Chulalongkorn University.

Lawwongngam, K., and Philp, R. P. 1993. Preliminary Investigation of Oil and Source Rock Organic Geochemistry from Selected Tertiary Basins of Thailand. Jour. S.E Asian Earth Sciences 8: 433-448.

Leeder, M. R. 1995. Continental Rifts and Proto-Oceanic Rift Troughs. In Busby, C.J., and Ingersoll, R.V. (eds.), Tectonics of Sedimentary Basins, pp. 119-148. Massachuchetts: Blackwell Science.

Lekuthai, T., Sangsuwan, J., and Thongpenyai B. 1984. A Petroleum Source Rock Potential in Chumphon Basin. Symposium of Cenozoic Basins of Thailand, Geology and Resources, pp. 43-66. Chiang Mai University, Thailand.

Lekuthai, T. 1992 a. Evolution and Hydrocarbon Prospectivity of the Kra basin, Thailand. Master's Thesis, RHBNC. University of London, England.

Lekuthai, T. 1992 b. Geothermal Gradient in the Gulf of Thailand. Bangkok: Department of Mineral Resources. (Mimeographed)

Lian, H.M., and Bradley, K. 1986. Exploration and Development of Natural Gas, Pattani Basin, Gulf of Thailand. The forth Circum-Pacific Energy and Mineral Resources, Singapore.

Loomis, F. B. 1961. Subsurface Geology. In Moody, G. B. (ed.), Petroleum Exploration Handbook, pp. 13-1 - 13-74. New York: McGraw Hill.

Lockhart, B. L., Chinoroje, O., Enomoto, C. B., and Hollomon, G. A. 1994. Early Tertiary Deposition in the Southern Pattani Trough, Gulf of Thailand. The International Conference on Stratigraphy and Tectonic Evolution of Southeast Asia and the South Pacific, pp. 476-489. Bangkok, Thailand.

Maldonado, S., and Astudillo, L. 1989. Formation and Evolution of Intermontane Basins of Central and Northern Zones from Ecuador. In Thanasuthipitak, T. and Ounchanum, P. (eds.), International Symposium on Intermontane Basins: Geology &Resources, pp. 318-325. Chiang Mai University, Thailand.

Miall, A.D. 1990. Principles of Sedimentary Basin Analysis. 2nd ed. New York: Springer Verlag.

Nakanart, A. 1978. Up to 1978: Petroleum Exploration in Thailand Offshore. Jour. Geol. Soc. Thailand 3 : p2-1–p2-14.

Nakornthap, K., and Chinbunchorn, N. 1988. Nang Nuan Oil Field : the Neo Petroleum Potential in the Gulf of Thailand. Conference in Mineral Resource of Department of Mineral Resources, pp. 153-160. Bangkok. (in Thai)

Nilsen, T. H., and Sylvester, A. G. 1995. Strike-Slip Basins. In Busby, C.J., and Ingersoll, R.V. (eds.), Tectonics of Sedimentary Basins, pp. 425-458. Massachuchetts: Blackwell Science.

Noibanchong, C. 1990. Facies Model of North Malay basin. Proceedings of the Conference on Development Geology for Thailand into the Year 2000, pp.430-443. Chulalongkorn University.

O'Leary, J., and Hill, G. S. 1989. Tertiary Basin Development in the Southern Central Plains, Thailand. In Thanasuthipitak, T. and Ounchanum, P. (eds.), International Symposium on Intermontane Basins: Geology&Resources, pp. 254-264. Chiang Mai University, Thailand.

Oudom-Ugsorn, P., Rojanachan, C., and Sakdejayont, K. 1986. Evaluation of Petroleum Potential of the Western Basin, Gulf of Thailand. Proceedings of the CCOP Twenty-third Session, pp. 80-97. Madang, Papua New Guinea.

Packham, G. H. 1993. Plate Tectonics and the Development of Sedimentary Basins of the Dextral Regime in Western Southeast Asia. Jour. S.E Asian Earth Sciences 8 : 497-511.

Paul, D. D., and Lian, H. M. 1975. Offshore Tertiary Basins of Southeast Asia, Bay of Bengal to South China Sea. Ninth World Petroleum Congress, pp. 1-15. Japan.

Perrodon, A., and Masse, P. 1984. Subsidence, Sedimentation and Petroleum System. Jour. Petroleum Geology 7: 5-26.

Pigott, J. D. 1985. Assessing Source Rock Maturity in Frontier Basins: Important of Time, Temperature, and Tectonics. AAPG. Bull. 69: 1269-1274.

Pigott, J. D., and Sattayarak, S. 1993. Aspects of Sedimentary Basin Evolution Assessed through Tectonic Subsidence Analysis. Example: Northern Gulf of Thailand. Jour. S.E Asian Earth Sciences 8 : 407- 420.

Pisutha-Arnond, S. 1990. A Preliminary Investigation into Porosity Depth Relationship of Sandstones and Shales below the Middle Miocene Unconformity in Pattani Basin, Eastern Gulf of Thailand. Proceedings of the Conference on Development Geology for Thailand into the Year 2000, pp.444-459. Chulalongkorn University.

Pisutha-Arnond, S. 1999. A Disscussion on the Pre-Tertiary Rocks in the Gulf of Thailand. In Krantraprab, C. (ed.), Symposium on Mineral, Energy, and Water

Resources of Thailand: Towards the Year 2000, pp. 572-576. Chulalongkorn University.

Polachan, S., and Sattayarak, S. 1989. Strike-Slip Tectonics and the Development of Tertiary Basins in Thailand. In Thanasuthipitak, T. and Ounchanum, P. (eds.), International Symposium on Intermontane Basins: Geology&Resources, pp. 243-252. Chiang Mai University, Thailand.

Polachan, S., Pradidtan, S., Tongtaow, S., Janmaha, S., Intarawijitr, K., and Sangsuwan, J. 1991. Development of Cenozoic Basins in Thailand. Marine and Petroleum Geology 8 : 84-97.

Polahan, P. 1986. Oil Potential in the Gulf of Thailand. Offshore Technology Conference, pp. 255-259. Houston, Texas.

Pradidtan, S., and Tongtaow, C. 1984. Cenozoic Basins with Petroleum Potential in Thailand. Conference on Application of Geology and the National Development, pp. 33-42. Chulalongkorn University.

Pradidtan, S. 1989. Characteristics and Controls of Lacustrine Deposits of some Tertiary Basins in Thailand. In Thanasuthipitak, T. and Ounchanum, P. (eds.), International Symposium on Intermontane Basins: Geology&Resources, pp. 133-145, Chiang Mai University, Thailand.

Pradidtan, S., Singhasenee, C., and Charusirisawad, R. 1990. Stratigraphy of Tertiary Basins in the Gulf of Thailand. Proceedings of the Conference on Development Geology for Thailand into the Year 2000, pp. 408-429. Chulalongkorn University.

Pradidtan, S., and Dook, R. 1992. Petroleum Geology of the Northern Part of the Gulf of Thailand. National Conference on “Geological Resources of Thailand: Potential for Future Development”, pp. 235-246. Department of Mineral Resources, Bangkok, Thailand.

Pradidtan, S., Jaroonsitha, S., and Gonecome, Y. 1999. Petroleum Systems of the Petroliferous Basins in the Gulf of Thailand. In Krantraprab, C. (ed.), Symposium on Mineral, Energy, and Water Resources of Thailand: Towards the Year 2000, pp. 557-562. Chulalongkorn University, Thailand.

Premier Oil Pacific, 1988. Songkhla-1 Final Well Report. Bangkok: Thailand. (Unpublished Manuscript)

Premier Oil Pacific, 1990. Bua Ban-1 Final Well Report. Bangkok: Thailand. (Unpublished Manuscript)

Premier Oil Pacific, 1990. Songkhla South-1 Final Well Report. Bangkok: Thailand. (Unpublished Manuscript)

Premier Oil Pacific, 1990. Songkhla Southwest-1 Final Well Report. Bangkok: Thailand. (Unpublished Manuscript)

Premier Oil Pacific, 1997. Benjarong-1 Final Well Report. Bangkok: Thailand. (Unpublished Manuscript)

Ratanasthein, B., and Kandharosa, W. 1987. Coal-, Oil-, Oil Shale Bearing Formations in Intermontane Basins of Thailand. Proceedings Sixth Regional Conference on the Geology, Mineral and Hydrocarbon Resources of Southeast Asia, pp. 363-369. Jakarta, Indonesia.

Ratanasthein, B. 1994. Neogene Events Recorded in Thailand. In Tsuchi, R. (ed.), Pacific Neogene Events in Time and Space, pp. 65-77.

Sattayarak, N. 1992. Petroleum Exploration Opportunities in Thailand. National Conference on "Geological Resources of Thailand: Potential for Future Development", pp. 668- 675. Department of Mineral Resources, Bangkok, Thailand.

Schumberger. 1987. Log Interpretation Principles/Application. Texas.

Sengor, A. M. C. 1995. Sedimentation and Tectonics of Fossil Rifts. In Busby, C.J., and Ingersoll, R.V. (eds.), Tectonics of Sedimentary Basins, pp. 53-118. Massachuchetts: Blackwell Science.

Shelton, W. J. 1984. Listric Normal Faults: An Illustrated Summary. AAPG. Bull. 68: 801-815.

Sheriff, R. E. 1980. Seismic Stratigraphy. Boston: IHRDC.

Sinding-Larsen, R. 1992. Petroleum Resources Management. National Conference on "Geological Resources of Thailand: Potential for Future Development", pp. 222-224. Department of Mineral Resources, Bangkok, Thailand.

Snansieng, S., Chaodumrong, P., Pradidtan, S., and Boripatkosol, S. 1982. The Tertiary Sedimentary Rocks of Thailand. Conference on Geology and Mineral Resources of Thailand, pp. 1-13. Department of Mineral Resources, Bangkok, Thailand.

Song, T., and Cawood, A. P. 2001. Effects of Subsidary Faults on the Geometric Construction of Listric Normal Fault Systems. AAPG. Bull. 85: 221-232.

Tapponnier, P., Peltzer, G., and Armijo, R. 1986. On the Mechanism of the collision between India and Asia. Geol. Soc. Lond. Spec. Pulb. 19: 115-157.

Tissot, B.P., Pelet, R., and Ungerer, P.H. 1987. Thermal History of Sedimentary Basins, Maturation Indices, and Kinetics of Oil and Gas Generation. AAPG. Bull. 71: 1445-1466.

Tissot, B. P., and Welte, D. H. 1978. Petroleum Formation and Occurrence. Berlin: Springer-Verlag.

Trangcotchasan, T., and Gladnaka, C. 1992. Petroleum Exploration History in Thailand. National Conference on "Geological Resources of Thailand: Potential for Future Development", pp. 653-667. Department of Mineral Resources, Bangkok, Thailand.

Vacher, M. 1995. Petroleum Geology of the Northern Part of the Western basin, Gulf of Thailand. Master's Thesis, Department of Geology, Graduate School, Chulalongkorn University.

Walker, G. R. 1984. Facies Model. 2nd ed. Canada: Ainsworth Press Limited.

Waples, D. W. 1980. Time and Temperature in Petroleum Formation: Application of Lopatin's Method to Petroleum Exploration. AAPG. Bull. 64: 916-926.

Watanasak, M. 1989. Palynological Zonation of Mid-Tertiary Intermontane Basins in Northern Thailand. International Symposium on Intermontane Basins:Geology & Resources, pp. 216-225, Chiang Mai University, Thailand.

Watanasak, M. 1990. Mid-Tertiary Palynological of Thailand. Jour. S.E Asian Earth Sciences 4: 203-218.

Weeks, L. G. 1961. Origin, Migration and Occurrence of Petroleum. In Moody, G. B. (ed.), Petroleum Exploration Handbook, pp. 5-1 – 5-49. New York: McGraw Hill.

Williamson, C. R. 1992. Funan Field – First Gas Production from the Eastern Pattani Basin. National Conference on "Geological Resources of Thailand: Potential for Future Development", pp. 225-234. Department of Mineral Resources, Bangkok, Thailand.

Woolland, M. A., and Haw, D. 1976. Tertiary Stratigraphy and Sedimentation in the Gulf of Thailand. Seapex Program, Offshore South East Asia Conference, pp.1-22. Singapore.

BIOGRAPHY

Miss. Sonchawan Ac-kagosol was born in Nakornratchasima province on August 21, 1975. In 1998, she graduated with a B.Eng. degree in Geotechnology from Suranaree University of Technology. After graduation, she studied the M.Sc. degree in Geology at Chulalongkorn University.