វិទ្យាស្ថានបច្ចេកវិទ្យាកម្ពុជា

INSTITUTE OF TECHNOLOGY OF CAMBODIA

GRADUATE SCHOOL

SOURCE ROCK EVALUATION AND DEPOSITIONAL ENVIRONMENT OF SEDIMENTARY ROCKS CHARACTERIZATION IN KAMPONG-SOM AND TONLE SAP SEDIMENTARY BASIN, ONSHORE CAMBODIA

PECH SOPHEAP

DOCTORAL THESIS

DECEMBER 2023

SOURCE ROCK EVALUATION AND DEPOSITIONAL ENVIRONMENT OF SEDIMENTARY ROCKS CHARACTERIZATION IN KAMPONG-SOM AND TONLE SAP SEDIMENTARY BASIN, ONSHORE CAMBODIA

A THESIS PRESENTED BY

PECH SOPHEAP

TO

THE INSTITUTE OF TECHNOLOGY OF CAMBODIA

IN PARTIAL FULFILMENT OF THE REQUIREMENTS

FOR THE AWARD OF

DOCTOR OF ENGINEERING

SPECIALIZATION: *ENERGY TECHNOLOGY AND MANAGMENT*

SUPERVISOR: **Assoc. Prof. Dr. OR Chanmoly**

CO-SUPERVISOR: **Asst. Prof. Dr. ENG Chandoeun**

Dr. Afikah Binti Rahim

EXAMINATION COMMITTEE

SIM Tepmony, Asst. Prof. Dr., Graduate School, ITC	*Chair*
CHEY Chen Oeurn, Prof., Faculty of Science, RUPP	*Reviewer*
CHENG Horchhong, Dr., Faculty of Electrical Engineering, NPIC	*Reviewer*
SREU Tola, Dr., Faculty of Geo-resources and Geotechnical Engineering, ITC	*Reviewer*
KRET Kakda, Dr., Energy Technology and Management Unit, RIC, ITC	*Reporter*
OR Chanmoly, Assoc. Prof. Dr., Research and Innovation Center, ITC	*Member*
ENG Chandoeun, Asst. Prof. Dr., Fac. Geo-resources and Geotechnical Eng., ITC	*Member*
Afikah Binti Rahim, Dr., Faculty of Civil Engineering, UTM	*Member*

PHNOM PENH, 22 DECEMBER 2023

ក្រសួងអប់រំ យុវជន និងកីឡា
វិទ្យាស្ថានបច្ចេកវិទ្យាកម្ពុជា

និក្ខេបបទបណ្ឌិត
របស់និស្សិត ម៉ិច សុភាព

កាលបរិច្ឆេទការពារ ៖ ២២ ធ្នូ ២០២៣

អនុញ្ញាតឱ្យការពារនិក្ខេបបទ

ន. នាយកវិទ្យាស្ថាន ៖ ____________

សុយ_ធី

ថ្ងៃទី ខែ ឆ្នាំ ២០២៣

ប្រធានបទ ៖ ការវាយតម្លៃគុណភាពសិលាប្រភពរ៉ែប្រេងកាត និងការកំណត់លក្ខណៈនៃបរិស្ថានដាក់បន្តរបស់សិលាកម្ទេចកំណ ក្នុងអាងសិលាកម្ទេចកំណកំពង់សោម និងទន្លេសាប លើដែនគោក នៃប្រទេសកម្ពុជា

នាយកសាលាក្រោយបរិញ្ញាបត្រ ៖ សាស្ត្រាចារ្យជំនួយ ស៊ិម ទេពមុនី ____________

សហសាស្ត្រាចារ្យណែនាំ ៖ ១. សាស្ត្រាចារ្យរង អោ ច័ន្ទម៉ូលី ____________

២. សាស្ត្រាចារ្យជំនួយ អេង ចាន់ខឿន ____________

៣. បណ្ឌិត Afikah Binti Rahim ____________

រាជធានីភ្នំពេញ ឆ្នាំ២០២៣

MINISTRY OF EDUCATION,

YOUTH AND SPORT

INSTITUTE OF TECHNOLOGY OF CAMBODIA

DOCTORAL THESIS

Of Ms. PECH Sopheap

Defense Date: December 22, 2023

PERMISSION TO DEFEND THE THESIS

F. **Director of Institute:** ____________

SOY TY

Phnom Penh, , 2023

Thesis's Title: Source Rock Evaluation and Depositional Environment of Sedimentary rocks Characterization in Kampong-Som and Tonle Sap Sedimentary Basin, Onshore Cambodia

Director of Graduate School: Asst. Prof. Dr. SIM Tepmony ____________

Supervisors: 1. Assoc. Prof. Dr. OR Chanmoly ____________

2. Asst. Prof. Dr. ENG Chandoeun ____________

3. Dr. Afikah Binti Rahim ____________

PHNOM PENH, CAMBODIA

Acknowledgements

It is my deep honor to express my gratitude to generous people who have shared their time, their support and their knowledge for this research.

I would like to express my respect to **H.E. Prof. Dr. PO Kimtho**, Director of Institute of Technology of Cambodia for his good leadership and management.

I would like to express my great pleasure to thank **Assoc. Prof. Dr. OR Chanmoly** who is the principal investigator (PI) of project HEIP-SGA #13, and my kind and supportive advisor. This research would not have been done completely without his enthusiastic support.

I also would like to express my gratitude to **Asst. Prof. Dr. ENG Chandoeun** and **Dr. Afikah Binti Rahim**, my Co-Advisor for their instruction, advice, and reviewing throughout this dissertation.

I specially thank to the Cambodia **Higher Education Improvement Project** (Credit No. 6221-KH) for fund supported in this research study. I would like to thank the **Ministry of Mine and Energy (MME), the General Department of Petroleum (GDP), and my teamwork, especially Mr. Heng Ratha** for assisting during the fieldwork investigation and laboratory testing.

Finally, special thanks turn to my beloved family, who have always provided me with both support and love. I thought you could see what I obtained today with pride, without you there is nothing for me today. This success may reflect the real brightness and happiness in my academic career.

សេចក្តីសង្ខេប

អាងសិលាកម្ទេចកំណកំពង់សោម និងអាងសិលាកម្ទេចកំណទន្លេសាប ត្រូវបានគេជឿជាក់ថាជាអាងលើដែនគោក ដែលមានសក្តានុពលខ្ពស់ សម្រាប់ការរុករករ៉ែប្រេងកាត។ ទោះបីជាយ៉ាងណាក៏ដោយ សកម្មភាពរុករករ៉ែប្រេងកាតនានា និងឯកសារស្រាវជ្រាវសម្រាប់អាងសិលាកម្ទេចកំណទាំងពីរ នៅមានកម្រិតតិចតួចនៅឡើយ។ ការសិក្សានេះ ជាដំណាក់កាលសិក្សាបឋមនៃការរុករករ៉ែប្រេងកាត ដោយពឹងផ្អែកលើការវិភាគសិលាលេចឡើងលើផ្ទៃដី និងព័ត៌មានភូគព្ភសាស្ត្រនៃអាងសិលាកម្ទេចកំណទាំងពីរ។ តំបន់សំឡូត និងតាក្រៀម ក្នុងខេត្តបាត់ដំបង ត្រូវបានជ្រើសរើសសម្រាប់អាងសិលាកម្ទេចកំណទន្លេសាប រីឯភ្នំចក្រី ភ្នំតាគុង ភ្នំជ្រោយចេក ភ្នំមាន់ព្រៃ ភ្នំខ្លី និងភ្នំបូកគោត្រូវបានជ្រើសរើសសម្រាប់អាងសិលាកម្ទេចកំណកំពង់សោម។

ការសិក្សាស្រាវជ្រាវផ្តោតសំខាន់លើ ការវាយតម្លៃគុណភាពសិលាប្រភពរ៉ែប្រេងកាត និងការកំណត់លក្ខណៈនៃបរិស្ថានចាក់បង្គរបស់សិលាកម្ទេចកំណ ក្នុងអាងសិលាកម្ទេចកំណកំពង់សោម និងទន្លេសាប ដែនគោកនៃប្រទេសកម្ពុជា។ និក្ខេបបទនេះចែកចេញជា 6ជំពូក ដូចមានរៀបរាប់ខាងក្រោម៖

ជំពូកទី1 គឺជាជំពូកណែនាំលើទិដ្ឋភាពទូទៅនៃអាងសិលាកម្ទេចកំណនៃប្រទេសកម្ពុជា ការសង្ខេបពីសក្តានុពលសម្រាប់ការរុករករ៉ែប្រេងកាត ទីតាំងស្រាវជ្រាវ ការបង្កើតបញ្ហា គោលបំណងនៃការសិក្សាស្រាវជ្រាវ និងអត្ថប្រយោជន៍នៃការសិក្សាស្រាវជ្រាវនេះ។

ជំពូកទី2 បង្ហាញពីភូគភ្ភសាស្ត្រនៃប្រទេសកម្ពុជា សេចក្តីលម្អិតនៃអាងសិលាកម្ទេចកំណនៃប្រទេសកម្ពុជា និយមន័យនិងការធ្វើចំណាត់ថ្នាក់លើសិលាកម្ទេចកំណ និយមន័យនិងការធ្វើចំណាត់ថ្នាក់លើសារធាតុសរីរាង្គ លក្ខខណ្ឌវាយតម្លៃគុណភាពសិលាប្រភពរ៉ែប្រេងកាត និងគំរូបរិស្ថានចាក់បង្គរមួយចំនួនលើដែនគោកនិងដែនសមុទ្រ។ ដំណើរការនៃការវាយតម្លៃសិលាប្រភពរ៉ែប្រេងកាត និងការកំណត់លក្ខណៈនៃបរិស្ថានចាក់បង្គរបស់សិលាកម្ទេចកំណដោយភ្ជាប់មួយនឹងវិធីសាស្ត្រ និងការអនុវត្ត។

ជំពូកទី3 បង្ហាញពីការកំណត់លក្ខណៈនៃបរិស្ថានចាក់បង្គរបស់សិលាកម្ទេចកំណ នៃអាងសិលាកម្ទេចកំណទន្លេសាប ដោយការសិក្សាលើផ្នែកសិលាលេចឡើងលើផ្ទៃដី Sedimentology ការវិភាគLithofacies Paleontology និងគីមីសាស្ត្រនៃសិលា។ Redox condition, Water column deposit និង Depositional setting ត្រូវបានវិភាគដោយការធ្វើសមាមាត្រធាតុ V ធៀបនឹង Cr, Uauthigenic ធៀបនឹង V/Cr, Sr ធៀបនឹង Ba, Ca ធៀបនឹង (Fe + Ca) និង Fe_2O_3/TiO_2 ធៀបនឹង $Al_2O_3/(Al_2O_3 + Fe_2O_3)$។ លើសពីនេះទៅទៀត ដ្យាក្រាមទាំងនេះ ត្រូវបានប្រើដើម្បីកំណត់លក្ខខណ្ឌជាក់លាក់នៃការចាក់បង្គរបស់សិលាកម្ទេចកំណផងដែរ។ ផ្អែកលើលទ្ធផល តំបន់សំឡូត និងតាក្រៀម ជាប្រភេទសិលាភក់ និងសិលាកំបោរ។ ការវិភាគភូគព្ភសាស្ត្របង្ហាញថា សិលាភក់នៃតំបន់សំឡូត បានចាក់បង្គរក្នុងតំបន់ទឹកសាប ក្រោមលក្ខខណ្ឌ Dysoxic នៃបឹងទឹកសាបកំឡុងពេលទឹកសមុទ្រស្រក ចំណែកឯសិលាកំបោរនៃតំបន់សំឡូត និងសិលាកម្ទេចកំណនៃតំបន់តាក្រៀម ត្រូវបានចាក់បង្គរនៅក្នុងតំបន់ទឹកសមុទ្រដែលមានជាតិប្រៃខ្ពស់ ក្រោមលក្ខខណ្ឌ Oxic នៃតំបន់ទឹកសមុទ្ររាក់។ លើសពីនេះ សិលាកំបោរនៃតំបន់សំឡូត មានហ្វូស៊ីល Fusulinid foraminifera បំណែក Bivalve shell និងBryozoan ដែលបង្ហាញពីបរិស្ថាន Barrier។ ទន្ទឹមនឹងនោះ តំបន់តាក្រៀមមាន

សិលាកម្ទេចកំណាដែលជាប្រភេទគ្រាប់តូចល្អិតខ្លាំង ដែលចង្អុលបង្ហាញថាពួកវាចាក់បង្គរក្នុងតំបន់ទឹកស្ងប់នៃដែនសមុទ្រ។ ដូច្នេះហើយ អាងសិលាកម្ទេចកំណាទន្លេសាប ត្រូវបានកំណត់ថា ផ្ទុកសិលាកម្ទេចកំណាដែលចាក់បង្គរក្នុងបរិស្ថាន Barrier និងបរិស្ថាន Lake សម្រាប់តំបន់សំឡូត និងបរិស្ថាន Lagoon សម្រាប់តំបន់តាក្រៀម។

ជំពូកទី4 ពិពណ៌នាអំពី Lithostratigraphy, Lithofacies analysis និង Paleontology របស់សិលាកម្ទេចកំណា នៃអាងសិលាកម្ទេចកំណាកំពង់សោម ដែលត្រូវបានគេជឿថាជា តំបន់ប្រមូលផ្តុំរ៉ែប្រេងកាត នៅលើដែនគោក នៃប្រទេសកម្ពុជា។ សិលាលេចឡើងលើផ្ទៃដីចំនួនប្រាំមួយទីតាំង នៅក្នុងខេត្តកំពត ត្រូវបានជ្រើសរើសដើម្បីធ្វើការសិក្សា និងធ្វើជាតំណាងសម្រាប់សិលាកម្ទេចកំណាក្នុងអាងសិលាកម្ទេចកំណាកំពង់សោម។ ការសិក្សាស្រាវជ្រាវនេះមានគោលបំណងកំណត់លក្ខណៈបរិស្ថានចាក់បង្គររបស់សិលាកម្ទេចកំណា នៃអាងសិលាកម្ទេចកំណាកំពង់សោម។ សំណាកគំរូសិលា ចំនួន 10 នៃសិលាភក់ សិលាកំបោរ និងសិលាក្រែ ត្រូវបានជ្រើសរើស និងធ្វើការសង្កេតយ៉ាងលម្អិតលើ Sedimentary texture, Sedimentary structure, Lithofacies, ហ្វូស៊ីល និងសារធាតុខនិចក្នុងសិលា។ អាងសិលាកម្ទេចកំណានេះ មានសិលាកម្ទេចកំណាបីយុគសម័យគឺ យុគសម័យ Permian, យុគសម័យ Triassic និងយុគសម័យ Jurassic ដែលមានកម្រាស់សរុបជាង 350ម៉ែត្រ។ Packstone ជាសិលាដែលបានរកឃើញនៅក្នុងយុគសម័យPermian មានពណ៌ប្រផេះចាស់ ហាប់ ណែន និងមានបំណែកហ្វូស៊ីលជាច្រើន ដូចជាបំណែកនៃថ្មប៉ប្រះទឹក, ផ្កាថ្ម, Crinoid, Syringopora និង Foraminifer ដែលត្រូវបានកំណត់ថា សិលានេះចាក់បង្គរក្នុងដែនសមុទ្រ នៃបរិស្ថានBarrier។ Terrigenous rocks នៃយុគសម័យ Triassic ដែលចាក់បង្គរដោយ conglomerate នៅផ្នែកខាងក្រោម ហើយបន្តដោយ ការចាក់បង្គរឆ្លាស់គ្នារវាងសិលាភក់ និងសិលាក្រែគ្រាប់ល្អិត ដែលបង្ហាញថាត្រូវបានចាក់បង្គរក្រោមដំណើរការ Turbiditic របស់បរិស្ថាន Submarine fan។ សិលាក្រែក្នុងយុគសម័យ Jurassic គឺត្រូវបានចាត់ចូលជា White quartz arenite ដែលភាគច្រើនត្រូវបានរកឃើញនៅលើភ្នំបូកគោ វាផ្សំឡើងជាចម្បងពីគ្រាប់ខ្សាច់ស ដែលបង្ហាញពីបរិស្ថានស្អាត នៃបរិស្ថានសមុទ្ររាក់។ ហេតុដូច្នេះហើយ សិលាកម្ទេចកំណានៃយុគសម័យ Permian-Jurassic បានបង្ហាញថា ការចាក់បង្គរនៃសិលានេះត្រូវបានទទួលឥទ្ធិពលពី Transgressive /Regressive, បរិស្ថាន Barrier, បរិស្ថាន Submarine fan, និងបរិស្ថានសមុទ្ររាក់ដោយមានការចូលរួមពី RIP current។

ជំពូកទី5 ពិភាក្សាអំពីការកំណត់ប្រភេទសារធាតុសរីរាង្គ និងការវាយតម្លៃគុណភាពសិលាប្រភពរ៉ែប្រេងកាតក្នុងសិលាភក់ នៃអាងសិលាកម្ទេចកំណាកំពង់សោម។ ការសិក្សានេះមានគោលបំណង កំណត់ប្រភេទសារធាតុសរីរាង្គ កំណត់ប្រភេទ Kerogen វាស់កាបូនសរីរាង្គសរុប(TOC) និងវាស់សីតុណ្ហភាពបញ្ចេញរ៉ែប្រេងកាត ដោយប្រើការអង្កេតទីវាល ការអង្កេតក្រោមមីក្រូទស្សន៍ ការស្កេនមីក្រូទស្សន៍អេឡិចត្រុង (SEM) ឧបករណ៍វិភាគជាតុកាបូនសរីរាង្គសរុប និងឧបករណ៍វិភាគ Rock-eval pyrolysis។ កាបូនសរីរាង្គ Bitumen គឺជាសារធាតុសរីរាង្គដែលលេចធ្លោនៅក្នុង KH-S1, CC-S1, និង TT-S1 ដែលមានចំនួន 73%, 80% និង 99% នៃសារធាតុសរីរាង្គ។ សារធាតុសរីរាង្គ Vitrinite និង Inertinite ដែលកើតចេញពីរុក្ខជាតិខ្ពស់នៅលើដី មានវត្តមានក្នុងបរិមាណតិចតួច។ សារធាតុសរីរាង្គ Alginite (3%) ត្រូវបានរកឃើញតែនៅក្នុង CC-S1 ប៉ុណ្ណោះ។ សារធាតុសរីរាង្គ Bitumen បានបង្ហាញរន្ធស្ពោតតិចតួចជា Nanopores ក្នុងកម្រិត1μm ដែលត្រូវបានសង្កេតឃើញ

ក្នុងសំណាក TT-S1 និង KH-S1 ប៉ុន្តែសំណាកទាំងពីរនេះគឺមិនទាន់គ្រប់សីតុណ្ហភាពបញ្ចេញរ៉ែប្រេងកាតនៅឡើយ សីតុណ្ហភាព415°C និង382°C។ ដូច្នេះ សិលាប្រភពរ៉ែប្រេងកាតនៃអាងសិលាកម្ទេចកំណកំពង់សោមផ្ទុកកាបូនសរីរាង្គសរុប(TOC) កម្រិតទាប(0.06wt% និង 0.07wt%) និងកាបូនសរីរាង្គសរុប(TOC) កម្រិតខ្ពស់(3.61wt% និង 9.45wt%)។ សិលាប្រភពរ៉ែប្រេងកាតទាំងអស់នេះ គឺមិនទាន់គ្រប់សីតុណ្ហភាពបញ្ចេញរ៉ែប្រេងកាតនៅឡើយ 415°C ក្នុងហេតុផលដែលសិលាទាំងនេះមិនទាន់កប់ចូលជ្រៅគ្រប់គ្រាន់មុនពេលដែលសិលាទាំងនេះលេចឡើងមកលើផ្ទៃដី។

ជំពូកទី6 គឺជាការសង្ខេប និងការសន្និដ្ឋាននៃការរកឃើញដ៏សំខាន់នៃការសិក្សាស្រាវជ្រាវ រួមទាំងចំណាប់អារម្មណ៍នៃការស្រាវជ្រាវសម្រាប់ការសិក្សានាពេលអនាគតលើការរុករករ៉ែប្រេងកាត នៅលើដែនគោក នៃប្រទេសកម្ពុជា។

Abstract

Kampong-Som and Tonle Sap sedimentary basin were believed as the high potential onshore sedimentary basin for hydrocarbon accumulation, beside Khmer sedimentary basin. However, the exploration activities and documents are still limited access for the onshore sedimentary basins. This is the preliminary stage of hydrocarbon exploration; the exposure outcrops and surface geological information of both basins were selected to analyze. Somlout and Takream areas in Battambong province are selected for Tonle Sap sedimentary basin while Chakrey mountain, Totong mountain, Chrous Chek mountain, Monprey mountain, Khley mountain, and Bokor mountain are selected for Kampong-Som sedimentary basin.

The research study focuses on source rock evaluation and depositional environment characterization of sedimentary rocks in Kampong-Som and Tonle Sap sedimentary basin, onshore of Cambodia. The dissertation is composed of six chapters as described in the following:

Chapter 1 is the introductory chapter which overviews of general background of Cambodia sedimentary basin, which brief the potential for hydrocarbon exploration, research location, problem formulation, main objectives, and the benefits of present research.

Chapter 2 presents the geological setting of Cambodia, sedimentary basin of Cambodia, definition and classification of sedimentary rock, definition and classification of organic matter, source rock evaluation parameters, and some depositional environment model of continental to marine depositional environment. The brief source rock evaluation, and depositional environment characterization with the methods and application approach.

Chapter 3 presents the depositional environment of sedimentary rocks in Tonle Sap sedimentary basin insights by field investigation, sedimentology, lithofacies analysis, paleontological aspect, and geochemical studies. The redox condition, water column deposit, and depositional setting were analyzed by plotting the ratio of V vs. Cr, Uauthigenic vs. V/Cr, Sr vs. Ba, Ca vs. (Fe + Ca), and Fe_2O_3/TiO_2 vs. $Al_2O_3/(Al_2O_3 + Fe_2O_3)$ diagram. Moreover, these diagrams can be used to predict depositional conditions as well. Based on the results, Somlout and Takream comprise calcareous shale and limestone facies. The geochemical analysis shows that Somlout calcareous shale samples were deposited in the dysoxic freshwater of the lake setting during the regression, while Somlout limestones and Takream were deposited in high salinity seawater, oxic condition of shallow-marine water. In addition, Somlout limestones consist of fragmental fusulinid foraminifera, bivalve shelve, and bryozoan, which suggest a barrier environment.

Meanwhile, Teakream consists of fine-grained calcareous shale, and lime-mudstone, which are presented to form in the quiet marine setting of the lagoon environment. Therefore, the Tonle Sap basin sediments were deposited in the Somlout area's barrier and lake environment, and the lagoon environment for Takream.

Chapter 4 describes the lithostratigraphy, lithofacies analysis, and paleontology concepts of sedimentary rocks in Kampong-Som basin that is believed as one prospect of the onshore hydrocarbon accumulation in Cambodia. Six well-exposure outcrops in Kampot province were selected to be studied and to be representative for Kampong-Som sedimentary rocks. This research study aims to characterize the depositional environment of sediments in the Kampong-Som sedimentary basin. Ten samples of limestones, shales, and sandstones were selected and were observed in detail of sedimentary texture, sedimentary structure, lithofacies, fossil content, and mineralogy. This basin consists of three main lithofacies, Permian packstone, terrigenous rocks of the Triassic age, and Jurassic sandstone with a thickness of more than 350m. Packstone mostly found in the age of Permian is dark grey color, massive, compacted, and abundant in fossils such as fragment of coral reef, Crinoid, syringopora, and foraminifer, which deposited in marine setting of barrier deposit. These facies were overlain by terrigenous rocks of the Triassic age, composed of the conglomerate in the bottom part and followed by an interbedded medium to fine sandstone with laminated black shale which suggest being deposited in which suggest being deposited in under turbiditic process of submarine fan deposit. The Jurassic white quartz arenite sandstone, mostly found in Bokor mountain, is composed mainly of white quartz arenite, which indicates the clean environment of shallow marine deposits. Therefore, the Permian-Jurassic sedimentary facies indicated the transgressive/ regressive succession of shelf see from barrier, submarine fan, and shallow marine deposits by RIP current.

Chapter 5 discusses the organic matter identifications and source rock evaluation of shale in Kampong-Som sedimentary basin. This study aims to identify the organic matter type, kerogen type, total organic carbon (TOC) content, and maturity temperature evolution by using field investigation, petrography, scanning electron microscope (SEM), Total carbon elemental analyzer, and rock-eval pyrolysis. Solid bitumen organic matter is the dominant organic component in KH-S1, CC-S1, and TT-S1, accounting for 73%, 80%, and 99% of total OM. Vitrinite and inertinite derived from terrestrial higher vegetation are present in minor amounts. Alginite (3%) was found only in CC-S1. Solid bitumen hosted secondary pores (nanopores 1μm), which were observed TT-S1 sample and KH-S1, however these both samples are immature in temperature ~415°C. The pore in SB is very rare and only small particles of SB of

KH-S1 sample, it is automatically that its source rock is immature and lower temperature (382°C) than TT-S1. So, the exposure source rocks of Kampong-Som basin are poor total organic content (0.06wt% and 0.07wt%) and excellent total organic content (3.61wt% and 9.45wt%). All these source rocks are immature below temperature 415°C in reason they don't go deep enough before they were exposed to the surface.

Chapter 6 is a summary and conclusion of major finding of present research including the research interest for the future study on hydrocarbon exploration.

TABLE OF CONTENTS

Chapter 5

Organic Matter Identifications and Source Rock Evaluation of Shale in Kampong-Som Basin, Onshore Cambodia

Chapter 6

Conclusions

List of Figures

List of Tables

Chapter 1.

Introduction

1.1 General Background

Cambodia consists of seven sedimentary basin, Khorat (southern portion), Preah, Chhung, Svayrieng, Tonle Sap, Kampong-Som, and Khmer sedimentary basin **(Figure 1.1)** (Vysotsky et al., 1994). Khmer and some part of Kampong-Som sedimentary basin are offshore; Khorat (southern portion), Preah, Chhung, Svayrieng, Tonle Sap, and Kampong-Som sedimentary basin are onshore. Vysotsky et al. (1994) believed that Kampong-Som and Tonle Sap sedimentary basin are potential onshore sedimentary basins for hydrocarbon exploration.

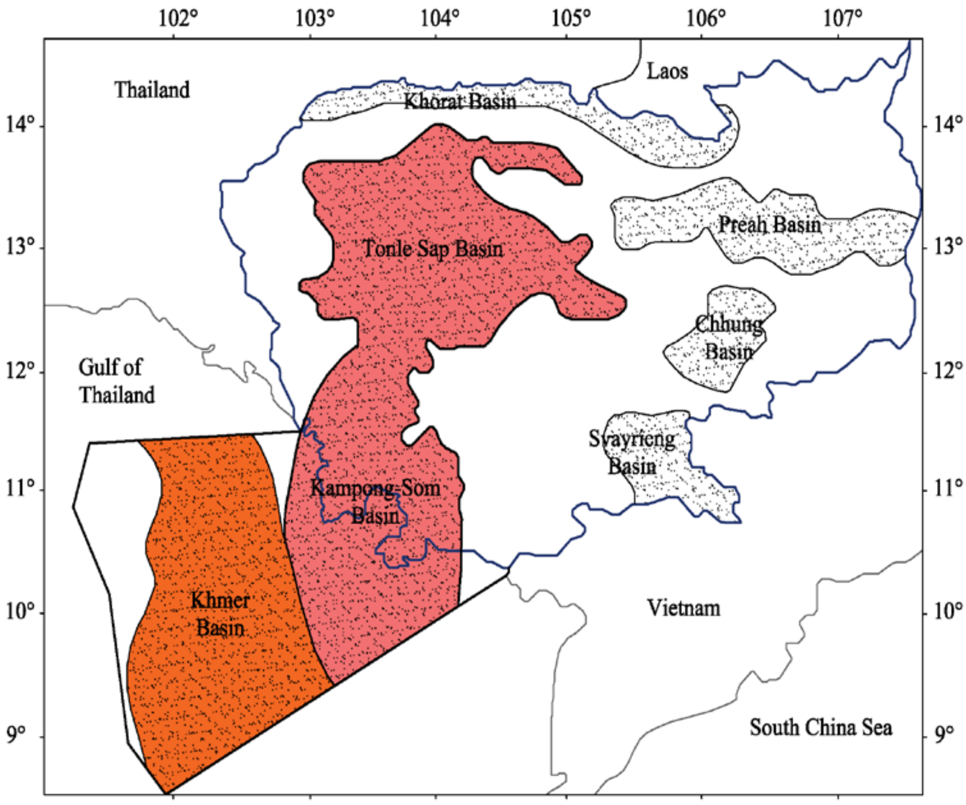

Figure 1.1: Sedimentary basins in onshore and offshore of Cambodia (Mao et al., 2014).

According to the surface investigation, there are some oil seepages in the central and southern Cambodia which have been notified by Polish geologists in the early 1960’s (Lim, 2006). Recently, Preah Sihanouk and Kampot provinces reported surface oil seepage, which makes these both sedimentary basins more interested in hydrocarbon exploration. Although these both were considered as hydrocarbon potential, the exploration activities are still limited and documented. This research is the preliminary study of onshore hydrocarbon exploration which will answer the hydrocarbon source rocks quality and their depositional environment. Therefore, source rock is the main element in petroleum system which needs to be well understood in the preliminary study for hydrocarbon exploration. Organic matter abundance is an important index by which to evaluate the quality of source rock. This study will evaluate the source rock quality and discuss their depositional environment, to enhance our knowledge and understanding of the Tonle Sap and Kampong-Som sedimentary basin.

In case, the petroleum system was found, it provides many benefits to Cambodian social:

- Economic growth: Oil production contributes significantly to a country’s economy by creating jobs, generating tax revenue, and attracting foreign companies to invest in this sector. It promotes economic growth and development, especially in oil-rich areas.
- Energy security: Oil is an important source of energy worldwide, and countries with large oil reserves ensure their energy security by producing their own oil and gas. This leads the independence on imports and provides a reliable source of energy for domestic consumption.
- Revenue generation: Oil exports can generate substantial revenue for countries that can be used for infrastructure development, social welfare programs, education, health care and other public services. This income can help improve people’s living standards and reduce poverty.
- Job opportunities: Oil production creates employment opportunities in various fields, including exploration, drilling, refining, transportation, and distribution. It employs engineers, geologists, technicians, truck drivers and other skilled, and unskilled workers also get this opportunity.

1.2 Research Location

This present research is a part of hydrocarbon exploration, the well exposure outcrop was selected to study replace using core samples. The research areas are quarry sites which located in the Tonle Sap and Kampong-Som sedimentary basin, the western and southern part of the onshore Cambodia **(Figure 1.2)**. The two outcrops of Permian sedimentary rock, Takream and Somlout, which are located in Banan district and Somlout district of Battambang province. They were selected to represent the Permain unit in Tonle Sap sedimentary basin, which exposed in the western part of the Tonle Sap sedimentary basin. Another six outcrop of Permian-Jurassic sedimentary rocks, Chakrey mountain, Monprey mountain, Chrous Chek mountain, Totong mountain, Kley mountain, and Bokor mountain, where are located in Tuek Chhou district, Bonteay Meas district, Touk Meas district, and Krong Kampot. These six outcrop are represent the sedimentary rock of Kampong-Som sedimentary basin, where exposed in the central of the Kampong-Som sedimentary basin.

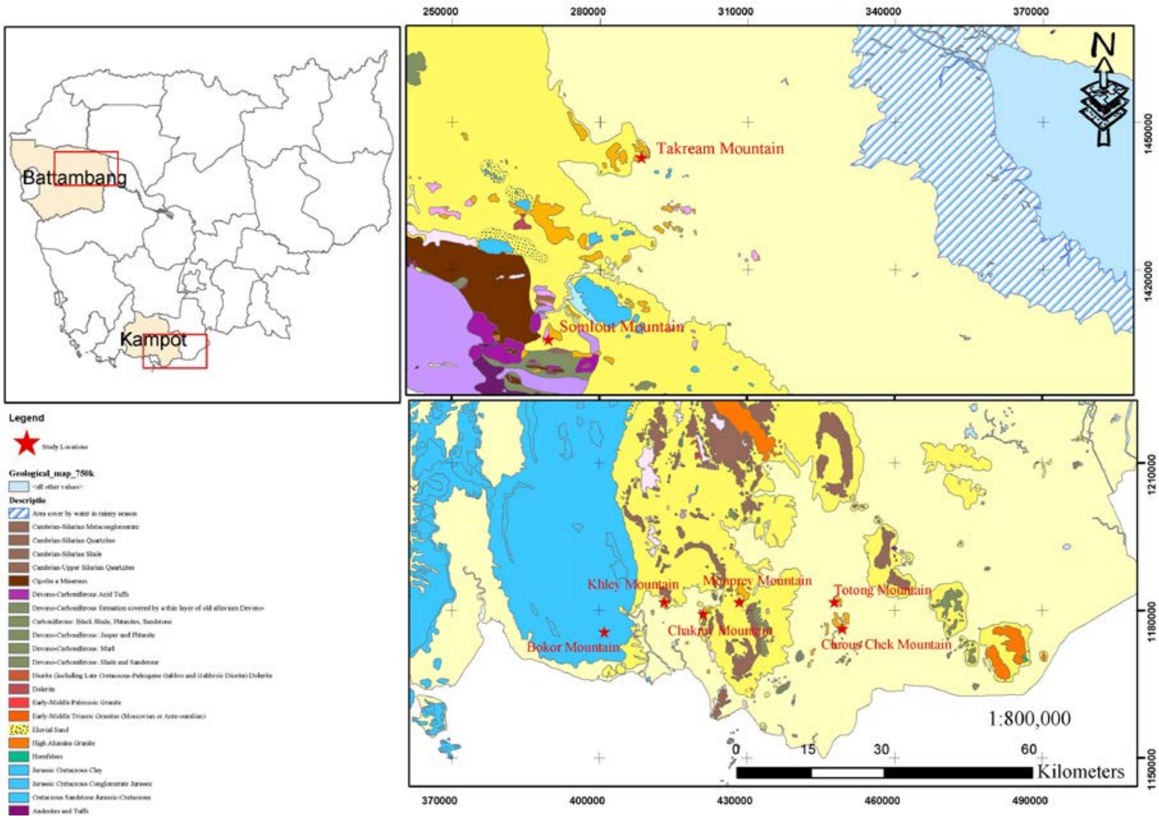

Figure 1.2: Map showing the location of research location (GDMR-JICA, 2010).

1.3 Problem Formulation

Based on preliminary studies, the Ministry of Mine and Energy (MME) and Cambodian National Petroleum Authority (CNPA) of Cambodia, the Tonle Sap and Kampong-Som sedimentary basin of onshore Cambodia may have a potential hydrocarbon system. However, the quality and quantity of source rocks and deposition environment have not been revealed yet. This research evaluates the quality and quantity of source rock and defines the depositional environment of sedimentary rocks in western and southern Cambodia by conducting geological fieldwork and laboratory works.

Therefore, this research fatefully answers the following questions:

- What is the sedimentology in Tonle Sap and Kampong-Som sedimentary basins?
- What is the quality of the source rock of Kampong-Som sedimentary basin?

1.4 Objectives

The main objective of this research is to evaluate the quality and quantity of hydrocarbon source rock and to characterize the depositional environment of sediments in the Kampong-Som basin, onshore Cambodia. This general objective contains two more specific objectives:

- To characterize the depositional environment of sedimentary rocks, using field observation and geochemical studies or paleontology
- To identify organic matter type and evaluate the quality of the source rocks

1.5 Research Scope

This research study is preliminary hydrocarbon exploration which focuses on source rock evaluation and depositional environment characterization of sedimentary rocks in Tonle Sap and Kampong-Som sedimentary basin, the western and southtern Cambodia. This study is depend on the exposure outcrop in Somlout and Takream for represent Tonle Sap sedimentary basin, and Chakrey mountain, Totong mountain, Chrous Chek mountain, Monprey mountain, Khley mountain, and Bokor mountain for represent Kampong-Som sedimentary basin. All the exposure outcrops were conducted geological field investigation, stratigraphy column construction in detail of lithology, sedimentary structure, paleontology, and sample selections. Shale, fine grain sedimentary rock, is considered as hydrocarbon source rocks and selected as representative samples that need to analysis in laboratory works.

To reconstruct the depositional environment of sedimentary rocks in Tonle Sap sedimentary basin, the mineral compositions, x-ray fluorescence (XRF), and inductively coupled plasma mass spectrometry (ICP-MS), are used to define the redox conditions, water column environment, and depositional setting by plotting the ratio of V vs. Cr, Uauthigenic vs. V/Cr, Sr vs. Ba, Ca vs. (Fe + Ca), and Fe_2O_3/TiO_2 vs. $Al_2O_3/(Al_2O_3 + Fe_2O_3)$ diagram.

To reconstruct the depositional environment of sedimentary rocks in Kampong-Som sedimentary basin, the petrography analysis of thin section of shale, limestone and sandstone samples are play an importance role to identify the rock classification, and micro fossil idetification. The sedimentology and paleontology aspect are applied to analyse the depositional environment of sediemntary rocks in Kampong-Som sedimentary basin.

To evaluate the quality of hydrocarbon source rock of Kampon-Som sedimentary basin, various four geochemical methods will be analyzed, such as total organic carbon (TOC) content, rock-eval pyrolysis, petrography, and scanning electron microscope (SEM). TOC content, organic matter type, kerogen type, and thermal maturity are the important index to reveal the qulaity of hydrocarbon source rocks.

1.6 Outline of Dissertation

Four chapters in which the objectives and contents of each are described in the following compile of the dissertation:

Chapter 1 is the introductory chapter which overviews of general background of sedimentary basin, research location, problem formulation, and the main objective of present research.

Chapter 2 presents geological setting, sedimentary basin of Cambodia, definition and classification of sedimentary rock, definition and classification of organic matter, source rock evaluation, and depositional environment. The brief source rock evaluation, and depositional environment with the methods and application approach.

Chapter 3 presents the sedimentological feature and detail lithofacies which are obtained by applied field observation and sedimentology concept. Various geochemical elements, major and minor elements, are used to interpret redox conditions, water column environment. Synthesize these data, the depositional setting of sedimentary rock finally defines.

Chapter 4 aims to identify depositional environment by applying sedimentological and paleontology concepts. The lithofacies of Permian, Jurassic, and Triassic sedimentary rock are defined during field observation and under petrographically. The macro fossils were observed by necked eyes, and micro fossils were observed under microscope. The depositional environment of Permian, Jurassic, and Triassic sedimentary rock are well defined, after rock properties, stratigraphy column and fossils content were understood.

Chapter 5 discusses organic matter type and source rock evaluation. Lithostratigraphy and sedimentary rock properties are obtained from petrographically analysis. The total organic carbon (TOC) content was analyzed with Carbon elemental analyzer. To understand more on source rock properties, rock-eval pyrolysis was pyrolyzing the sample powder and detecting thermal temperature which source rock used to experience. Organic matter types were observed under scanning electron microscope (SEM).

Chapter 6 is a summary and conclusion of major finding of present research.

Chapter 2.

Literature Review

2.1 Geological Setting

Cambodia is in southwestern Indochina, bordering Thailand, Laos, and Vietnam. This country were probably affected by the combination of three main collisions such as Sibumasu-Sukhothai Arc and Indochina, South China and Indochina, and Paleo-Pacific and Indochina (Cai and Zhang, 2009; Fyhn et al., 2016) that produced three regional Fold Belts in Indochina as well as inside Cambodia such as Loei, Truong Son and Dalat-Kratie Fold Belts (Sirisokha et al., 2019; Khin et al., 2014). In term of local, three-fold belts have been observed, Phetchabun

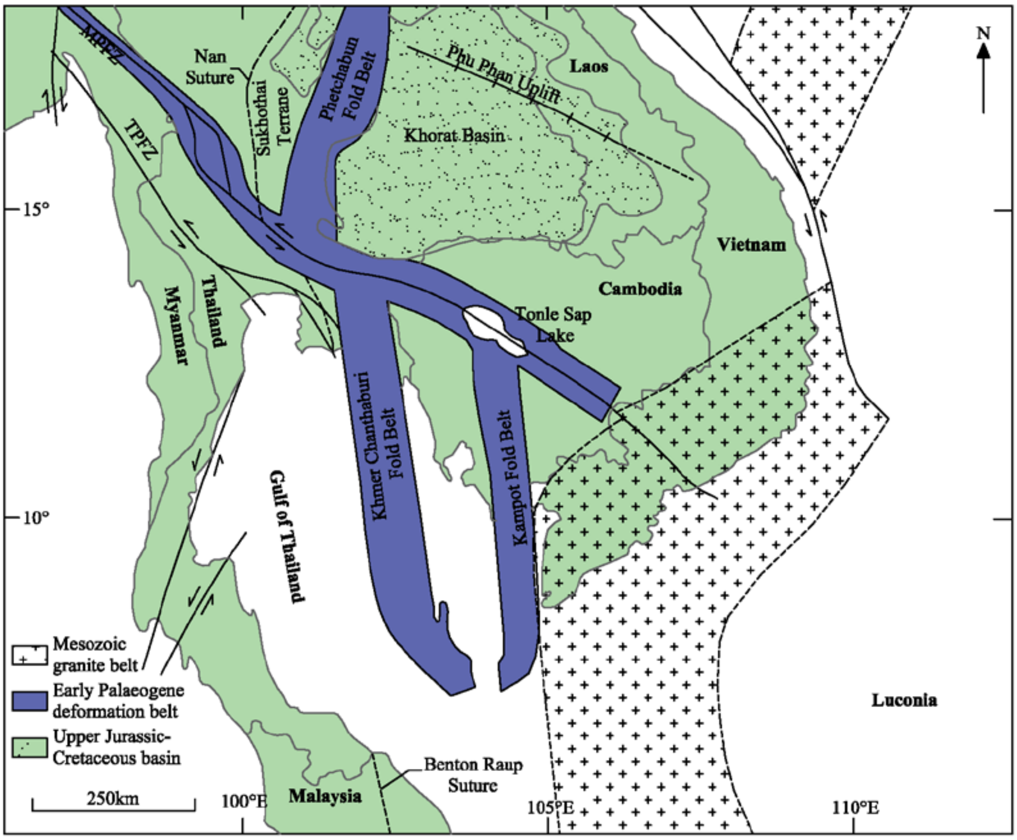

Figure 2.1: Indochina map with selected structural elements (Fyhn et al., 2010b).

fold belts in the northwestern part, Khmer Chanthaburi fold belt, and Kampot fold belt in the southwestern part, that they might be affected by the many phases of folding orogeny during the collision of Sukhothai Arc and western Indochina Terrane in Late Triassic-Early Jurassic **(Figure 2.1)** (Fyhn et al., 2010b, 2016; Lepvrier et al., 2008; Vysotsky et al., 1994; Mao et al., 2014). Mae Ping Fault is the main strike-slip fault, it is the left-lateral strike-slip fault in Middle Eocene-Early Oligocene and ended in Early Oligocene (Fyhn et al., 2010a; Morley, 2001); and change direction to be right-lateral in Early Miocene (Charusiri et al., 2007; Fyhn et al., 2010a). This strike-slip fault was extended from Thailand in the northwest, cutting the Tonle Sap sedimentary basin and continue to southeastward to the Vietnam Sea.

2.2 Sedimentary Basins of Cambodia

There are seven sedimentary basin, six onshore and one offshore in Cambodia **(Figure 1.1)**. These basins are associated with Paleozoic-Mesozoic regional uplifts and Permian-Jurassic folding and trusting of the Indosinian Orogeny or Sundaland Accretion during collision between Indochina, Sibumasu, and South China plates; these basins are also associated with Mesozoic granite magmatism (Mao et al., 2014). The granites were formed a north-south-trending magmatic arc and entered to the Gulf of Thailand to the east of Kampong Som Fold Belt; and they can be traced from the offshore by extending this fold belt crossed the eastern Cambodia border to south China and farther to the northeast. This structure confined Mesozoic Cambodian basin development to a once continuous, large basin that covered the entire area of the modern country. This basin is dominated by uppermost Permian-Triassic syn-rift sediments and overlying post-rift Jurassic to Cretaceous sediments of the Bokor Formation (Vysotsky et al., 1994; Fyhn et al., 2010b). Cambodian basin is structurally sub-divided into the Khorat, Tonle Sap, Preah, Chhung, Svayrieng, and Kampong-Som troughs.

The north-south-directed thrusting and uplift were concentrated along the Khmer and Kampong-Som fold belts and merged with the Mae Ping and Three Pagoda fault zones, which confine the onshore and offshore basin. The activation of the Mae Ping Fault Zone has been linked with right-and subsequent left-lateral displacements. In addition, the Three Pagoda Fault Zone appeared to link up with the Khmer fold Belt, suggesting a connection between the rifting of the western Kampong-Som Trough and late Eocene left-lateral fault motion (Hall, 2011; Watcharanantakul et al., 2000). This indicated that the Kampong-Som Trough was in the central motion along the Three Pagoda Fault Zone, causing the southwestern part of the trough to open as a full-apart basin. In turn, this led to the formation of a new Cenozoic Khmer Trough through the genesis of half-graben complexes that accumulated thick marine sediments during the

Cenozoic; these sediments overlie unidentified Mesozoic units equivalent to the Kampong-Som sediments (Mao et al., 2014).

2.2.1 Tonle Sap Sedimentary Basin

The foreland Tonle Sap sedimentary basin covers an area of 23,800 km^2, borders to the north by a regional orogenic uplift (Vysotsky et al., 1994) that is comparable to the transpression zone of the northwest–southeast-trending Mae Ping Fault Zone (Fyhn et al., 2010b), and farther to the north by the southernmost monocline of the Khorat basin. Tonle Sap basin is in the southern part of the onshore Kampong Som basin.

The basement of the Tonle Sap sedimentary basin is a complex Paleozoic graben that is dominated by metamorphic rocks. This graben may have developed between the late Carboniferous and the Middle Triassic and is filled with sediments dominated by terrigenous sandstones and carbonates, with a total thickness of >1000m. These horizons may have potential for both gas generation and hydrocarbon reservoirs. The overlying Upper Triassic to Middle Jurassic strata has an average thickness of 2000 m and have entered oil window, indicating that these strata are a possible source rock for liquid hydrocarbons. Other possible reservoirs and seals may also be presented within Upper Jurassic–Lower Cretaceous intervals, which have a total thickness of ~2000m; these intervals are collectively termed the Bokor formation (Fyhn et al., 2010b). Tonle Sap Trough also contains Carboniferous–Permian and Upper Triassic–Middle Jurassic coals, with the Middle Jurassic coals (Vysotsky et al., 1994).

2.2.2 Kampong-Som Sedimentary Basin

The Kampong-Som sedimentary basin is a foreland basin (Mao et al., 2014; Vysotsky et al., 1994; Fyhn et al., 2010b) that have been formed in response to the Sundaland Accretion. It is the southern extension of the Khorat Plateau basin, approximately 100km wide, and is flanked to the east by the Kampong-Som fold belt and to the west by the Khmer Fold Belt (Mao et al., 2014). This basin covers a total area of about 28,000km^2 offshore and 12,000km^2 onshore. In the center of this basin consists of deformed Paleozoic complex basement and overlying Upper Triassic-Cretaceous orogenic complex sediments. The Mesozoic sediments are dominated by terrigenous sandstones with widespread silt and clay horizons that were deposited during the development of the trough (Mao et al., 2014).

The upper Jurassic-Cretaceous units within the trough have just entered the main stage of oil generation with the vitrinite reflectance value Ro 3.3 to 4.5%, suggesting that gas generation may already have taken place in the section (Mao et al., 2014; Vysotsky et al., 1994; Fyhn et al., 2016). Gas and condensates may have been generated within upper Carboniferous to Triassic succession, although the most promising targets for hydrocarbon exploration are upper Triassic to middle Jurassic, and upper Jurassic to Cretaceous sequence within the trough (Fyhn et al., 2010b; Mao et al., 2014). This basin also consists middle Jurassic and Cretaceous coals at depths of 250 and 2000m (Mao et al., 2014; Vysotsky et al., 1994).

2.3 Sedimentary Rocks

The sedimentary rock is type of rock that is formed from pre-existing rocks or pieces of once-living organisms. It is generally formed on or near the Earth's surface with low temperature and pressure. The common sedimentary rocks are sandstone, shale, and limestone.

2.3.1 Shale

Shale is a very fine-grained sedimentary rock with a particle size less than 0.006 mm. It is formed from silts and clays which have been deposited and compacted or hardened into rocks (Okeke and Okogbue, 2010). Shale is the most abundant of all sedimentary rock (constituting about 60%) and is distributed in wide range of geologic ages from Paleozoic to Cenozoic (Boggs, 2006). Its color may range from white through green to grey and black depending on the composition and environment of deposition (Okeke and Okogbue, 2010).

Table 2.1: Average mineralogical composition of shales (Okeke and Okogbue, 2010).

Mineral	Composition (%)
Clay minerals	57
Quartz and chert	25
Feldspar	8
Calcite/ dolomite	3
Pyrite/mica	3
Iron oxides	2
Organic carbon	1
Other (heavy minerals, etc)	1
Total	**100**

Shale has definite mineralogical and chemical composition which are controlled by the properties of parent rock and depositional environment. The clay minerals are dominant minerals about 57% **(Table 2.1)**. The main clay minerals are smectites (montmorillonite), illite, kaolinite and chlorite. Generally, the smectites are expansive and characteristic of low energy marine alkaline environment. The other clay minerals are not expansive and occur in high-energy (where rate of leaching is high) and non-marine (continental or transitional) neutral/acidic environments (Okeke and Okogbue, 2010). The average clay minerals content of shale may be constant but there is steady conversion from smectite to illite as the depth of burial/geological age increases due to the increasing temperature and pressure.

2.3.1.1 Classification Based on Mineralogical Compositions

Shales can be classified as clayey, silty or sandy shales on the basis of texture. Okeke and Okogbue (2010) classified shales based on mineralogical composition, cementing materials, organic matter content and depositional environment. Shale is observed in different colors like gray, black, green, brown, or even yellow. The color of shale indicates the presence of various minerals during its deposits. The presence of organic material appears black and the presence of sulfide material like pyrite and deposition under a reducing environment also produces black color in shale. Red shale is due to the presence of hematite, yellow shale is related to presence of limonite, while the presence of chlorite or illite will provide them a green color (Gamero-Diaz et al., 2013).

According to Ternary plot of shale lithofacies classification (Gamero-Diaz et al., 2013), there are three main components such as siliceous (quartz, feldspar, mica), carbonate (calcite, dolomite) and argillaceous (clay, organic particles) as shown in **Figure 2.2**. Siliceous is dominated by silica between 50% and 80% (50% < QFM < 80%) with microcrystalline quartz filling intergranular pore. Carbonate is dominated by carbonate minerals from 50% to 80% (50% < Carbonate < 80%), microcrystalline calcite and crystalline quartz. Argillaceous is dominated by clay minerals between 50% to 80% (50% < Clay < 80%), those clay minerals

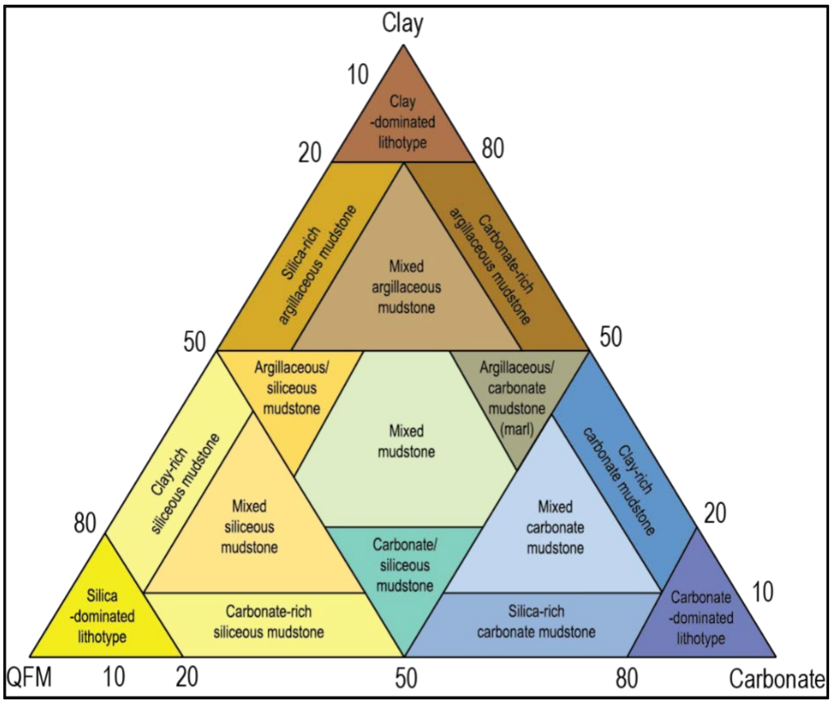

Figure 2.2: Ternary plot of shale classification with the three main components clay, carbonate and quartz, feldspar, mica (QFM), (Gamero-Diaz et al., 2013).

such as, illite, illite-smectite, kaolinite, chlorite and smectie, originated from weathering of rock, minerals, and volcanic ash.

2.3.2 Carbonate

Carbonate rocks originate by precipitation of minerals from water through various chemical or biochemical processes. Carbonate rocks can be divided based on mineralogy into limestones and dolomites (dolostone). Limestones are composed mainly of calcite minerals, and dolomites are composed mainly of the mineral dolomite (Boggs, 2006).

2.3.2.1 Carbonate Classification

The ***Dunham Classification*** is the most widely used scheme for description of limestone in the field. The primary criterion used in this classification scheme is the texture which is described in terms of the proportion of carbonate mud present and the framework of the rock **(Figure 2.3)**. The first stage in using Dunham classification is to determine whether the fabric is matrix or clast supported. Matrix-supported limestone is divided into **carbonate mudstone** (less than 10% clasts) and **wackestone** (with more than 10% clasts). If the limestone is clast-supported, it is termed a **packstone** if there is mud present or a **grainstone** if there is little or no matrix. **Floatstone** (matrix-supported limestone conglomerate) and **rudstone** (clast supported limestone conglomerate) are used for carbonate intraformational conglomerate made up of material deposited in an adjacent part of the same environment and then redeposited. A **boundstone** has an organic framework such as a coral colony. The original scheme (Dunham, 1962) did not include the sub-division of boundstone into **bafflestone**, **bindstone** and **framestone**, which describes the type of organism that builds up the framework (Nichols, 2009)**.**

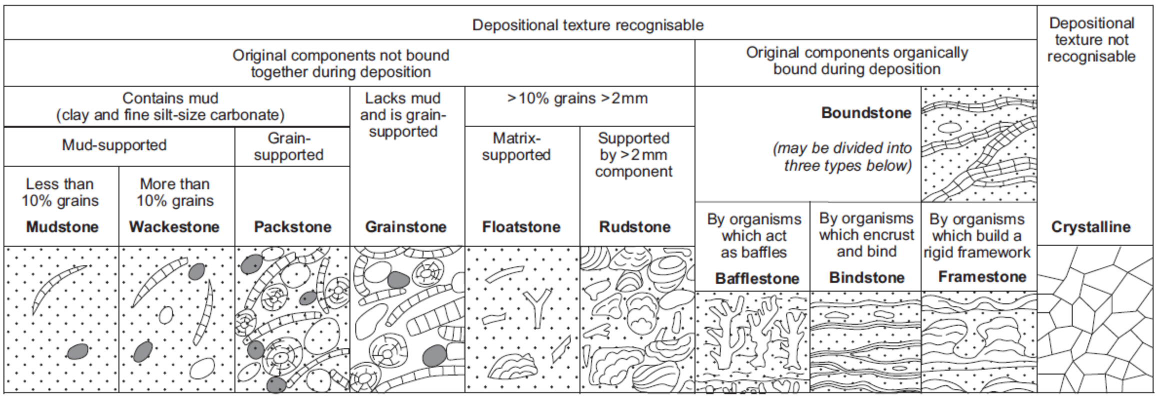

Figure 2.3: The Dunham classification of carbonate sedimentary rock (Dunham 1962). This one is the most used for description of limestones in field and in hand specimen.

2.4 Organic Matter

2.4.1 Organic Matter under Reflected Light

2.4.1.1 Alginite

Alginite is defined as discrete algal bodies that are either elliptical or disc shaped. Under optical microscope, alginite is pale yellow, dark, brown in reflected light and it represented by elongate algal bodies **(Figure 2.4)**, (compacted Tasmanites cysts), (Liu et al., 2017; Pickel et al., 2016).

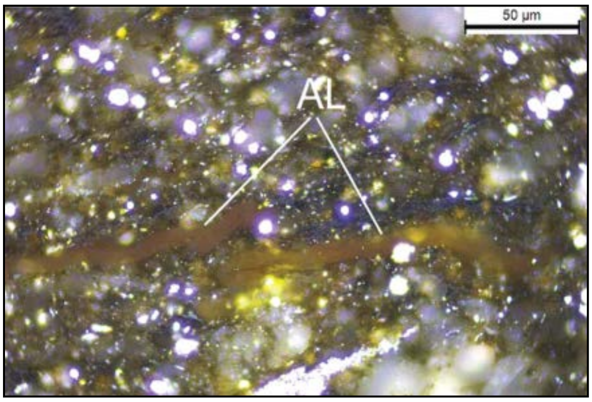

Figure 2.4: The organic maceral alginite (AL) show as elongate bodies under reflected light (Liu et al., 2017).

2.4.1.2 Vitrinite and Inertinite

Vitrinite and inertinite are derived from terrestrial vegetation, wood tissues, occurs as discrete particles **(Figure 2.5)** in the mineral matrix and they were transported to the marine environment from the continent, no pore observed in vitrinite and under microscopic observation show gray to dark gray color, sometime angular of shape (Liu et al., 2017).

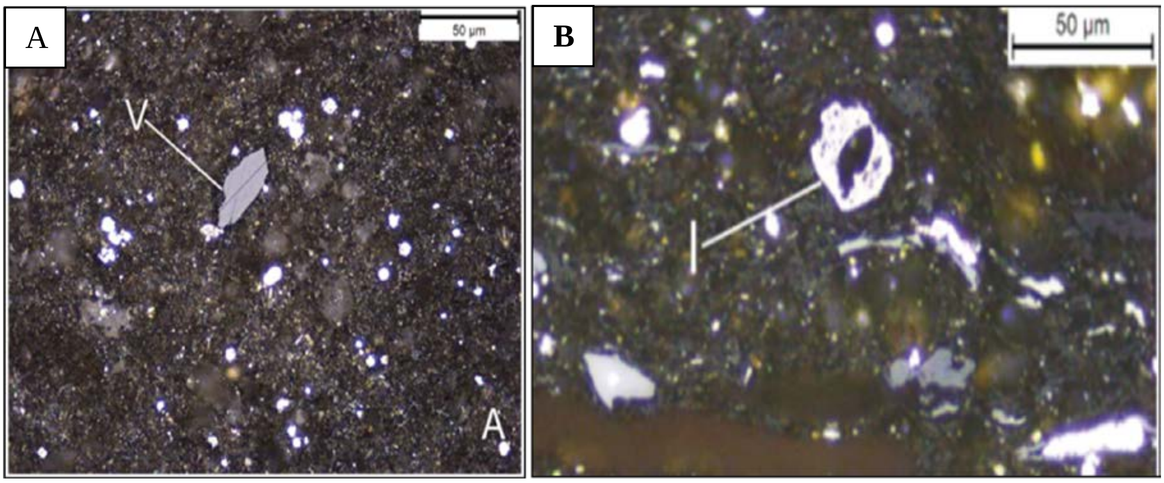

Figure 2.5: Organic maceral under microscopy, (A). Vitrinite, (B). Inertinite (Liu et al., 2017).

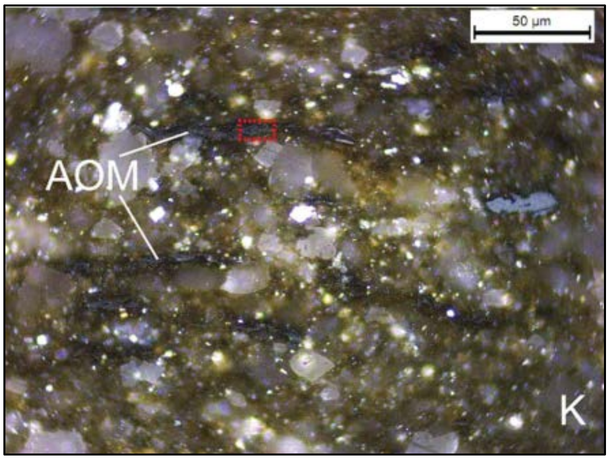

Figure 2.6: AOM under reflected light of microscopy (Liu et al., 2017).

2.4.1.3 Amorphous Organic Matter (AOM)

AOM is the primary organic matter, occurs as organic streaks parallel to the bedding plane and in the microscope including phytoplankton and higher plant resins. In the microscope observation, AOM is dark gray between quartz grain **(Figure 2.6)** and no pore were observed in AOM. It's also very difficult to distinguished of its shape (Liu et al., 2017).

2.4.1.4 Solid Bitumen

Solid bitumen is secondary organic matter that occurs as pore and fracture fillings occupies interparticle space and cavity space. Transition of AOM to solid bitumen indicated that a solid bitumen network started to replace the original AOM network (Liu et al., 2017). Solid bitumen-hosted nanopores can be round or irregular in shape. Moreover, microscope observation shows that solid bitumen is gray to dark-gray color, occurs in authigenic quartz **(Figure 2.7)**, low-reflecting and typically isotropic.

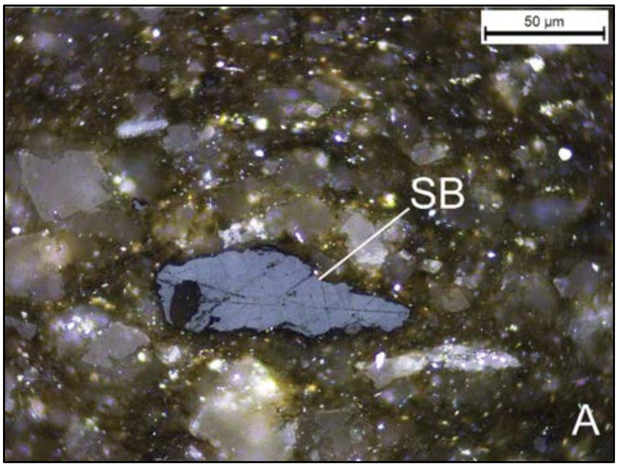

Figure 2.7: Photomicrographs of solid bitumen (SB) under reflected light (Liu et al., 2017).

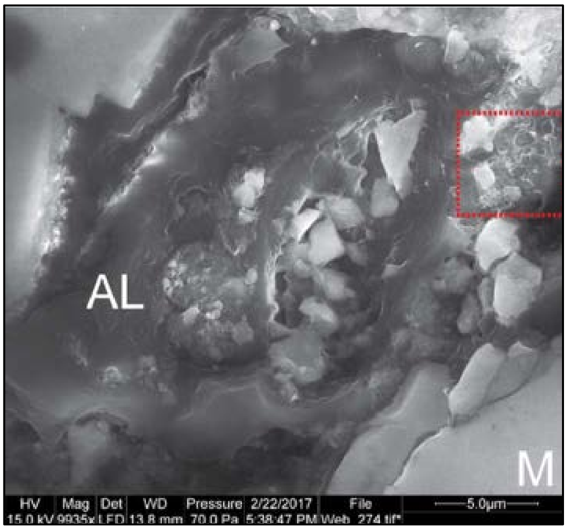

Figure 2.8: Alginite shows as dark gray color and associated with quartz (Liu et al., 2017).

2.4.2 Morphology of Organic Matter under SEM

The organic matter is identified in SEM images from flat, smoothly polished surface of petrographic by low secondary electron yield and low backscatter intensity, appearing dark in standard grayscale image (Camp, 2016). However, SEM is poorly suited for interpreting specific organic maceral and kerogen type as described by optical petrographic evidence into three main types such as, structured, amorphous and void filling. specific organic maceral and kerogen type as described by optical petrographic evidence into three main types such as, structured, amorphous and void filling.

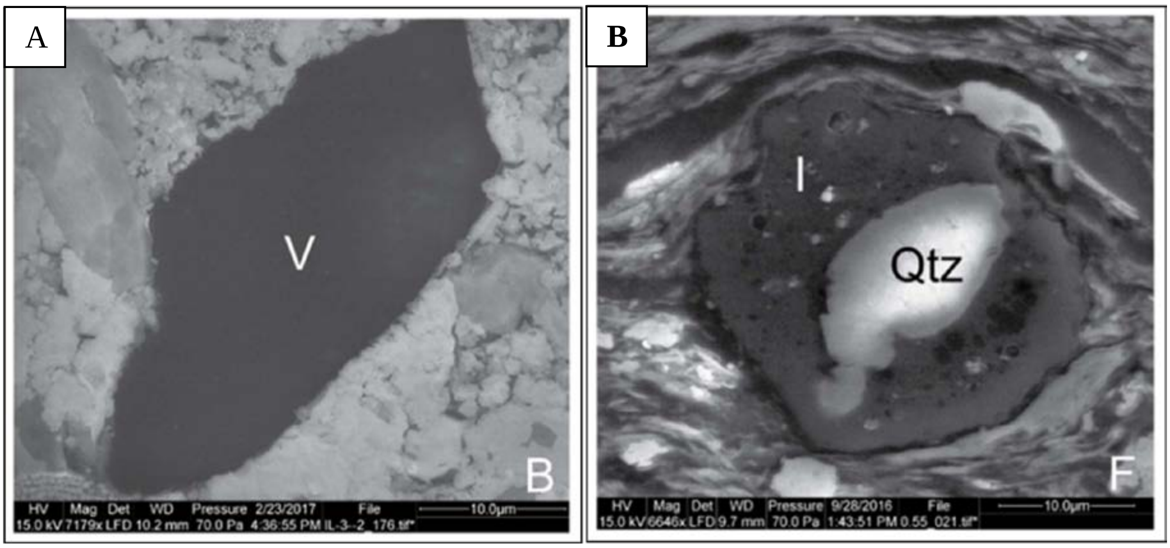

Figure 2.9: SEM observed of OM. (A) Vitrinite. (B) Inertinite in rounded shape filled with authigenic quartz (Liu et al., 2017).

2.4.2.1 Alginite

Under SEM observation alginite shows elongated bodies with dark gray in color **(Figure 2.8)**. Moreover, it is frequently associated with authigenic minerals such as pyrite, quartz and no pore were observed in alginite (Liu et al., 2017).

2.4.2.2 Vitrinite and Inertinite

The morphology of vitrinite and inertinite in SEM is represented as sub-rounded to angular shape. They are also present as discrete particles and do not show secondary pore **(Figure 2.9A)**. But sometime, the cellular pore in inertinite could still be observed **(Figure 2.9B)** and it is typically filled with authigenic quartz (Liu et al., 2017).

2.4.2.3 Amorphous Organic Matter (AOM)

Amorphous organic matter is the primary OM (kerogen) that is deposited at the same time as the mineral matrix. In the SEM observation, AOM is demonstrated in the structureless and sometime difficult to distinguish because of it occurs in nanoscale **(Figure 2.10A)**. No pore were observed in AOM under SEM (Liu et al., 2017).

2.4.2.4 Solid Bitumen

Solid bitumen can be observed in SEM as porous, void filling and fracture filling occur interparticle **(Figure 2.10B)** space filled with authigenic quartz and pyrite minerals. Solid bitumen demonstrates that, SEM cannot distinguish OM type and grain size is commonly larger than 50 µm (Liu et al., 2017).

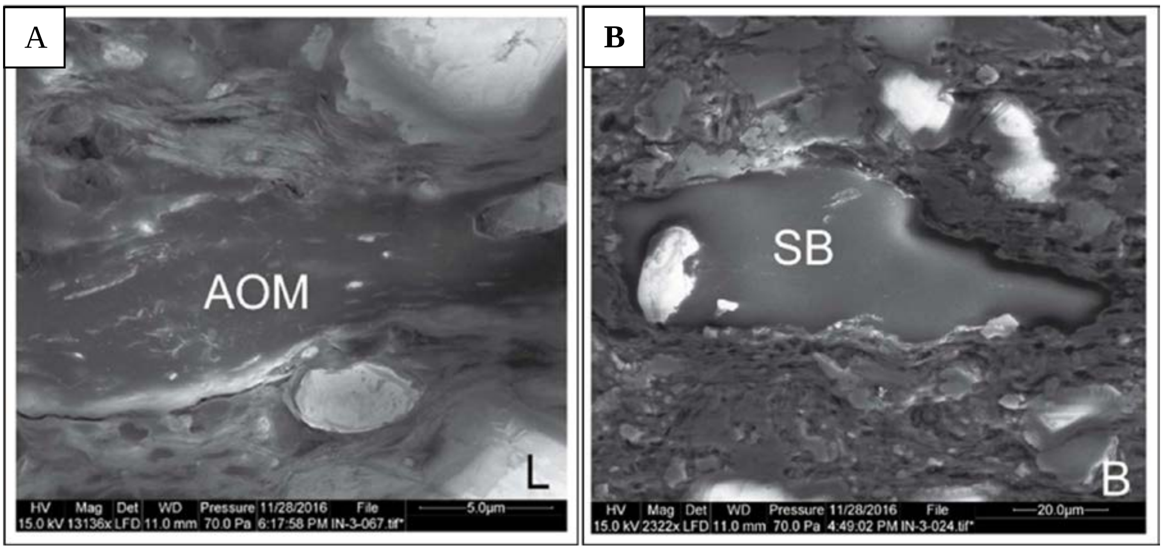

Figure 2.10: Organic matter in SEM observation. (A) Amorphous organic matter (AOM). (B) Solid bitumen (SB) (Liu et al., 2017).

2.5 Source Rock Evaluation

The contribution of organic geochemistry to sedimentary basin analysis can provide analytical on the richness, type and thermal maturity of source rock and are necessary step toward determining the stratigraphic and geographic extend of a pod of active source rock in the petroleum system. The volume, richness and thermal maturity of the pod of active source rock of traps (Peters and Cassa.,1994).

2.5.1 TOC Content

The TOC content is expressed as weight percent and indicator of total amount of organic matter present in the sediment. It is an important index which evaluates the quality of hydrocarbon source rocks. The TOC content of source rocks is expressed as a weight percent and is an indicator of the total amount of organic matter presented in sediments. At the end of the 20th century, TOC > 2% were still classified as very good potential source rocks by petroleum industry, while those over 4% TOC were regarded as excellent potential source rocks (He et al., 2019; Peters and Cassa.,1994).

An important characteristic of excellent source rocks is a TOC content above 12%, but in the petroleum industry, exploration targets generally have TOC values in the range of 2%-10%, while rocks with TOC above 10% are usually considered as being too immature for development and therefore of little value (He et al., 2019).

He et al. (2019) and Peters and Cassa. (1994) have classed source rock into five ranges such as poor, fair, good, very good and excellent by plotting genetic potential (GP) and TOC **(Table 2.2)**. The GP (GP = $S_1 + S_2$) of a given formation is defined as the amount of petroleum (oil and gas) that kerogen can generate, if it is subjected to an adequate temperature and sufficient interval of time **(Figure 2.11)**.

Table 2.2: Geochemical parameters description of petroleum potential of immature source rock (Peters and Cassa.,1994).

Petroleum potential	**Organic matter**		
	TOC	**Rock-eval pyrolysis**	
	(Wt. %)	**S_1[a]**	**S_2[b]**
Poor	0-0.5	0-0.5	0-2.5
Fair	0.5-1	0.5-1	2.5-5
Good	1-2	1-2	5-10
Very Good	2-4	2-4	10-20
Excellent	>4	>4	>20

Noted: [a]mg HC/g dry rock distilled by pyrolysis

[b]mg HC/g dry rock cracked from kerogen by pyrolysis.

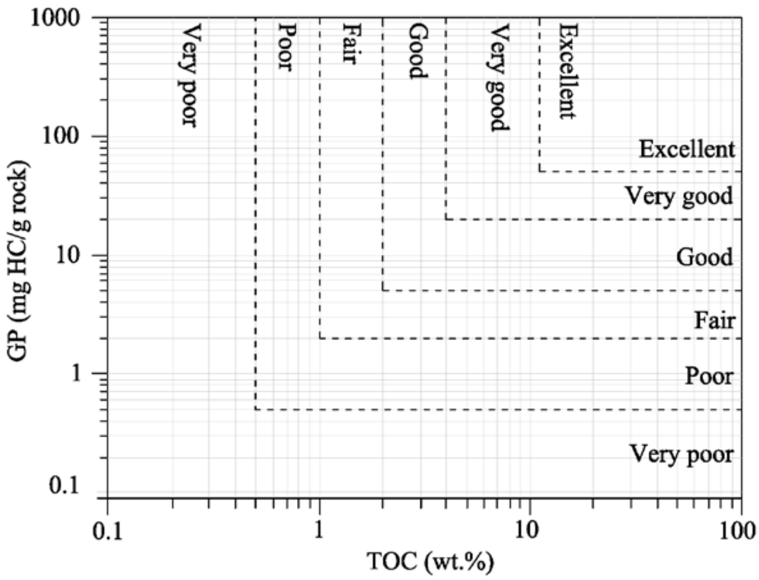

Figure 2.11: The hydrocarbon potential of source rock as measured by TOC vs GP (He et al., 2019).

The TOC content value is less than 2% have been marginalized and the higher than 12% have been recognized as transgressive (El Kammar, 2015).

2.5.2 Kerogen Type

Kerogen is an insoluble material formed by the degradation of organic matter; and it is the essential ingredient in the generation of hydrocarbon. Kerogen has been classified into three groups, namely type I, type II, and type III **(Table 2.3)**. The predominantly derived from lacustrine algae is type I, a mixture of phytoplankton, zooplankton and microorganisms (bacteria) is type II, and continental plant is considered as type III. Kerogen type I highly likely related to oil-prone, while type II is likely related waxy oil, and type III is mainly related to gas-prone (He et al., 2019). For non-marine source rocks, researcher have divided the type II kerogen into type II_1 and type II_2 (He et al., 2019; Guo et al., 2014). The kerogen type I and type II_1 usually relate to oil-prone, while the kerogen type II_2 and type III mainly relate to gas prone source rocks. Based on the results of the pyrolysis analysis and TOC measurements, the plots of hydrocarbon index (HI in mg HC/g TOC) vs. oxygen index (OI in mg CO_2/g TOC) **(Figure 2.12A)** and the plot of HI vs. T_{max} were constructed **(Figure 2.12B)**. The result of PCI (PCI=S1/GP (Where GP=S1+S2)) calculations can be used to estimate the kerogen type of hydrocarbon also (He et al., 2019); 0-15, 15-40, 40-75 and more than 75 are type III, type II_2, type II_1 and type I, respectively **(Figure 2.12C)**.

Table 2.3: Geochemical parameters describing Kerogen type (Quantity) and the character of expelled products (Peters and Cassa.,1994).

Kerogen Type	HI (mg HC/g TOC)	S_2/S_3	Atomic H/C	Main Expelled Product at Peak Maturity
I	>600	>15	>1.5	Oil
II	300-600	10-15	1.2-1.5	Oil
II/III[b]	200-300	5-10	1.0-1.2	Mixed oil and gas
III	50-200	1-5	0.7-1.0	Gas
IV	<50	<1	<0.7	None

2.5.3 Thermal Maturity

The thermal evolution of the source rock during diagenesis, catagenesis, and metagenesis changes in many physical or chemical properties of the organic matter, and converts it into oil, wet gas, dry gas and pyrobitumen (He et al., 2019). The level of thermal maturity for different types of organic matter can be used to estimate from the T_{max} range, vitrinite reflection (R_o) and production index (PI). The continuous increase of PI with depth makes a value index of maturation (Tissot and Welte, 1978).

Thermal maturity is a key parameter for the determination of potentially prospective source rock accumulations at initial stages of exploration. Based on thermal maturity values, source rocks are categorized as thermally immature, mature, or post-mature rocks in terms of capability to generate hydrocarbons **(Table 2.4)** (He et al., 2019).

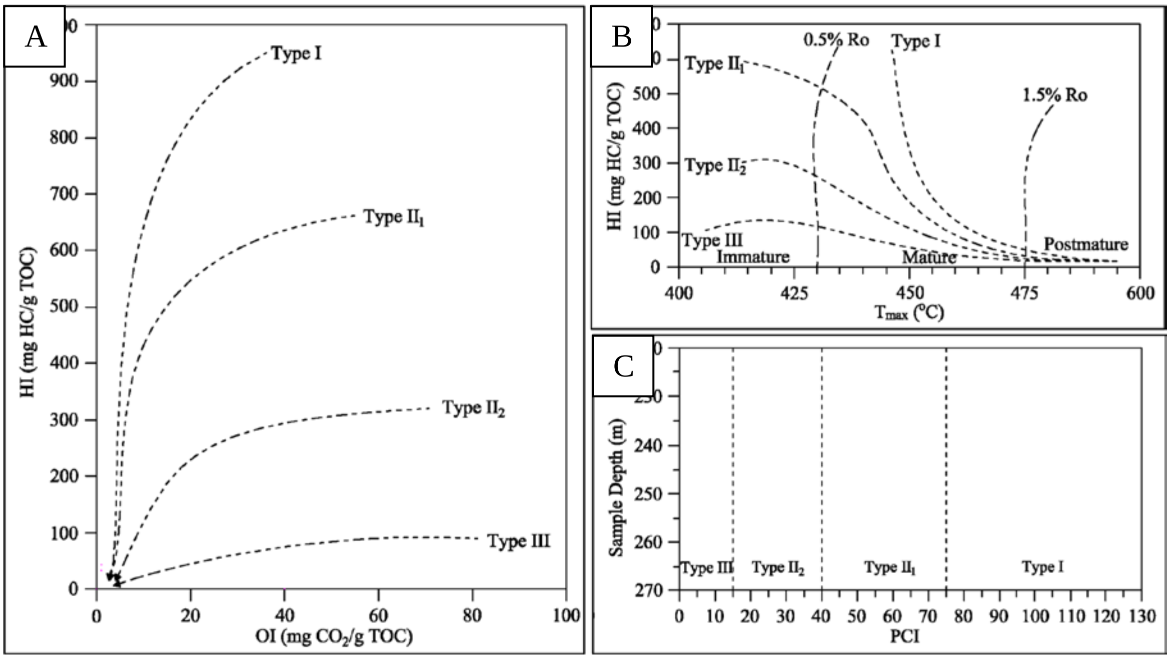

Figure 2.12: Kerogen type classification (He et al., 2019).

Immature source rocks, are still at relatively small depths, may generate (biogenic) natural gas which is formed by certain bacteria species as a result of their metabolic activity. Normally, these processes occur at temperatures below 50°C, and the degree of organic matter alteration, as expressed by reflectance index, is not more than 0.5% R_o.

As the source rock is buried, the processes of bacterial organic matter alteration subside, while temperatures and pressures of the rock increase and gradually trigger chemical changes that lead to the generation of oil and smaller quantities of natural gas. A rock which had been heated so as to generate crude oil is called mature rock in the oil generation phase or in the so-called "oil window", and its alteration degree, expressed as vitrinite reflectance index, ranges from 0.5 to 1.2% R_o **(Figure 2.13)**.

Table 2.4: Geochemical parameters describing level of thermal maturation (Peters and Cassa.,1994).

Stage of thermal maturity	Maturity			Generation		
	R_o (%)	T_{max} (°C)	TAI[a]	Bitumen/ TOC[b]	Bitumen (mg/g rock)	PI[c] $[S_1/(S_1+S_2)]$
Immature	0.2-0.6	<435	1.5-2.6	<0.05	<50	<0.10
Mature						
Early	0.6-0.65	435-445	2.6-2.7	0.05-0.10	50-100	0.10-0.15
Peak	0.65-0.9	445-450	2.7-2.9	0.15-0.25	150-250	0.25-0.40
Late	0.9-1.35	450-470	2.9-3.3	-	-	>0.40
Postmature	>1.35	>470	>3.3	-	-	-

Note: [a]TAI, thermal alteration index.

[b]Mature oil-prone source rocks with type I or II kerogen commonly slow bitumen/TOC ratios in the range 0.05-0.25. Caution should be applied when interpreting extract yields from coals. For example, many gas-prone coals show high extract yield normalized to TOC is low (<30mg HC/g TOC). Bitumen/TOC ratios over 0.25 can indicate contamination or migrated oil or can be artifacts caused by ratios of small, inaccurate numbers.

If it is buried deeper, the source rock will generate mostly (thermogenic) natural gas. Accordingly, a mix of the previously generated oil and of the "newly generated" natural gas (the so-called condensate) is expected to occur in the rock.

If the rock medium is even deeper buried, organic matter will generate (thermogenic) natural gas only. Moreover, any oil previously accumulated in the rock will be transformed into (thermogenic) natural gas. This degree of thermal alteration called the "gas window" occurs at

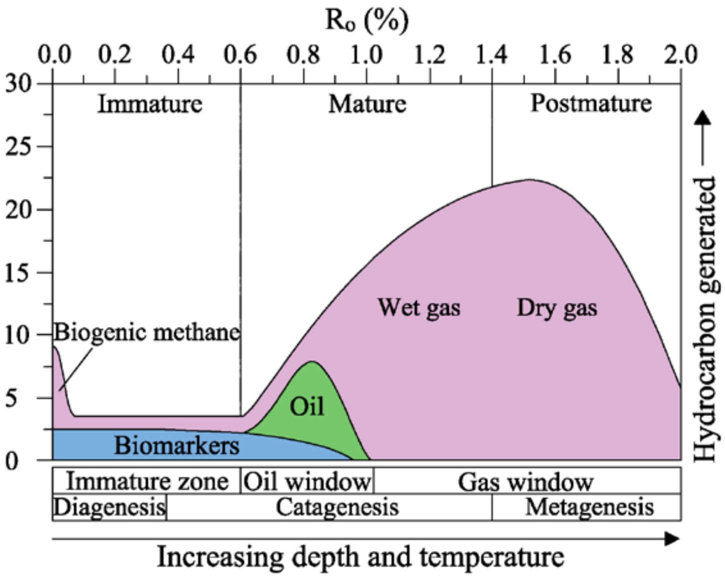

Figure 2.13: Hydrocarbon generation stage (He et al., 2019).

temperatures in the order of 475 – 535°C and is expressed by reflectance index values ranging from approx. 1.2 to 2.0% R_o.

The process will continue until alteration processes reach the degree at which the source rock becomes over-mature, and its hydrocarbon generative potential is exhausted (>3.0% R_o). This occurs at temperatures more than 615°C.

It should be noted that the oil and gas generation cycle, as presented above, is much simplified, and petroleum basins vary in terms of hydrocarbon generation conditions. In fact, each basin has its specific thermodynamic conditions, different types of organic matter distributed within the rocks, different rock-building minerals, different burial rates and several other factors.

2.6 Depositional Environment

2.6.1 Trace Element and TS

The concentrations of trace elements and TS (total Sulphur) are included Ts, Li, Be, Sc, Ti, V, Cr, Mn, Co, Ni, Cu, Zn, Ga, Rb, Sr, Zr, Nb, Mo, Cd, Sn, Cs, Ba, Hf, Ta, W, Pb, Bi, Th, and U. In general, shales have higher concentrations of the trace element than the upper crust. of TS, V, Co, Cu, Zn, Rb, Nb, As, Bi, Ce, La, Nd, Pd, W and Y than those of the upper crust, excepting Ga, Sn, Ta, Bi and Sr (Cao et al., 2012; He et al., 2019). The concentrations of elements Cr, Ni, Ba, and Zr are similar to those in the upper crust (He et al., 2019). The enrichment of element V, Ni, Cd, Cs, and Bi may be described as the accumulation of minerals (clay minerals) or organic matter. The depletion of element Cr and Mo is likely due to the weathering of mudstone (Cao et al., 2012).

The light rare earth elements (LREE) include La, Ce, Pr, Nd, Sm, Eu and heavy REEs HREES) include Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu. The concentration of LREE is higher than HREEs (LREEs = La + Ce + Pr + Nd + Sm + Eu) is higher than heavy REEs (HREEs = Gd + Tb + Dy + Ho + Er + Tm + Yb + Lu) (Cao et al., 2012).

2.6.2 Major Element

The 10 major element concentrations are SiO_2, Al_2O_3, Fe_2O_3, MgO, CaO, Na_2O, K_2O, MnO, TiO_2, and P_2O_5. Shale has higher concentrations of Fe_2O_3, CaO, Na_2O, and P_2O_5, but lower concentrations of SiO_2, Al_2O_3, MgO, K_2O, MnO and TiO_2 (Cao et al., 2012; He et al., 2019).

2.6.3 Redox Condition

Redox conditions play an important role in the alteration, paragenesis, and precipitation of variable elements. Under oxidizing conditions, such elements occur in a high-valence state and are easily altered. Under reducing conditions, these elements tend to occur in a low-valence state and are easily precipitated. Therefore, trace-metal elements are sensitive to redox conditions of paleolakes. V (vanadium) and Ni (nickel) are very important indicators of redox conditions (He et al., 2019).

A previous study showed $V/(V+Ni) \geq 0.6$ indicates an anoxic environment, while $V/(V+Ni) < 0.46$ indicates oxic environments. Values ranging from 0.46 to 0.6 indicate dysoxic environments. It also has been proposed that V/Cr ratios<2 suggesting oxic conditions, 2–4.25 suggesting dysoxic conditions, and >4.25 suggesting suboxic to anoxic conditions. In general, the V/Cr vs. V/ (V + Ni) discrimination diagram indicates a dysoxic to anoxic bottom waters environment **(Figure 2.14)** (He et al., 2019).

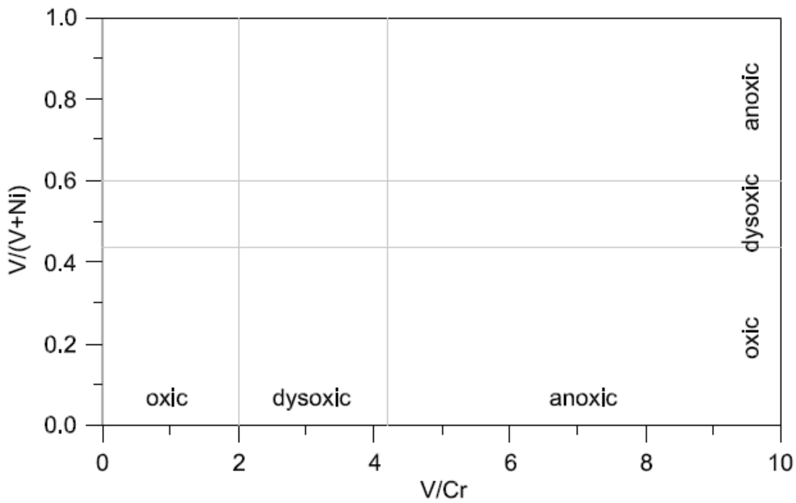

Figure 2.14: The cross plot of V/Cr vs. V(V+Ni).

2.6.4 Water Column Environment

The trace element concentration of mudstones may provide new clue in the defining the depositional environment of sediments. For example, the content of Sr in modern seawater and saline lake water is generally between 0.5‰ and 1.0‰, while is 0.1–0.3‰ in the fresh lake water (Cao et al., 2012).

The Sr/Ba ratio is also regarded as the special indicator of paleosalinity, as the two elements display contrasting geochemical behaviors in various sedimentary environments. In general, high Sr/Ba ratio indicates high salinity, and low Sr/Ba ratio indicates low salinity. So, the Sr/Ba ratio >0.8 reflects to sea water, 0.8-0.5 to brackish water, and <0.5 to freshwater. TOC/Ts ratio can used as an indicator of lacustrine versus marine environment for sediment also. The TOC/Ts is less than 2.8 indicates the sea water environment while more than 2.8 indicates the freshwater environment. In addition, the Ca/(Fe+Ca) ratios of argillaceous sediments can be used to estimate paleosalinity throughout the freshwater to marine range. In general, the values for modern sea samples are more than 0.8, whereas the values for modern lake samples are less than 0.6 **(Figure 2.15)** (He et al., 2019).

2.6.5 Depositional Setting

The $Al_2O_3/(Al_2O_3+Fe_2O_3)$ ratio of the siliceous rock can be used as an index to determine their sediments depositional environment, with values ranging from 0.4 to 0.7 in the oceanic basin indicating a deep-water environment **(Figure 2.16)** (He et al., 2019).

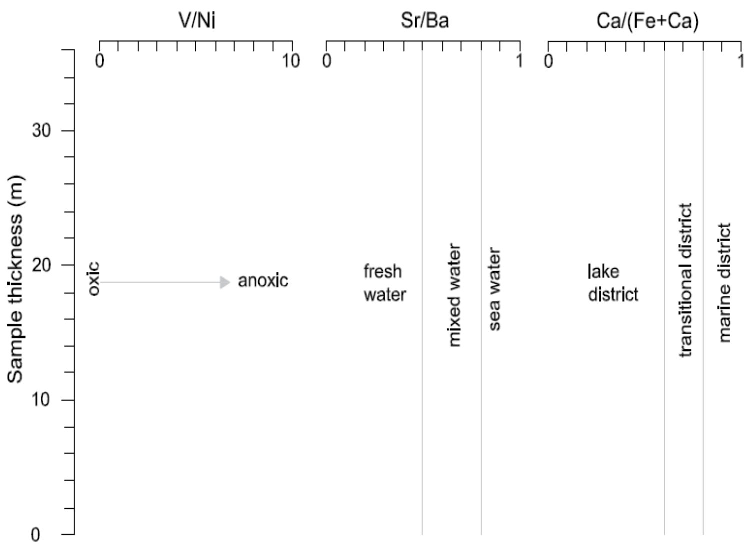

Figure 2.15: The diagram of element ratios.

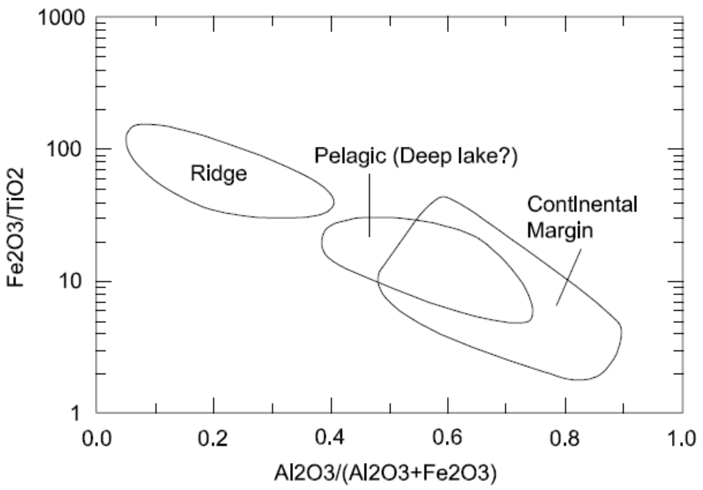

Figure 2.16: The discrimination diagram of Fe_2O_3/TiO_2 vs. $Al_2O_3/(Al_2O_3+ Fe_2O_3)$

2.7 Depositional Environment

The sedimentary rocks are formed by 5 processes, erosion, weathering, transportation, deposition, and diagenesis process (Boggs, 2006). The properties of sedimentary rocks such as sediment textures and structures, are formed by chemical, physics, and biological processes. These both have a close genetic relationship. In sedimentology, determining the depositional environments from the properties of sediment or sedimentary rocks is the main purpose and focus. The sedimentary rocks have been deposited through time in three major depositional settings, recognized such as continental or terrestrial, transitional or marginal and marine environment **(Table 2.5)** (Boggs, 2006; Okeke and Okogbue, 2010). The continental environments include fluvial (alluvial fans, braided stream, and meandering stream), desert, lacustrine (lake) and glacial. It’s also dominantly of siliciclastic sediments deposited characterized by general scarcity of fossils. The marginal environment is the boundary of sea and continental, and the marine environment is the ocean proper (Boggs, 2006). The facies can be grouped into lithofacies association which can be interpreted of depositional environment by combination of physical, chemical and biological process (Nichols, 2009).

2.7.1 Continental Environment

There are sub several depositional environments of continental deposit such as fluvial, desert, lacustrine, and glacial deposit. Among these, the lacustrine deposit is one of the most suitable environments, which allowed source rock to be deposited. Generally, common good source rocks (Kerogen type I and type II) were found in lacustrine deposit (Nichols, 2009).

Table 2.5: Simplified classification of ancient depositional environments (Boogs, 2006).

Primary Depositional Setting		Major Environment
Continental	*Fluvial	*Alluvial fan *Braided stream *Meandering stream
	*Desert	
	Lacustrine	
	*Glacial	
	*Deltaic	*Delta plain *Delta front *Prodelta
Marginal-marine	*Beach/barrier island	
	*Lagoonal	
	Tidal flat	
Marine	Neritic	Continental shelf **Organic reef
	Oceanic	Continental slope Deep ocean floor

Note: *Dominantly siliciclastic deposition

**Dominantly carbonate deposition

Environments not marked by an asterisk(s) may be siliciclastic, carbonate, evaporite or mixed sediment deposition depending upon conditions.

2.7.1.1 Lacustrine Environment

The lacustrine (lake) deposits are characterized by mixture of clay, silt and sands, inorganic carbonate precipitates and various fresh water invertebrate organisms including bivalves, ostracods, gastropods, diatoms and various plant deposits (Okeke and Okogbue, 2010). Lake form where there is a depression on the land surface which is bounded by a sill such that water accumulating in the depression is retained (Nichols, 2009). Sand, mud and shale are the most common components of lake deposits. Plants and animals living in a lake may be preserved as fossils in lacustrine deposit and concentrations of organic material can form beds of coal or oil and gas source rocks (Nichols, 2009). Most shale deposit in lake are less than 10 m of thick (Okeke and Okogbue, 2010). The sedimentary structures of lake deposits mostly finely laminated, cross-beds, wave ripples (Prothero and Schwab, 2013). Laminae bedding forms as a result of suspension settling of fine-size sediments in a variety of depositional environments. Parallel laminae form by variety of caused including wind transport, transport by steady-flow currents in the upper flow regime, low-flow regime transport during turbidity current flow and the oscillatory equivalent of plan-bed transport whereas, ripple cross-lamination forms under condition where abundant sediment is present, particularly sediment in suspension which quickly buries and preserves rippled layers (Boggs, 2009).

2.7.2 Transitional Environment

The transitional environment lies along the boundary between the continental and the marine depositional. It is dominated by rivers, ocean currents, winds, waves, and tidal processes, which all have an influence on the interface between continents and oceans (Boggs, 2006). The characteristics of transitional environments are high-energy waves and currents, although some lagoonal and estuarine environments are dominated by quiet-water conditions. The depositional settings in transitional sediment are delta, beach, and barrier island, estuarine, lagoonal, and tidal flat (Boggs, 2006).

2.7.2.1 Beaches and Barrier

The Beach and Barrier Island are developed on wave-dominated coast where tidal range is small to intermediate. The Beach and Barrier Island are dominated by sea processes and sand transportation by wind on a small scale. The Beach environment can be divided into several zones; (1) the backshore, which extends landward from the beach berm above high tide level and commonly includes back-beach dune deposits; (2) the foreshore, called littoral zone or zone between high tide level to low tide level; (3) the shoreface, called nearshore, located on low tide level to transition zone between beach and sediment on shelf **(Figure 2.17)** (Boggs, 2009). The barrier is not a single environment but a composite of three separate environments, (1) the sandy barrier-island chain itself (the subtidal to subaerial barrier-beach complex); (2) the

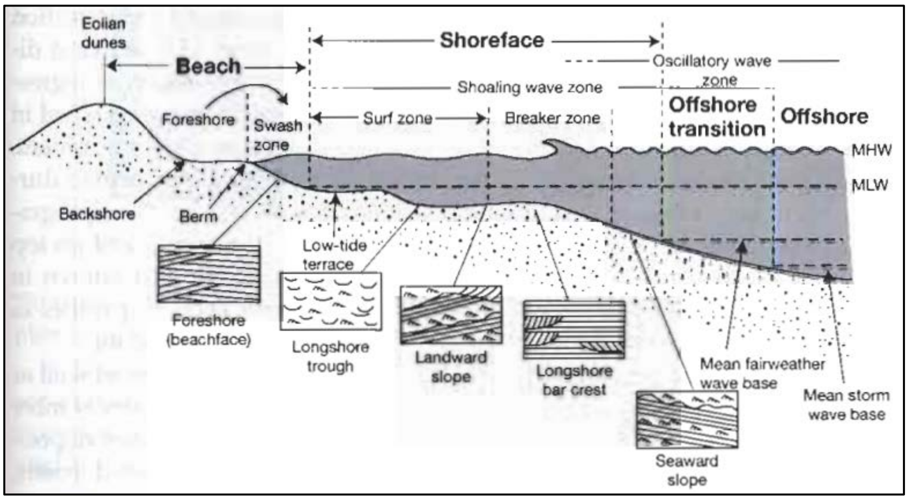

Figure 2.17: Generalized cross-sectional profile of the beach and nearshore zone, and typical setting structures formed in the beach and nearshore zone (Boggs, 2006).

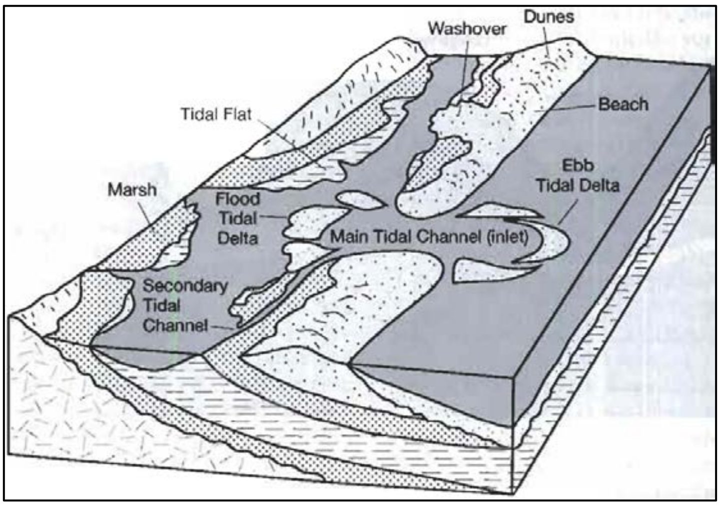

Figure 2.18: Generalized model illustrating the various sub-environments in transgressive barrier-island system (Boggs,2006).

enclosed lagoon, estuary, or marsh behind it (the back-barrier, subtidal-intertidal region); and (3) the channels that cut through the barrier and connect the back-barrier lagoon to the open sea (the subtidal-intertidal delta and inlet-channel complex) (Boggs, 2006) **(Figure 2.18)**.

2.7.2.2 Lagoon Environment

The coastal lagoon is a shallow morphological feature that is filled with water and located near the sea. Moreover, lagoonal environment is made up of both terrestrial and marine components. It is separated from the terrestrial environment by reef, barrier, sandbank, and spit. It has low energy, that is why it is dominant of fine-grained sediment such as shale (Boggs, 2006).

2.7.3 Marine Deposit

Marine, including terrigenous shelves or shallow seas, carbonate shelves or platforms, continental slopes, continental rises, basin plains, ocean ridges, and ocean trenches **(Figure 2.19)** Dominated by the process of transport and deposition.

2.7.3.1 Shallow marine

The area between the shore and the beginning of the reef wall is referred to as the shallow water marine environment. Many organisms live in this environment and leave their mark in the form of ooids, trace fossils, bore holes, and a variety of other ways. After the shallow water marine environment was lithified, the vast majority of the fossil record was discovered. Many of these fossils were deposited when much of the earth was covered in shallow seas, which supported a diverse range of organisms and other living creatures. The sediment is frequently made up of limestone, which forms easily in shallow, warm, calm waters. Shallow marine environments do not consist solely of siliciclastic or carbonaceous sediment. While they cannot always coexist,

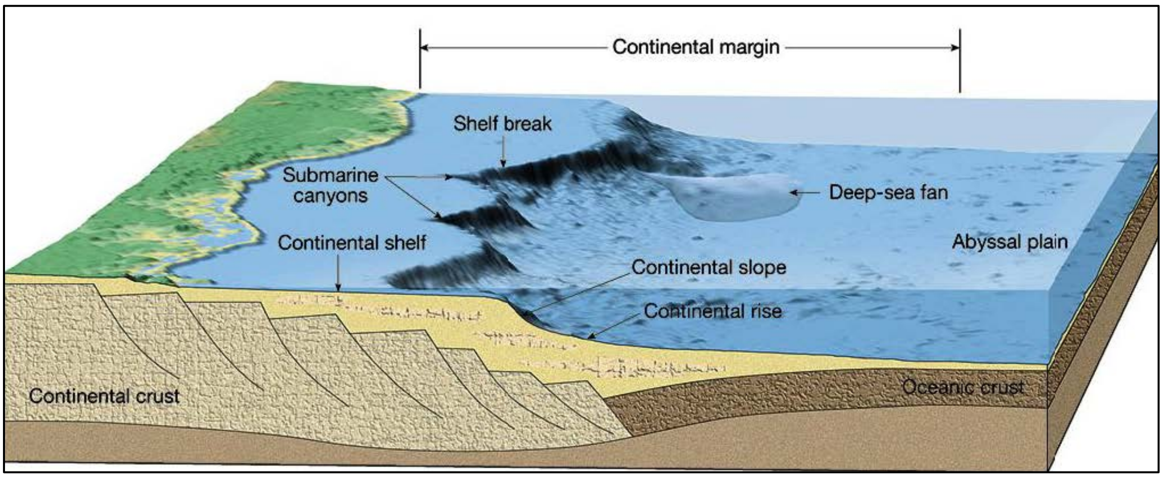

Figure 2.19: The illustration of marine depositional setting of sedimentary rocks.

a shallow marine environment composed entirely of carbonaceous sediment or entirely of siliciclastic sediment is possible. Because smaller grains have been washed out of higher energy areas, shallow water marine sediment contains smaller grain sizes (Boggs, 2012).

2.7.3.1 Continental rise

The continental rise environment is defined as the end of the continental margin, located between the continental shelf and the oceanic basin **(Figure 2.19)** (Walker and James, 1992). The sediments deposited in the setting are made up of suspended sediments that have been carried away from the shelf by tidal currents or density interfaces. Internal wave and tide motions can cause seabed sediments to resuspension and re-deposition of sediments from the seafloor. Internal wave and tide motions can cause seabed sediments to resuspension and re-deposition of sediments from the seafloor (Pickering and Hiscott, 2015). Internal wave or tide motions have the primary effect of suspending material from the seabed or preventing material that is already suspended from being deposited (Mccave, 2002).

Chapter 3.

Depositional Environment of Sediments in Tonle Sap Sedimentary Basin, Western Part of Cambodia: Insights from Field and Geochemical Studies

3.1 Introduction

Tonle Sap sedimentary basin is a foreland basin, which covers an onshore area of 23,800 km^2 in central of Cambodia (Mao et al., 2014; Vysotsky et al., 1994). In 1996, hydrocarbon exploration was surveyed with airborne gravity and magnetic survey around this basin by Japan National Oil Corporation (JNOC). Based on these geophysical data, this sedimentary basin was defined into two sub-sedimentary basins (Lim, 2006), and it consists of two potential hydrocarbon source rocks, Triassic organic rich lacustrine and late Carboniferous/ low Permian shallow marine organic shales, carbonates, and coals. These source rocks suggested as mature and potential for oil generation (Vysotsky et al., 1994). However, there is no detailed study of the depositional environment of the Permian unit in this basin yet. Hence, this study investigates two outcrops of Permian sediments exposed in the western part of the Tonle Sap sedimentary basin. They were selected to represent the Permian unit in this basin **(Figure 3.1)**.

The characterization of the depositional environment of sediments in the Tonle Sap sedimentary basin was obtained from field investigation, lithological, sedimentological, paleontological, and geochemical analysis. The two primary purposes of this research are (1) to investigate detailed lithostratigraphy of these Permian sedimentary rocks and (2) to discuss the depositional environment using sedimentology paleontology, and geochemistry studies.

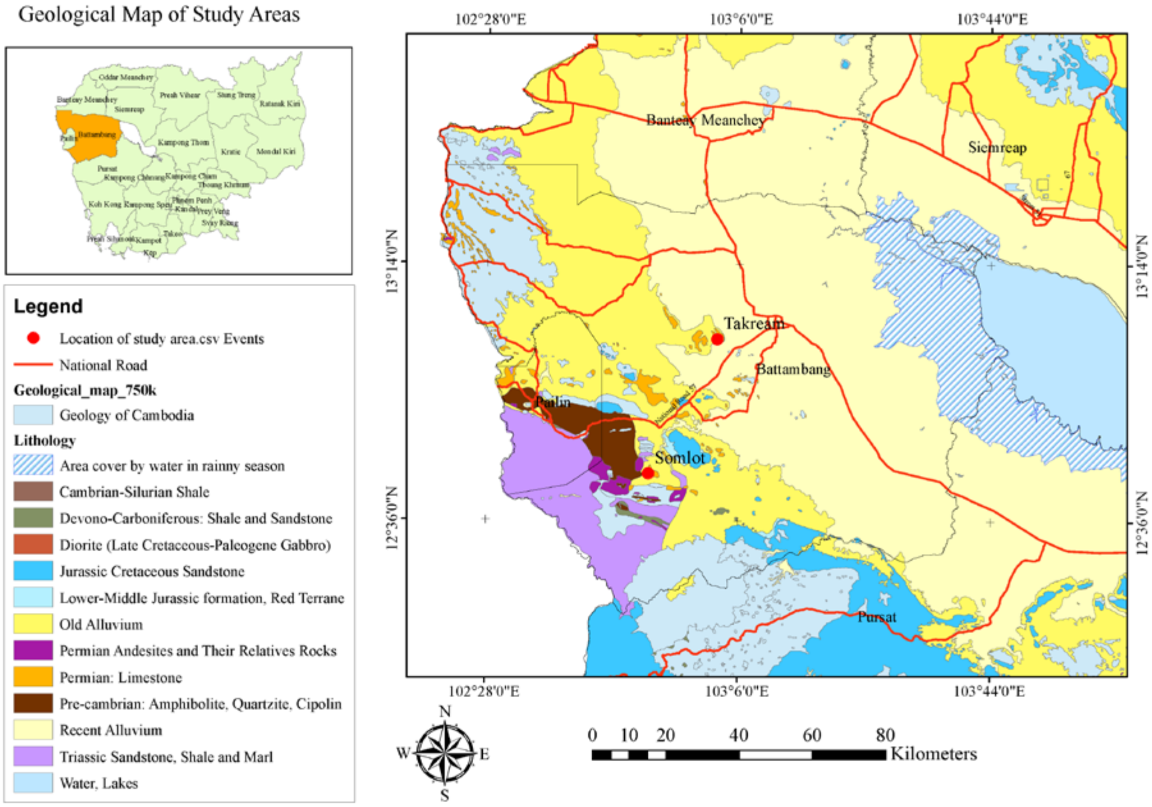

Figure 3.1: Geological map of Battambang province. The red dots are sampling locations: Somlout and Takream (GDMR-JICA, 2010).

3.2 Materials and Methods

3.2.1 Stratigraphy Measurement

The geological fieldwork was conducted in Takream commune, Banan District, and Somlout commune, Somlout District in Battambang Province, the western part of the Tonle Sap sedimentary basin. The thickness of individual facies succession was measured from these two well-exposed Permian sedimentary outcrops, Takream and Somlout with geological tools in **Figure 3.2**. Each stratigraphy interval's sedimentary texture, sedimentary structure, fossil content, and thickness were recorded for facies analysis as evidence to interpret the sedimentary process and the details of the depositional environment.

3.2.2 Laboratory Works

There are 13 representative samples of shales and limestones, five samples from Somlout and eight samples from Takream. All samples were collected by using geologist hammer and chisel during the construction stratigraphy column. These samples were prepared through laboratory works, petrography, X-ray fluorescence (XRF), and inductively coupled plasma mass spectrometry (ICP-MS).

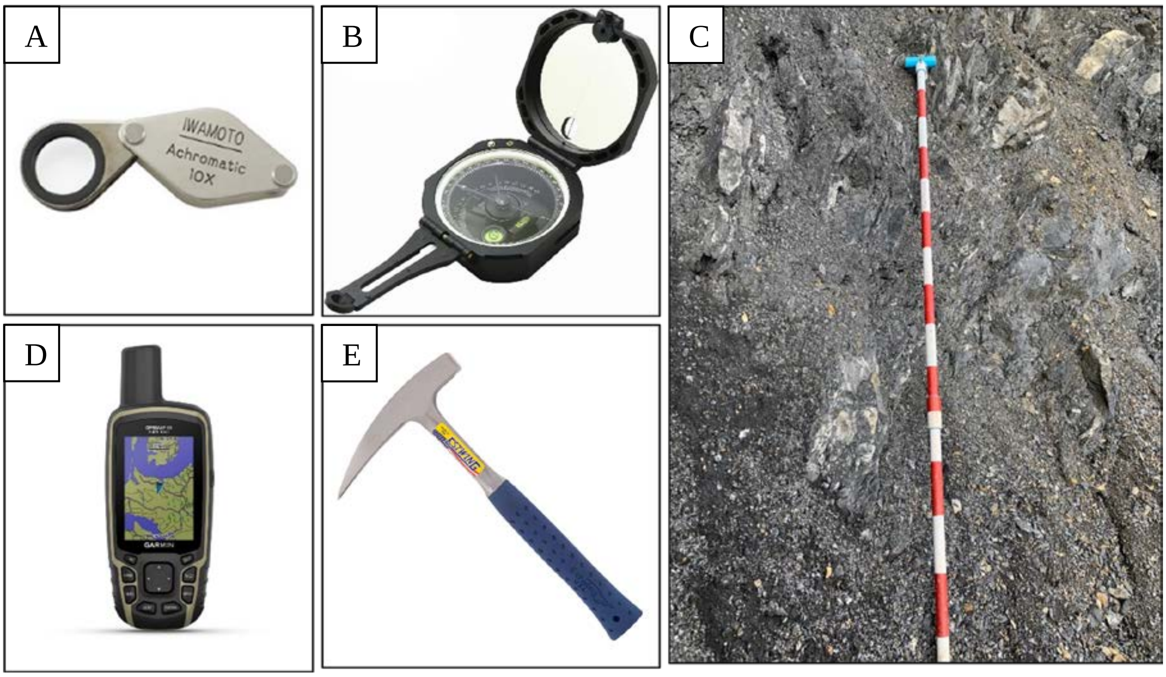

Figure 3.2: Geological tools: (A) Hand len, (B) Compass, (C) Jacob staff, (D) Garmin GPS, and (E) Geological hammer.

3.2.2.1 Petrography Analysis

The samples were cleaned, cut, and ground with diamond powder **(Figure 3.3)** to get a thickness of 30 micrometers for petrography analysis to identify the minerals and fossil contents with Eclipse Ci-Pol. All thin sections were observed under transmitted light of Nikon ECLIPSE Ci-POL with magnification lenses of 5X, 10X, and 20X **(Figure 3.4)**. The observation was performed in plane-Polarized Light (PPL) and crossed-Polarized Light (XPL).

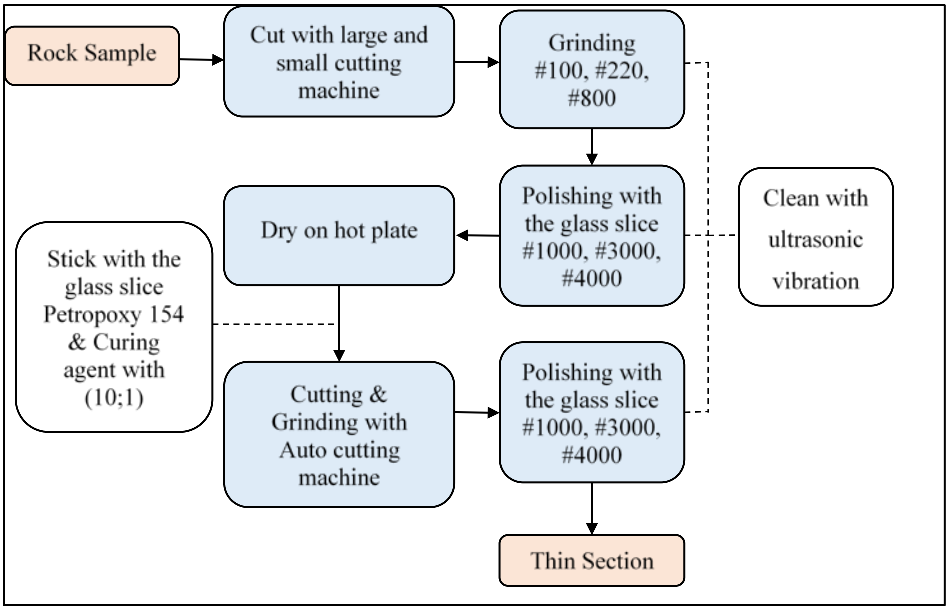

Figure 3.3: Flow chart of thin section processing.

The procedure of thin section preparation:

- Step 1: Select the fresh samples to make a thin section and which part of the sample decided to cut. If the samples are large, it was cut with a large-scale cutting machine and then continue to a small-scale cutting machine to fit the glass slice (26x75x2mm).
- Step 2: Grind the samples on grinding machine with carborundum abrasive powder, #100, #220 and #800. Then samples are polished with the polishing glasses plate with powder grit size #1000, #3000, and #4000, each step has to clean the samples with ultrasonic cleaner for one hour.
- Step 3: After grinding with glass slice #1000, #3000, and #4000 dry the samples for six hour or more on the electronic hot plate. Mix the Petropoxy 154 Resin and Curing agent (glue) with the ratio 10:1 in the plastic beaker. Stir it until homogenous and leave it for a while to let the bubble away. Clean the glass slice with ethanol, stick the samples and glasses slice with glue, attach the glass with the sample, and keep it overnight on the electronic hot plate to become hard.
- Step 4: Cut the samples that are attached with glasses slice with an auto cutting machine and grind it with the same machine. Then, continue to polish with glass slide until reaching the thickness of 30 µm. Finally, a thin section was obtained.

Figure 3.4: Nikon ECLIPSE Ci-POL use to analyse minerals and fossils content.

To obtain the percentage of the mineral compositions of sedimentary rock using microscope observation, the point counting method was applied. At least five views of the photomicrograph were grided and counted each mineral on each view to receive the average percentage.

Figure 3.5: (A) Grinding samples, (B) Pressing the sample with hydraulic press machine, (C) Prepared samples.

3.2.2.2 X-Ray Fluorescence (XRF) Analysis

All selected sample were grounded to be powder with agate mortar in particle size 149 microns, place the ring on the stainless steel die and then pour the sample powder into ring, set the pressing die in the hydraulic press and then lock the air by turning the air lock to the right, start pressing slowly until pressure gauge indicator reach 7 ton and hold for 2 minutes, continue pressing until 18 tons and hold for 2 minutes again, then release air by turning air lock to the left, and the end these XRF were ready **(Figure 3.5)**. All prepared samples were analyzed with the model Rigaku ZSX Primus III+ **(Figure 3.6)**.

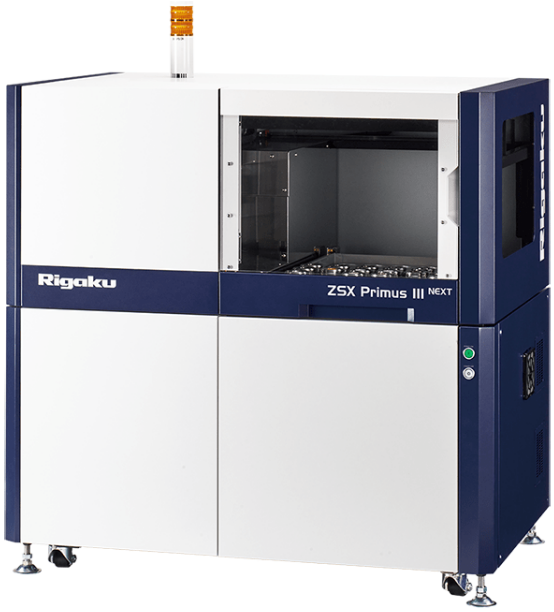

Figure 3.6: XRF analyzer model Rigaku ZSX Primus III+.

3.2.2.3 ICP-MS Analysis

The oxide compound of these samples can be identified. The other parts of the samples were ground to 74 micrometers in a ball mill of about 0.25mg per sample and analyzed with ICP-MS at ALS analytical services in Vientiane, Laos. For this analysis, powder samples were digested with perchloric, nitric, hydrofluoric, and hydrochloric acids. The residue was topped up with dilute hydrochloric acid. The trace and major elements were plotted in indicating depositional conditions.

3.3 Result

3.3.1 Sedimentological Features

According to stratigraphy measurement, the stratigraphy column of Takream and Somlout outcrops consist of the same lithofacies of sediments, calcareous shale, and limestone, however, the results of petrography, XRF, and ICP -MS analysis showed that the properties of these facies are different in compositions **(Table 3.1, Table 3.2)**. The details of lithofacies analysis and interpretation are described in the following sections.

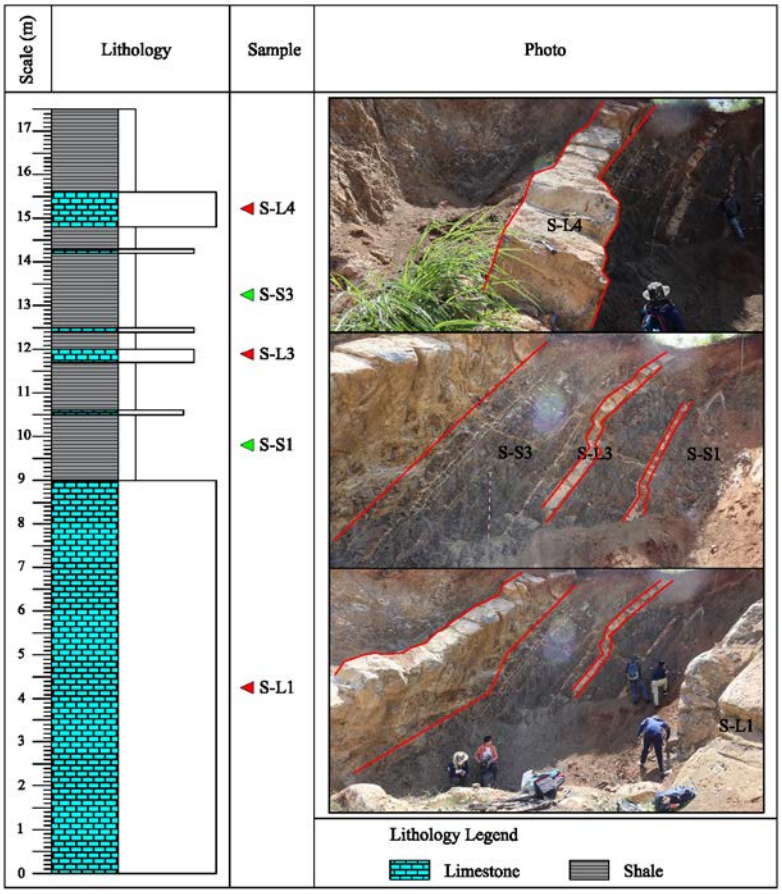

Figure 3.7: Stratigraphy column of Somlout, the green triangle is shale sample, and the red triangle is limestone sample.

3.3.2 Somlout Outcrop

Somlout outcrop is controlled by an anticline structure with a total thickness of approximately 17.5m **(Figure 3.7)**, including two lithofacies of calcareous shale and limestone. Those lithofacies have a strike N080ºE 70º NW from the horizontal plane. The calcareous shale facies were exposed to approximately 0.4-2.0m bedding. It is black, silt to clay size, and some parts were affected by moderate to predominantly weathered. The limestone facies are subdivided into medium and coarse-grained limestone. The dark grey medium-grained limestone facies exposed approximately 0.1-0.3m in thickness with moderately sorted. It is composed of mainly carbonated grain and micrite. The coarse-grained limestone facies are medium grey color and poorly sorted. It was deposited at the bottom of the formation with thicknesses of about 9m. It is dominated by carbonate grain, micrite, and lithic fragments with the raging size of 0.5-1cm.

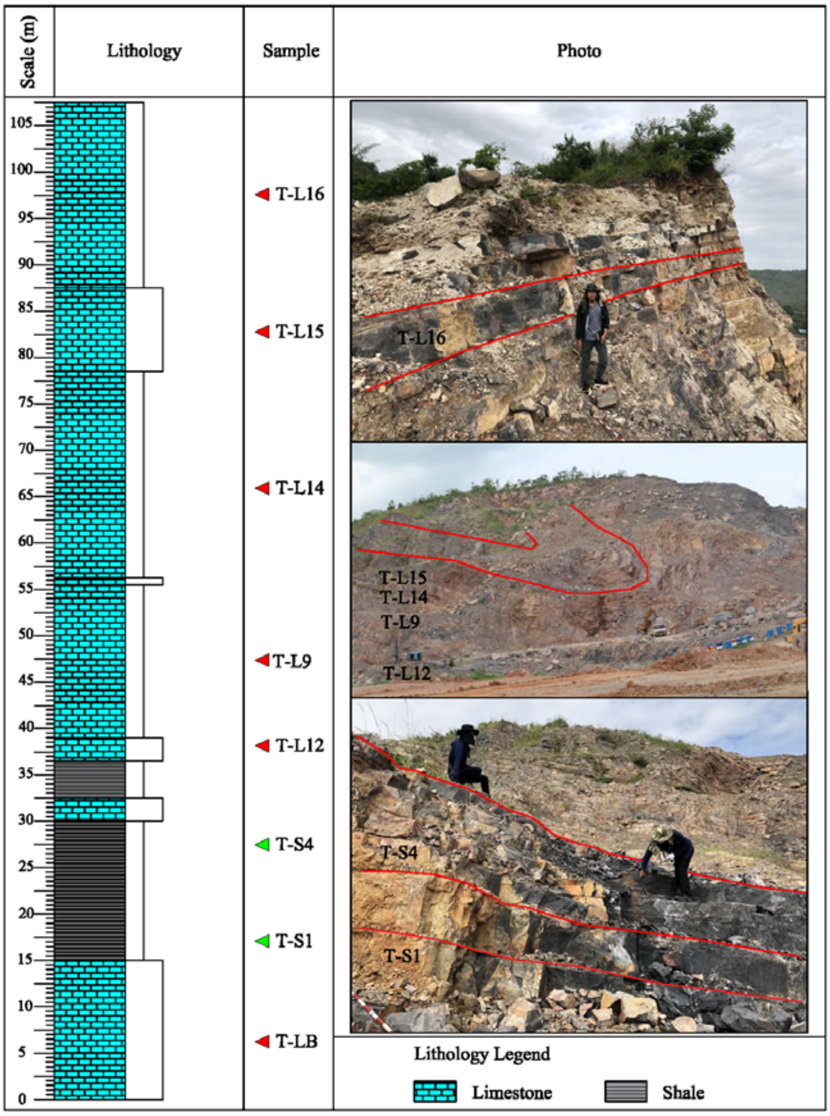

Figure 3.8: Stratigraphy column of Takream, the green triangle is shale sample, and the red triangle is limestone sample.

3.3.3 Takream Outcrop

Takream outcrop is well bedded with a total thickness of approximately 105.0m **(Figure 3.8)**, including two distinguish lithofacies of calcareous shale and limestone with N055ºE 20ºNW of dipping angle. Shale facies were deposited approximately 4.0-15.0m, and the bedding also contained sub-bedding in them with a thickness between 0.2-0.4m. Moreover, these facies were exposed as an interbedded layer with limestone bedding. Its grain size varies from silt to clay grain, black color, a massive structure, and is rich in carbonate minerals.

Limestone facies were exposed as inter-bedded, with thicknesses between 2.5-40.0m, and they also contain sub-bedding in them with a varied range of thickness of 0.2-0.6m. These facies are characterized as dark grey color, very fine grain, and massive structure. Moreover, according to physical properties, it is dominated by calcite and matrix and considered matrix-supported limestone.

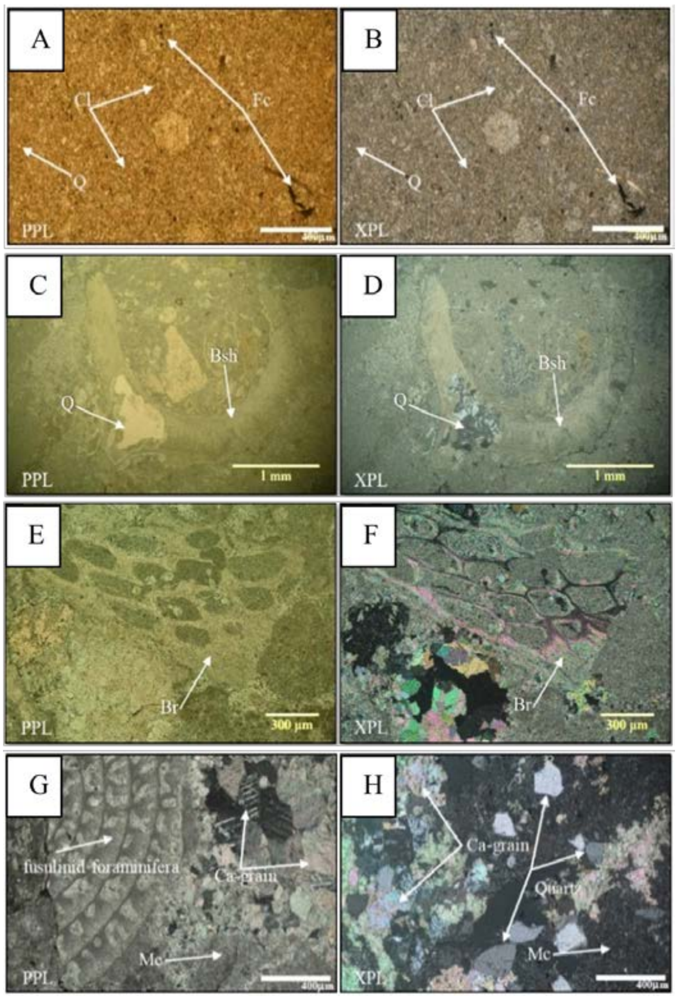

Figure 3.9: The Petrographic analysis of Somlout Samples. (A) and (B) are S-S1, showing the fracture creaking of organic matter in black color; (C) and (D) are S-L1, showing bivalve shell that was replaced by quartz; (E) and (F) are S-L3, showing bryozoan; (G) and (H) are S-L4, showing fusulinid foraminifera. Q: Quartz, Cl: Clay minerals, FC: Fracture creaking of organic matter, Bsh: Bivalve shell, Br: Bryozoan, Ca: Calcite, and Mc: Micrite

3.3.4 Lithofacies Analysis

According to the examined of petrographically analysis, Somlout shale consists mainly of clay minerals, less quartz, and fracture creaking of organic matter (black color), which indicates as the high temperature was applied after deposition **(Figure 3.9A &B)** (Kobchenko et al., 2011). This shale is dominated by clay ~96.20%, and quartz ~3.8%, and is classified as a clay-dominated lithotype (Gamero-Diazet al., 2013). Furthermore, limestone consists mainly of calcite grain, quartz, micrite, and fossil. They are dominant grains, ranging from ~46.79% - 64.22% and micrite ~35.78% -53.28%. Limestones are classified as wackestone and packstone (Dunham, 1962). The presence of substantial micrite in limestone is commonly interpreted to indicate the deposition under the low energy flow (Boggs, 2009). Therefore, fragmental fossils such as 2 mm of bivalve shells in S-L1 **(Figure 3.9C &D)**, 1-2 mm bryozoan **(Figure 3.9E &F)**, and 1 mm fusulinid foraminifera in S-L3 **(Figure 3.9G &H)** were found to be depositional indicators.

Takream calcareous shale consists of carbonate mud, calcite minerals, and organic matter. It comprises carbonate mud ~50.80% - 60.60%, quartz ~30.20% to 43.00%, and clay minerals ~6.20% to 9.20%. It is classified as silica-rich carbonate mudstone (Gamero-Diazet al., 2013). Under the microscope, sample T-S1 showed carbonate mud, calcite mineral, siliceous sponge spicules, and organic matter **(Figure 3.10A &B)**. Limestone mainly comprises carbonate mud ~22.60% to 96.80% and calcite grain ~3.20% to 77.40% **(Figure 3.10C &D)**. It is classified as packstone and lime-mudstone (Dunham, 1962).

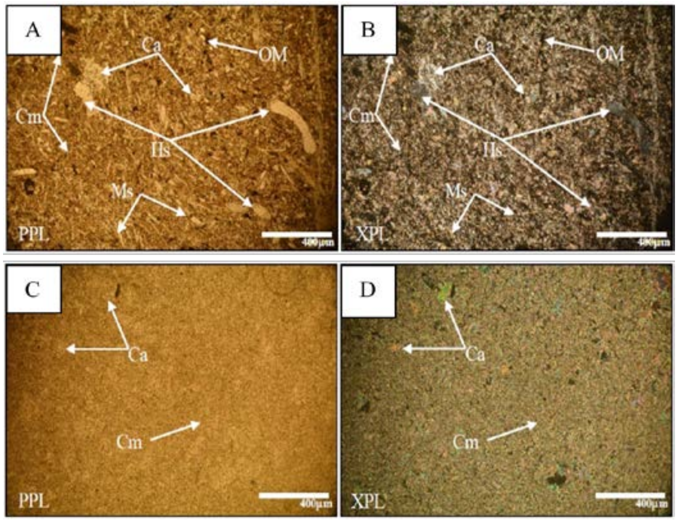

Figure 3.10: Petrographic analysis of Takream samples. (A) and (B) are T-S1 under PPL and XPL, (C) and (D) are T-LB under PPL and XPL. Ca: Calcite grain, OM: Organic matter, Cm: carbonate mud, Hs: Hexactine sponge, Ms: Monaxon sponge.

3.3.5 Major Elements

Major oxide concentrations in calcareous shales and limestones of Somlout and Takream were obtained from XRF analysis **(Table 3.1)**. Calcareous shale has a high concentration of SiO_2 ranging from 42.00% to 75.00% with a mean value of 62.68%, CaO ranges from 0.96% to 26.30% with a mean value of 12.01%, Al_2O_3 ranges from 0.97% to 10.05% with a mean value of 5.92%, and Fe_2O_3 ranges from 1.40% to 5.29% with a mean value of 3.56%. Meanwhile, limestone concentrations of SiO_2 range from 0.38%-15.85% with the mean value of 9.97%, CaO ranges from 42.60%-57.00% with the mean value of 47.99%, Al_2O_3 ranges from 0.04-2.49% with the mean value of 0.75%, and Fe_2O_3 ranges from 0.05-1.68% with the mean value of 0.56%. These represent the most abundant elements (Si, Ca, Al, and Fe), consistent with the abundant occurrence of carbonate minerals, quartz, and pyrite in calcareous shale and limestones of the Tonle Sap sedimentary basin.

Table 3.1: Major elements concentration (wt%) of Somlout and Takream samples.

Sample	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	MnO	TiO_2	P_2O_5
S-L1	9.15	0.56	0.55	0.52	49.00	0.19	0.06	0.14	0.03	0.05
S-S1	75.00	8.94	5.29	1.63	0.96	0.55	0.98	0.02	0.40	0.06
S-L3	11.85	2.49	1.68	1.07	43.90	0.40	0.18	0.12	0.12	0.07
S-S3	73.60	10.05	5.20	1.48	1.19	0.46	1.23	0.02	0.46	0.06
S-L4	9.22	1.42	1.00	0.89	48.30	0.38	0.09	0.14	0.06	0.08
T-LB	1.86	0.04	0.05	0.28	54.40	0.01	0.02	<0.01	<0.01	<0.01
T-S1	42.00	3.71	2.35	0.40	26.30	0.13	0.21	0.03	0.16	0.04
T-S4	60.10	0.97	1.40	0.96	19.60	0.05	0.10	0.01	0.04	0.01
T-L12	12.60	0.14	0.25	0.35	47.10	0.02	0.02	0.01	0.01	0.06
T-L9	15.70	0.42	0.35	1.07	42.60	0.02	0.06	0.01	0.02	0.01
T-L14	15.85	0.45	0.43	0.46	43.60	0.03	0.06	0.01	0.02	0.01
T-L15	0.38	0.09	0.11	0.22	57.00	0.03	0.02	0.01	0.01	0.01
T-L16	13.15	1.10	0.65	0.74	46.00	0.04	0.08	0.03	0.04	0.03
Mean S	62.68	5.92	3.56	1.12	12.01	0.30	0.63	0.02	0.27	0.04
Mean L	9.97	0.75	0.56	0.62	47.99	0.12	0.07	0.05	0.03	0.04
UC	66.60	15.45	5.04	2.48	3.59	3.27	2.80	0.10	0.64	0.15
Mean S/UC	0.94	0.38	0.71	0.45	3.35	0.09	0.23	0.20	0.41	0.28
Mean L/UC	0.15	0.05	0.11	0.25	13.37	0.04	0.02	0.52	0.05	0.24

3.3.6 Trace Elements

Trace element concentrations of shale and limestone of both locations in Battambang province were obtained from ICP-MS analysis and are presented in **Table 3.2**. The concentration of V, Cr, Ga, Rb, Nb, Ba, Th, Zr, Hf, Ce, La, Nd, W, and Y (mean value for shale 75.25, 65.00, 6.98, 18.00, 1.73, 65.20, 1.26, 40.50, 1.13, 10.00, 5.13, 5.55, 0.25, 9.25 and mean value for limestone 21.22, 31.11, 0.91, 1.23, 0.20, 41.64, 0.08, 3.78, 0.11, 9.27, 5.67, 5.02, 0.00, 8.50, respectively) are smaller than those of UC, except Sr which is higher than UC (1.52 for shale, and 3.29 for limestone).

3.4 Discussion

3.4.1 Redox Conditions

The Vanadium (V) and Chromium (Cr) are essential indicators for redox conditions to estimate the degree of oxygen dissolved in water during the sediment deposited (Jones and Manning, 1994). Cr is usually incorporated within the detrital clastic fraction of s sediment where it may substitute for Al within clays, be adsorbed, or occur as chromite. Vanadium in contrast may be bound to organic matter by the incorporation into porphyrins and is concentrated in sediments deposited under reducing conditions. The ratio V/Cr has been suggested as an index of palaeo-oxygenation, oxic to anoxic bottom waters environment (Jones and Manning, 1994; He et al., 2019). It has been proposed that the value of V/Cr ratio is less than 2 suggests the oxic condition (the oxygen concentration range from 2-860ml/L), 2 to 4.25 indicates the dysoxic condition (the oxygen concentration range from 2-0.2 ml/L), and more than 4.25 suggests suboxic to anoxic condition (Dunham, 1962; Jones and Manning, 1994; Tyson and Pearson, 1991). Somlout samples have a V/Cr value ranging from 0.93 to 3. 87, shale sample values are 3.30 and 3.87 are suggested as dysoxic conditions and other samples are suggested as oxic conditions **(Figure 3.11A)**. Takream samples have a V/Cr value ranging from 0.28 to 1.30, which is suggested as the oxic condition.

The Uauthigenic value less than 5 ppm, from 5 ppm to 12 ppm, and higher than 12 ppm, indicated oxic, dysoxic, and anoxic conditions, respectively (Myers and Wignall, 1987). The average of Uauthigenic of Somlout and Takream samples is equal to 0.42 ppm and 2.28 ppm, respectively, which suggests to oxic condition environment **(Figure 3.11B)**. Moreover, the oxic condition is generally defined as a reducing environment (Jones and Manning, 1994; Isaksen and Bohacs, 1995).

3.4.2 Water Column Environment

The chemical precipitate is resulted from the interaction between sediments and calcium. Calcium is a major chemical constituent of seawater (Deng and Qian, 1993). The Ca/(Fe+Ca) ratios of argillaceous sediments can provide a direct estimate of paleosalinity throughout the fresh water to marine water (He et., 2019; Deng and Qian, 1993). The values for modern sea samples are more than 0.8, whereas the values for modern lake samples are less than 0.6 (He et., 2019). In addition, (Gamero-Diaz et al., 2013; He et., 2019) suggests that a high Sr/Ba ratio value of more than 0.8 indicates high salinity, while a low Sr/Ba value of less than 0.5 indicates low salinity water or freshwater environment. Shale samples from Somlout have the value of Ca/ (Fe + Ca) **(Figure 3.11C)** and Sr/Ba (**Figure 3.11D**) range from 0.15 to 0.18 and 0.24 to 0.32, averaging 0.17 and 0.28, respectively, indicating a freshwater lake environment (He et., 2019). In limestone samples in this formation range from 0.96 to 0.98 and 0.95 to 110, averaging 0.97 and 49.11, respectively, which suggests high salinity seawater environment. This condition indicated that the lithologies (shale and limestone) in Somlout samples were deposited in two different conditions involving sea-level fluctuation. The Ca/(Fe+Ca) and Sr/Ba

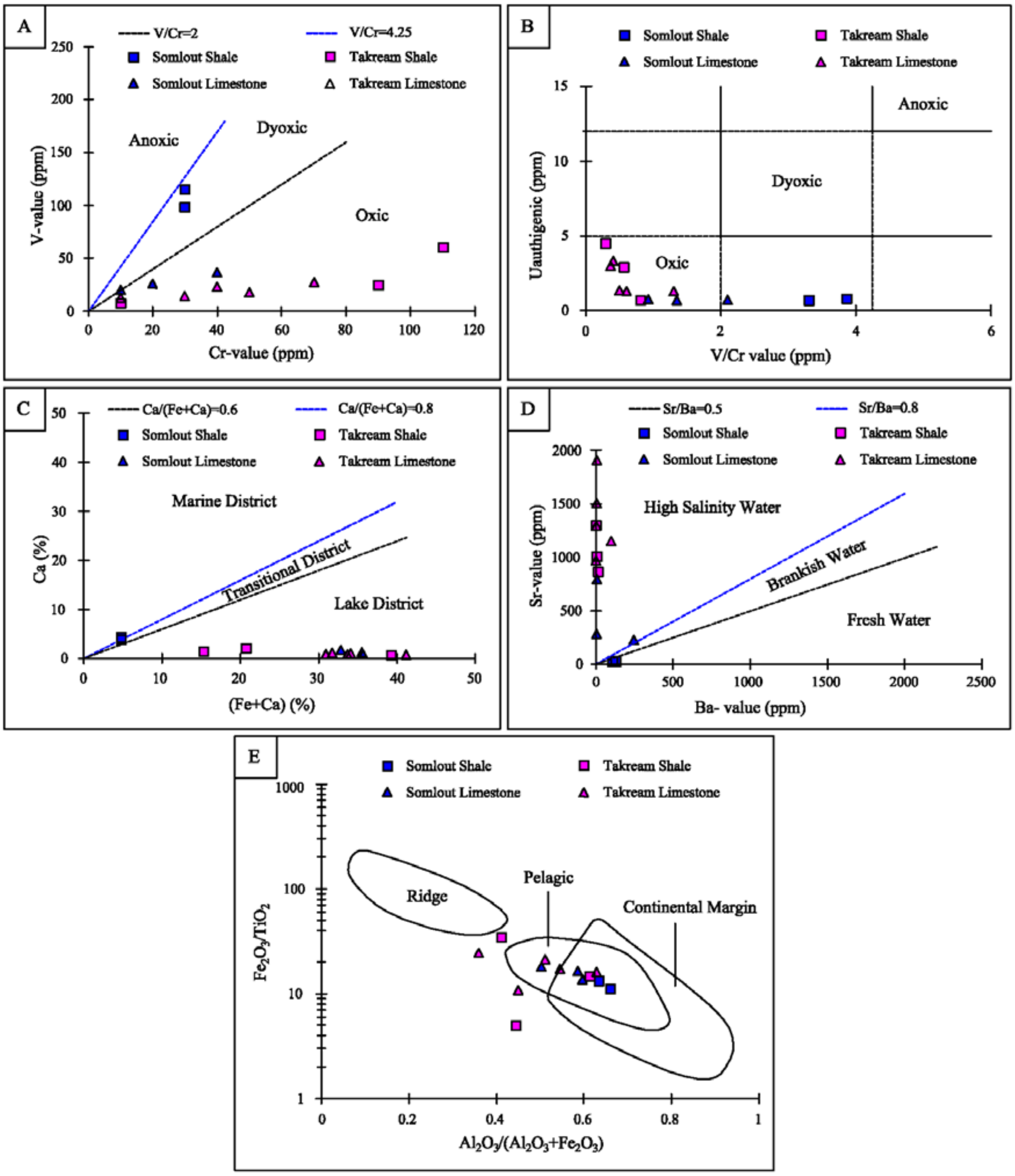

Figure 3.11: Plotting diagram showing depositional setting of calcareous shale and limestone in Somlout and Takream samples, (A) is V vs. Cr ratio (He et al., 2019; Tyson and Pearson, 1991); (B) is Ca vs. (Fe+Ca) (He et al., 2019; Deng and Qian, 1993); (C) is Uauthigenic vs. V/Cr (Myers and Wignall, 1987); (D) is Sr vs. Ba ratio, showing water column environment (He et al., 2019; Nelson, 1967); (E) is Fe_2O_3/TiO_2 vs. $Al_2O_3/(Al_2O_3 + Fe_2O_3)$ diagram (He et al., 2019; Murray, 1994).

value of both calcareous shale and limestone of the Takream sample range from 0.91 to 0.97 and 11.8 to 1450, averaging 0.97 and 387.14, respectively, which indicate a high salinity seawater environment.

3.4.3 Depositional Setting

The Al_2O_3/ (Al_2O_3 + Fe_2O_3) ratio can be used as an index to determine the sedimentary environment, with a value ranging from 0.4 to 0.7 in the oceanic basin, indicating a deep-water, and from 0.5 to 0.9 in the continental margin (He et., 2019) **(Figure 3.11E)**. The concentration of Al_2O_3 is affiliated with aluminosilicate phases; it is an excellent indicator for terrigenous input, and Fe_2O_3 and TiO_2 are rich in the metalliferous mid-oceanic ridge (Murray, 1994).

Thus, Fe_2O_3/TiO_2 ratio in the mid-oceanic ridge is higher than the continental margin. Moreover, the cross-plot value of Fe_2O_3/TiO_2 with $Al_2O_3/(Al_2O_3 + Fe_2O_3)$ can be used to distinguish the continental margin from the mid-oceanic ridge (He et., 2019; Murray, 1994). The Al_2O_3/ (Al_2O_3 + Fe_2O_3) ratio of Somlout samples ranges from 0.50 to 0.66, all falling into the overlapping area of the oceanic basin and continental margin. The Al_2O_3/ (Al_2O_3 + Fe_2O_3) ratio of Takream samples ranges from 0.36 to 0.63, mostly falling into or near the overlapping area of the oceanic basin and continental margin.

Based on paleontological aspects, the presence of fusulinid and bivalve shelve was commonly suggested in a shallow water environment (Asl and Aleali, 2016; Boggs, 2012), while bryozoan mainly indicated a marine environment (Scholle and Ulmer-Scholle, 2003), because these types of micro-fossil mostly live in these conditions. The recognized fossils of bryozoans, fusulinids, and small foraminifers, are skeletal or fragmental debris, indicating that the depositional environment must be a barrier (Chutakositkanon et al., 2000). Somlout depositional condition might be a significant regression depending on the lithostratigraphy of limestone at the bottom, followed by shale at the top (Chutakositkanon et al., 2000). Takream fine-grained shale and limestone are suggested to form in a quiet marine water setting, a lagoon (Nichols, 2009).

3.5 Conclusion

According to various geochemical elements and the ratios of V vs. Cr, Uauthigenic vs. V/Cr, Sr vs. Ba, Ca vs. (Fe+Ca), and Fe_2O_3/TiO_2 vs. $Al_2O_3/(Al_2O_3 + Fe_2O_3)$ diagram, Somlout, and Takream are deposited in the shallow marine environment. Somlout shales sample were deposited in the dysoxic fresh water of the lake setting during the sea-level drop. Somlout limestones and Takream samples were deposited in high salinity seawater, oxic condition of shallow-marine water. In addition, Somlout limestones consist of fragmental fusulinid foraminifera, bivalve shelve, and bryozoan, which are indicated a barrier environment. Meanwhile, Teakream consists of fine-grained shale, and lime mudstone, which are suggested to be deposited in a quiet marine setting of the lagoon. In conclusion, Tonle Sap basin sediments were deposited in shallow marine, the barrier and lake environment for Somlout, and the lagoon environment for Takream.

Table 3.2: Trace elements concentrations (ppm) of Somlout and Takream samples.

Sample	V	Cr	Ga	Rb	Sr	Nb	Ba	Th	Zr	Hf	Ce	La	Nd	W	Y
S-L1	21.00	10.00	0.70	0.80	798.00	0.10	7.20	0.06	3.00	0.10	15.70	8.40	8.00	<1	11.30
S-S1	99.00	30.00	10.90	27.70	35.30	2.60	108.00	2.13	64.00	1.80	17.50	7.90	8.70	<1	12.50
S-L3	37.00	40.00	2.90	3.60	234.00	0.30	244.00	0.19	10.00	0.30	50.60	23.50	25.20	<1	25.30
S-S3	116.00	30.00	12.20	36.20	32.00	2.90	130.50	2.44	76.00	2.10	16.50	7.20	8.80	1.00	12.70
S-L4	27.00	20.00	1.50	1.30	288.00	0.20	8.10	0.11	6.00	0.20	10.30	8.40	5.40	<1	15.00
T-LB	8.00	10.00	0.20	<0.2	1305.00	0.10	0.90	<0.05	<2	<0.1	0.30	0.50	0.30	2.00	1.80
T-S1	61.00	110.00	3.60	5.20	865.00	1.00	14.30	0.30	15.00	0.40	3.80	3.20	2.90	<1	6.20
T-S4	25.00	90.00	1.20	2.90	1010.00	0.40	8.00	0.18	7.00	0.20	2.20	2.20	1.80	<1	5.60
T-L12	15.00	30.00	0.30	0.40	1300.00	0.10	3.10	<0.05	4.00	0.10	0.50	0.50	0.30	<1	1.40
T-L9	28.00	70.00	0.60	1.80	1910.00	0.20	6.00	0.10	3.00	0.10	1.90	3.70	2.40	<1	8.70
T-L14	18.00	50.00	0.70	1.50	1510.00	0.30	4.70	0.09	3.00	0.10	1.60	2.90	1.60	<1	6.10
T-L15	13.00	10.00	0.20	0.20	974.00	0.10	2.50	<0.05	<2	<0.1	0.50	1.00	0.50	<1	2.50
T-L16	24.00	40.00	1.10	1.50	1160.00	0.40	98.30	0.17	5.00	0.10	2.00	2.10	1.50	<1	4.40
Mean S	75.25	65.00	6.98	18.00	485.58	1.73	65.20	1.26	40.50	1.13	10.00	5.13	5.55	0.25	9.25
Mean L	21.22	31.11	0.91	1.23	1053.22	0.20	41.64	0.08	3.78	0.11	9.27	5.67	5.02	0.22	8.50
UC	97.00	92.00	17.50	84.00	320.00	12.00	628.00	10.50	193.00	5.30	63.00	31.00	27.00	1.90	21.00
M S/UC	0.78	0.71	0.40	0.21	1.52	0.14	0.10	0.12	0.21	0.21	0.16	0.17	0.21	0.13	0.44
M L/UC	0.22	0.34	0.05	0.01	3.29	0.02	0.07	0.01	0.02	0.02	0.15	0.18	0.19	0.12	0.40

Chapter 4.

Characterization of the Depositional Environment of Sediments in Kampong-Som Sedimentary Basin, Using Field Observation and Paleontology

4.1 Introduction

Depositional environment analysis is based on properties of rocks that have environmental significances, which are sedimentary structures, textures, fossils, and sedimentary facies associations. Based on the information, the facies model can be constructed to make a general summary of the characteristics of certain depositional systems. Then, from the characteristic

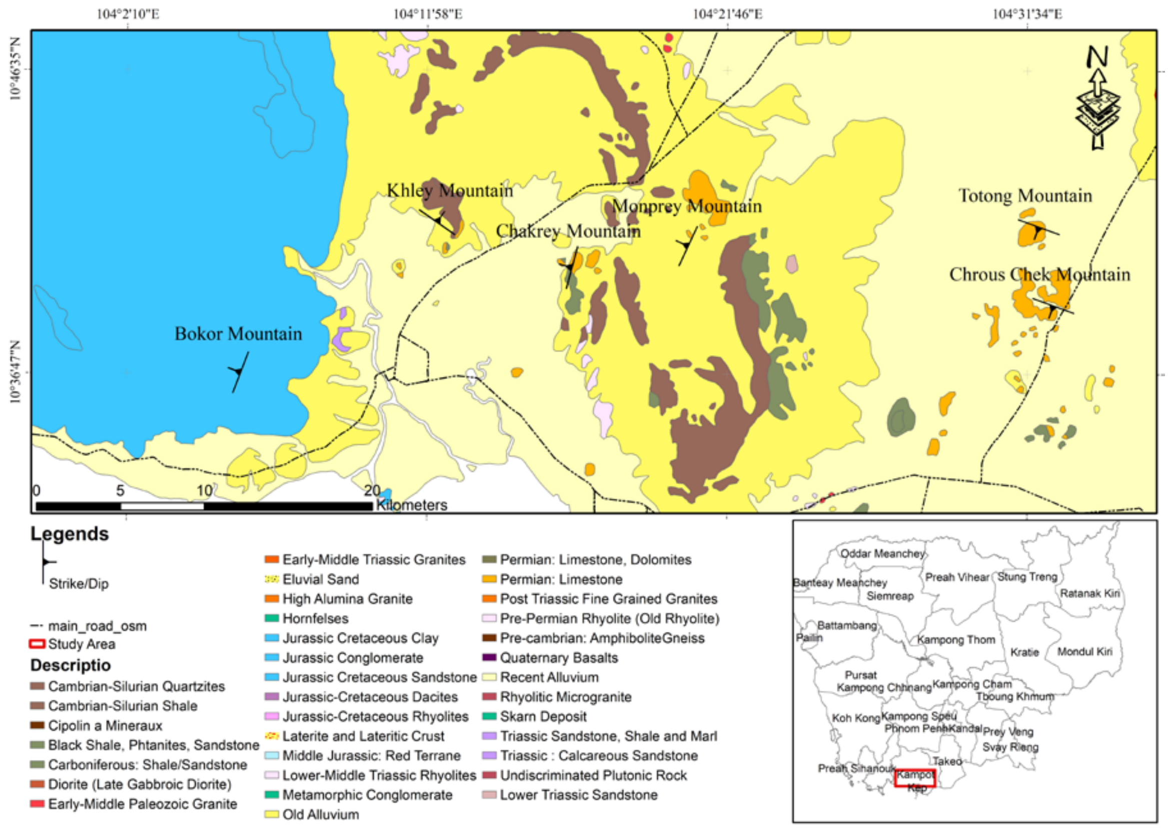

Figure 4.1: The sampling locations in Kampot province, Totong mountain, Chrous Chek mountain, Monprey mountain, Chakrey mountain, Khley mountain, and Bokor mountain.

depositional system, the depositional environments of sedimentary rock were well defined. To study the depositional environment without a borehole, the six outcrops of Permian carbonate, Triassic terrigenous sediments, and Jurassic massive sandstone were exposed, and represent the Permian, Triassic, and Jurassic units in this basin **(Figure 4.1)**.

This research focuses on the characterization of the depositional environment of sediments in the Kampong-Som sedimentary basin by using field investigation, lithology, sedimentology, paleontology, and petrography.

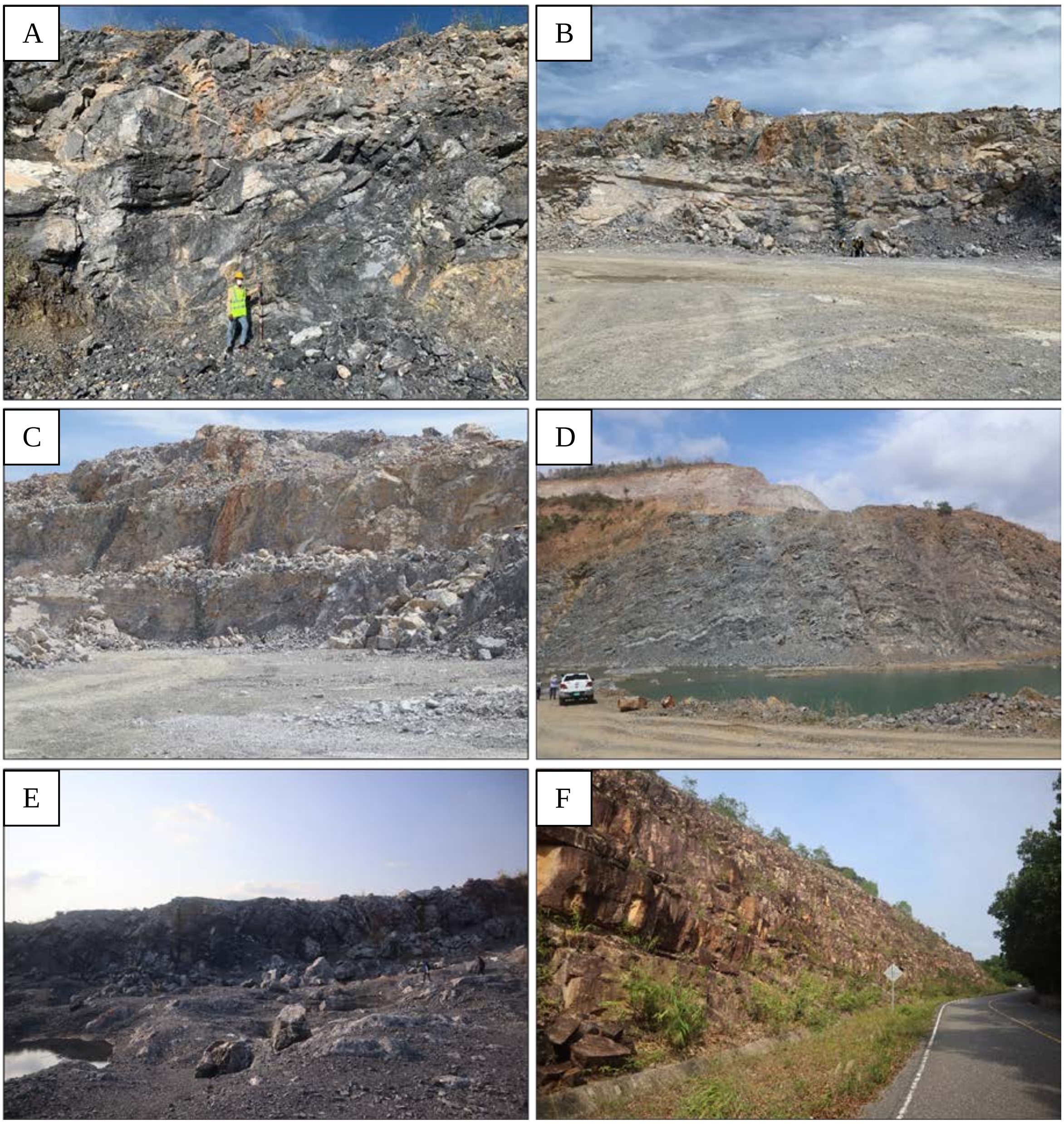

Figure 4.2: Six outcrop overview in Kampot province, (A) Chakrey mountain, (B) Totong mountain, (C) Chrous Chek mountain, (D) Khley mountain, (E) Monprey mountain and (F) Bokor mountain, which show well bedded exposure.

Pages 45-56 are intentionally left blank.

Contact to pechsopheap@itc.edu.kh for more information.

Chapter 5.

Organic Matter Identifications and Source Rock Evaluation of Shale in Kampong-Som Basin, Onshore Cambodia

5.1 Introduction

Hydrocarbon source rock is sedimentary rock which contains sufficient organic matter and has the ability to generate hydrocarbons when subjected to heat and pressure. It is usually shale or limestone, but shale is the most common hydrocarbon source rock as it is an organic-rich fine-grained sedimentary rock which is composed of quartz, clays, carbonates, felspars, apatite, pyrite, and organic matter (Curtis et al., 2012). In this article, Permian-Triassic shale in the southern part of Cambodia were selected to present as hydrocarbon source rock in Kampong-Som sedimentary basin **(Figure 5.1)** (Vysotsky et al., 1994). Fynh et al. (2010a) mentioned maturity of source rock in Kampot Fold Belt which regionally obtained R_o values of 3.3 to 4.5%. This means that these source rocks are in the postmature stage. To clarify this, organic matter identifications and source rock evaluation of shale need to be studied as these data are fundamental to hydrocarbon exploration. Total organic carbon (TOC) content is an important index by which to evaluate the quality of hydrocarbon source rock. Another important characteristic is thermal maturity which can indicate the maturity stage (He et al., 2019). This finding is the preliminary result, which enhance the understanding of petroleum system in onshore Cambodia.

Pages 58-71 are intentionally left blank.

Contact to pechsopheap@itc.edu.kh for more information.

Chapter 6.

Conclusions

The source rock evaluation and depositional environment of sediments characterization in Kampong-Som and Tonle Sap sedimentary basin were sucessfully syudied by using six outcrop exposure in Kampot province and two in battambang province. The fresh samples were sampling by geological hammer, testing with laboraotry works, and discussed on lithofacies, sedimentary rock properties, fossil contents, major and minor elements, organic matter type, kerogen type, thermal maturity, and depositional setting.

6.1 Major Finding of the Research

The major findings of the present research are summarized in the following paragraphs:

1. Using sedimentology and geochemistry aspect, Somlout, and Takream are deposited in the shallow marine environment. Somlout shales sample was deposited in the dysoxic fresh water of the lake setting during the sea-level drop. Somlout limestones and Takream samples were deposited in high salinity seawater, oxic condition of shallow-marine water. In addition, Somlout limestones consist of fragmental fusulinid foraminifera, bivalve shelve, and bryozoan, which are indicated a barrier environment. Meanwhile, Teakream consists of fine-grained shale, and lime mudstone, which are suggested to be deposited in a quiet marine setting of the lagoon. In conclusion, Tonle Sap basin sediments were deposited in shallow marine, the barrier and lake environment for Somlout, and the lagoon environment for Takream.
2. Based on sedimentological and paleontological aspects, Kampong-Som basin three main lithology types such as Permian packstone, Triassic parallel interbedded sandstone and shale, and Jurassic massive quartz arenite sandstone with a thickness of more than 350 m, where Permian packstone is dark grey color, massive, mud-supported, compacted, and abundant in fossils fragment of coral reef, Crinoid, syringopora, and foraminifer, which deposited in marine setting of barrier deposit. The Triassic age, composed of the conglomerate in the bottom part and followed by an interbedded of grey fine grain sandstone

and laminated foraminifer shale which suggest being deposited in under turbiditic process of submarine fan deposit. The Jurassic sandstone, white quartz arenite, suggested deposited in the clean environment of shallow marine deposits by RIP current. Therefore, the Permian-Jurassic sedimentary facies indicated the transgressive/regressive succession of shelf see from barrier, submarine fan, and shallow marine deposits by RIP current.

3. According to TOC content and Rock-eval pyrolysis result, KH-S1 and CK-S1 have TOC value 0.06wt% and 0.07wt%, which are classified as poor total organic content. Furthermore, TT-S1 and CC-S1 have TOC value 3.61wt% and 9.45wt%, indicating excellent concentration of organic matter. Kampong-Som source rocks are identified as kerogen Type III, which potential for gas generation, and are immature source rocks. Based on organic matter type analysis, solid bitumen organic matter is the dominant organic component in KH-S1, CC-S1, and TT-S1, accounting for 73%, 80%, and 99% of total OM. Vitrinite and inertinite derived from terrestrial higher vegetation are present in minor amounts. Alginite (3%) was found only in CC-S1. Solid bitumen hosted secondary pore (nanopores-1µm), which were observed TT-S1 sample and KH-S1, however these both samples are immature in temperature ~415°C. The pore in SB is very rare and only small particles of SB of KH-S1 sample, it is automatically that its source rock is immature and lower temperature (382°C) than TT-S1. So, the exposure source rocks of Kampong-Som basin are poor total organic content (0.06wt% and 0.07wt%) and excellent (3.61wt% and 9.45wt%). All these source rocks are immature below temperature 415°C in reason they don't go deep enough before they were exposed to the surface.

6.2 Future Possibility

Regarding to the results of this research, the hydrocarbon source rocks of Kampong-Som sedimentary basin reveal that total organic carbon (TOC) content are range from poor to excellent (0.06 wt% to 9.45 wt%), kerogen Type III, and immature stage source rocks. The depositional environments are oxygenated of turbidite and barrier deposit, which cause the total organic-carbon (TOC) contents are low. The remaining kerogen is oxygenated, with a negligible generative capacity for hydrocarbons, despite the burial depth does not reaching the generative temperature (415°C). Sometimes, it happens as this study is conducted with the exposure outcrop. Therefore, it might be a mistake in exposure outcrop selection might not be represented to the whole sedimentary stratigraphy, the outcrop should be conducted more for expanding the understand the as much as possible. Some criteria should be discussed:

1. Research location : Extending research location to Oral mountain, Kampong Speu province, as that area consists thick shale layer which might deposit in anoxic environment, which considered as the most potential to be study.
2. Sample selection : The number of representative samples should be increase to understand the properties, distribution of thermal histroy and pale-heat flow of hydrocarbon source rock.
3. Seismic line : Conducting at least one seismic line cross cut from Kampot to Kampong Speu province to obtain kampong-Som basin modelling, which indicate the rate of subsidence and burial histrory of hydrocarbon source rocks and reservoir rocks.

REFERENCES

Asl, S. S., & Aleali, M. (2016). Microfacies Patterns and Depositional Environments of the Sarvak Formation in the Abadan Plain, Southwest of Zagros, Iran. *Open Journal of Geology*, *6*, 201-209. https://doi:org/10.4236/ojg.2016.63018

Binczewska, A., Polovodova Asteman, I., & Farmer, E. J. (2015). Foraminifers (Benthic). In J. Harff, M. Meschede, S. Petersen, & J. Thiede (Eds.), *Encyclopedia of Marine Geosciences* (pp. 1–8). Springer Netherlands. https://doi.org/10.1007/978-94-007-6644-0_60-1

Blyth Cain, J. D. (1968). Aspects of the depositional environment and palaeoecology of crinoidal limestones. Scottish Journal of Geology, 4(3), 191-208.

Boggs, S. (2012). *Principles of Sedimentology and Stratigraphy*. Pearson Prentice Hall.

Boggs, S. J. (2009). Petrology of Sedimentary Rock. New York: United States of America by Cambridge University Press. https://doi:org/9780521897167

Boggs, S., & Krinsley, D. (2006). Application of cathodoluminescence imaging to the study of sedimentary rocks. Cambridge University Press.

Cai, J. X., & Zhang, K. J. (2009). A new model for the Indochina and South China collision during the Late Permian to the Middle Triassic. Tectonophysics, 467(1-4), 35-43.

Camp, W. K. (2016, October). Strategies for identifying organic matter types in SEM. In SEPM-AAPG Hedberg Research Mudstone Diagenesis Conference (pp. 16-19).

Cao, J., Wu, M., Chen, Y., Hu, K., Bian, L., Wang, L., & Zhang, Y. (2012). Trace and rare earth element geochemistry of Jurassic mudstones in the northern Qaidam Basin, northwest China. Geochemistry, 72(3), 245-252.

Charusiri, P., Rhodes, B.P., Saithong, P., Kosuwan, S., Pailopli, S., Wiwegwin, W., Doarerk, V., Hinthong, C., Klaipongpan, S. (2007). Regional Tectonic Setting and Seismiicity of Thailand with Reference to Reservoir Construction 274–287.

Chutakositkanon, V., Charusiri, P., & Sashida, K. (2000). Lithostratigraphy of Permian marine sequences, Khao Pun Area, central Thailand: Paleoenvironments and tectonic history. Island Arc, 9(2), 173-187.

Deng, H.W. and Qian, K. (1993). Analysis of Sedimentary Geochemistry and Environment. Gansu Science and Technology Publishing House, Lanzhou. (In Chinese)

Dunham, R. J. (1962). Classification of carbonate rocks according to depositional textures.

El Kammar, M. M. (2015). Source-rock evaluation of the Dakhla Formation black shale in Gebel Duwi, Quseir area, Egypt. Journal of African Earth Sciences, 104, 19-26.

Er, C., Li, Y., Zhao, J., Wang, R., & Wei, Z. (2016). Characteristics of lacustrine organic-rich shale: A case study of the Chang 7 member, Triassic Yanchang Formation, Ordos Basin, China. *Journal of Natural Gas Geoscience*, 1-13. https://doi:dx.doi.org/10.1016/j.jnggs.2016.04.001

Fyhn, M. B., Green, P. F., Bergman, S. C., Van Itterbeeck, J., Tri, T. V., Dien, P. T., ... & Nielsen, L. H. (2016). Cenozoic deformation and exhumation of the Kampot Fold Belt and implications for south Indochina tectonics. Journal of Geophysical Research: Solid Earth, 121(7), 5278-5307.

Fyhn, M. B., Boldreel, L. O., & Nielsen, L. H. (2010a). Escape tectonism in the Gulf of Thailand: Paleogene left-lateral pull-apart rifting in the Vietnamese part of the Malay Basin. Tectonophysics, 483(3-4), 365-376.

Fyhn, M. P. (2010b). Palaeocene early Eocene inversion of the Phuquoc Kampot Som Basin: SE Asian deformation associated with the suturing of Luconia. J. Geol. Soc., 167,281–295.

Gamero-Diaz, H., Miller, C., & Lewis, R. (2013, September). sCore: a mineralogy based classification scheme for organic mudstones. In SPE Annual Technical Conference and Exhibition. OnePetro.

GDMR-JICA. (2010). "Geological Map of Cambodia, ", 1:200,000, Cambodia: General Department of Mine Resources-JICA.

Guo, H., Jia, W., Lei, Y., Luo, X., Cheng, M., Wang, X., ... & Jiang, C. (2014). The composition and its impact on the methane sorption of lacustrine shales from the Upper Triassic Yanchang Formation, Ordos Basin, China. Marine and Petroleum Geology, 57, 509-520.

Hall, R., Cottam, M. A., & Wilson, M. E. (2011). The SE Asian gateway: history and tectonics of the Australia–Asia collision. Geological Society, London, Special Publications, 355(1), 1-6.

Hara, H., Ito, T., Tokiwa, T., Kong, S., & Lim, P. (2020). The origin of the Pailin Crystalline Complex in western Cambodia, and back-arc basin development in the Paleo-Tethys Ocean. Gondwana Research, 82, 299-316.

He, C., Ji, L., Su, A., Wu, Y., Zhang, M., Zhou, S., ... & Ma, Y. (2019). Source-rock evaluation and depositional environment of black shales in the Triassic Yanchang Formation, southern Ordos Basin, north-central China. Journal of Petroleum Science and Engineering, 173, 899-911.

Hutton, A. C. (1995). Organic Petrography: Principles and Techniques. In C. Snape (Ed.), *Composition, Geochemistry and Conversion of Oil Shales* (pp. 1–16). Springer Netherlands. https://doi.org/10.1007/978-94-011-0317-6_1

Isaksen, G.H. and Bohacs, K.M. (1995). Geological Controls of Source Rock Geochemistry through Relative Sea Level; Triassic, Barents Sea. In: Katz, B.J., Ed., Petroleum Source Rocks. Casebooks in Earth Sciences, Springer, Berlin, 25-50. https://doi.org/10.1007/978-3-642-78911-3_3

Jahan, S., & Uddin, A. (2022). Organic petrography and depositional environments of the upper Eocene Kopili Shale, Bengal Basin, Bangladesh. *Journal of Asian Earth Sciences*, 17. https://doi:doi.org/10.1016/j.jaesx.2022.100092

Jones, B. and Manning, D.A. (1994). Comparison of Geochemical Indices Used for S. Pech et al. DOI: 10.4236/ojg.2023.137028 666 Open Journal of Geology the Interpretation of Palaeoredox Conditions in Ancient Mudstones. Chemical Geology, 111, 111-129. https://doi.org/10.1016/0009-2541(94)90085-X

Khin, Z., Meffre, S., Lai, C. K., Burrett, C., Santosh, M., Graham, I., ... & Cromie, P. (2014). Tectonics and metallogeny of mainland Southeast Asia—A review and contribution. Gondwana Research, 26(1), 5-30.

Kobchenko, M., Panahi, H., Renard, F., Dysthe, D.K., Malthe-Sorenssen, A., Mazzini, A., et al. (2011). Fracturing Controlled Primary Migration of Hydrocarbon Fluids during Heating of Organic-Rich Shales. Journal of Geophysical Research, 2, 1-20.

Lepvrier, C., Van Vuong, N., Maluski, H., Thi, P. T., & Van Vu, T. (2008). Indosinian tectonics in Vietnam. Comptes Rendus Geoscience, 340(2-3), 94-111.

Lim, V. (2006). Petroleum Policy and Management Project: Update on Petroleum Activities in Cambodia. In CNPA. Siem Reap: Cambodia Case Study Workshop.

Liu, B., Schieber, J., & Mastalerz, M. (2017). Combined SEM and reflected light petrography of organic matter in the New Albany Shale (Devonian-Mississippian) in the Illinois Basin: A perspective on organic pore development with thermal maturation. International Journal of Coal Geology, 184, 57-72.

Lu, J., Ruppel, S. C., & Rowe, H. D. (2015). Organic matter pores and oil generation in the Tuscaloosa marine shale. AAPG bulletin, 99(2), 333-357.

Mao, C., Yamada, Y., & Matsuoka, T. (2014). A preliminary assessment of geological CO2 storage in Cambodia. International Journal of Greenhouse Gas Control, 30, 19-33.

Mccave, I. (2002). *Sedimentary Settings on Continental Margins—An Overview* (pp. 1–14). https://doi.org/10.1007/978-3-662-05127-6_1

Morley, C. K. (2001). Combined escape tectonics and subduction rollback–back arc extension: a model for the evolution of Tertiary rift basins in Thailand, Malaysia and Laos. Journal of the Geological Society, 158(3), 461-474.

Murray, R.W. (1994). Chemical Criteria to Identify the Depositional Environment of Chert: General Principles and Applications. Sedimentary Geology, 90, 213-232. https://doi.org/10.1016/0037-0738(94)90039-6

Myers, K.J. and Wignall, P.B. (1987). Understanding Jurassic organic-Rich Mudrocks—New Concepts Using Gamma-Ray Spectrometry and Palaeo-Ecology: Examples from the Kimmeridge Clay of Dorset and the Jet Rock of Yorkshire. In: Leggett, J.K. and Zuffa, G.G., Eds., Marine Clastic Sedimentology, Springer, Dordrecht, 172-189. https://doi.org/10.1007/978-94-009-3241-8_9

Nichols, G. (2009). Sedimentology and stratigraphy. John Wiley & Sons.

Okeke, O. O. (2010). Shale: A review of their classifications, properties and importance to the petroleum industry. 19.

Peters, K. E., & Cassa, M. R. (1994). Applied source rock geochemistry: Chapter 5: Part II. Essential elements.

Pickel, J. W. (2016). Settlement strategy in Symplectophyllum (Cnidaria, Rugosa). GEOLOGICA BELGICA, 19.

Pickering, K. T., & Hiscott, R. N. (2015). *Deep Marine Systems: Processes, Deposits, Environments, Tectonics and Sedimentation* (1st edition). American Geophysical Union.

Prothero, D. S. (2013). An introduction to sedimentary rocks and stratigraphy, Third edition. ed. W.H. Freeman, New York. Sedimentary geology.

Scholle, P.A. and Ulmer-Scholle, D.S. (2003). A Color Guide to the Petrography of Carbonate Rocks: Grains, Textures, Porosity, Diagenesis. In: AAPG Memoir 77, Vol. 77, American Association of Petroleum Geologists, Tulsa. https://doi.org/10.1306/M77973

Sirisokha, S., Yonezu, K., Tindell, T., Nakanishi, T., Watanabe, K., & Pelletier, J. (2019). Lithogeochemistry of Intrusive Rocks in the Halo Porphyry Copper-Molybdenum Prospect, Northeast Cambodia. Open Journal of Geology, 9(07), 342.

Tissot, B. P., du Petrole, E. N. S., & Welte, D. H. (1978). Petroleum formation and occurrence. A new approach to oil and gas exploration.

Tyson, R.V. and Pearson, T.H. (1991) Modern and Ancient Continental Shelf Anoxia: An Overview. Geological Society, London, Special Publications, 58, 1-24. https://doi.org/10.1144/GSL.SP.1991.058.01.01

Udchachon, M., Thassanapak, H., & Burrett, C. (2018). Early Permian radiolarians from the extension of the Sa Kaeo Suture in Cambodia–tectonic implications. Geological Magazine, 155(7), 1449-1464.

Vysotsky, V. I., Rodnikova, R. D., & Li, M. N. (1994). The petroleum geology of Cambodia. Journal of Petroleum Geology, 17(2), 195-210.

Walker, R. G., & James, N. P. (1992). Facies models: Response to sea level change. Geological Association of Canada = Association géologique du Canada.

Watcharanantakul, R., & Morley, C. K. (2000). Syn-rift and post-rift modelling of the Pattani Basin, Thailand: evidence for a ramp-flat detachment. Marine and Petroleum Geology, 17(8), 937-958.

Welte, D. H., & Tissot, P. (1984). *Petroleum formation and occurrence*. Springer.

Yagishita, K. (1994). Planar cross-bedding associated with rip currents of Upper Cretaceous formations, northeast Japan. Sedimentary Geology, 93(3-4), 155-163.

GRADUATE SCHOOL

INSTITUTE OF TECHNOLOGY OF CAMBODIA

Russian Federation Boulevard, P.O. Box 86 Phnom Penh, Cambodia

Email: graduate@itc.edu.kh