FACIES CHARACTERISTICS OF THE LATE CRETACEOUS - PALEOGENE SEDIMENTS (PHU KHAT FORMATION) IN THE NAKHON THAI REGION : IMPLICATIONS FOR TECTONIC EVOLUTION

Pradit Nulay

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy in Geotechnology

Suranaree University of Technology

Academic Year 2014

ลักษณะปรากฏของตะกอนในช่วงตอนปลายยุคครีเทเชียส ถึง ยุคพาลีโอจีน (หมวดหินภูขัด) บริเวณพื้นที่นครไทย เพื่ออธิบายวิวัฒนาการทางด้านธรณีแปรสัณฐาน

นายประดิษฐ์ นูเล

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิศวกรรมศาสตรดุษฎีบัณฑิต
สาขาวิชาเทคโนโลยีธรณี
มหาวิทยาลัยเทคโนโลยีสุรนารี
ปีการศึกษา 2557

FACIES CHARACTERISTICS OF THE LATE CRETACEOUS - PALEOGENE SEDIMENTS (PHU KHAT FORMATION) IN THE NAKHON THAI REGION : IMPLICATIONS FOR TECTONIC EVOLUTION

Suranaree University of Technology has approved this thesis submitted in partial fulfillment of the requirements for the Degree of Doctor of Philosophy.

Thesis Examining Committee

____

(Prof. Dr. Kittitep Fuenkajorn)

Chairperson

____

(Asst. Prof. Dr. Akkhapun Wannakomol)

Member (Thesis Advisor)

____

(Dr. Chongpan Chonglakmani)

Member

____

(Dr. Assanee Meesook)

Member

____

(Assoc. Prof. Dr. Benjavun Ratanasthien)

Member

____

(Asst. Prof. Dr. Mongkol Udchachon)

Member

____

(Prof. Dr. Sukit Limpijumnong)

Vice Rector for Academic Affairs and Innovation

____

(Assoc. Prof. Flt. Lt. Dr. Kontorn Chamniprasart)

Dean of Institute of Engineering

ประดิษฐ์ นูเล : ลักษณะปรากฏของตะกอนในช่วงตอนปลายยุคครีเทเชียส ถึง ยุคพาลีโอจีน (หมวดหินภูขัด) บริเวณพื้นที่นครไทย เพื่ออธิบายวิวัฒนาการทางด้านธรณีแปรสัณฐาน (FACIES CHARACTERISTICS OF THE LATE CRETACEOUS - PALEOGENE SEDIMENTS (PHU KHAT FORMATION) IN THE NAKHON THAI REGION : IMPLICATIONS FOR TECTONIC EVOLUTION) อาจารย์ที่ปรึกษา : ผู้ช่วยศาสตราจารย์ ดร.อัฆพรรค์ วรรณโกมล, 207 หน้า.

วัตถุประสงค์ของงานวิจัยนี้คือ เพื่อศึกษารายละเอียดสภาวะแวดล้อมการสะสมตัว แหล่งตะกอนต้นกำเนิด และธรณีแปรสัณฐานของหมวดหินภูขัดขณะสะสมตัวในยุคครีเทเชียสตอนปลาย ถึง ยุคพาลีโอจีน และเพื่ออธิบายวิวัฒนาการทางด้านธรณีแปรสัณฐาน วิธีการศึกษา ประกอบด้วย 1) การศึกษาลักษณะปรากฏของหมวดหินภูขัด 2) การศึกษาศิลาวรรณา และธรณีเคมี ร่วมกับการศึกษาอายุทางกัมมันตรังสีของธาตุยูเรเนียมและตะกั่ว ในแร่เซอร์คอนของหินทรายหมวดหินภูขัด

ผลการศึกษาลักษณะปรากฏ พบหมวดหินภูขัดวางตัวแบบผิดวิสัยอยู่บนหินทรายของหมวดหินเขาย่าปุก (หรือหมวดหินภูทอก) สามารถแบ่งลำดับชุดหินอย่างคร่าวๆออกเป็นสองลำดับ คือ ลำดับชุดหินชั้นล่างและลำดับชุดหินชั้นบน ลำดับชุดหินชั้นล่างแสดงลักษณะปรากฏของการสะสมตัวแบบเนินตะกอนน้ำพารูปพัด (alluvial fan) โดยมีลักษณะปรากฏที่เกิดร่วมกัน (facies association) สองลักษณะคือ ลักษณะปรากฏที่เกิดร่วมกันแบบเอ และบี ลักษณะปรากฏที่เกิดร่วมกันแบบเอ ประกอบด้วย หินกรวดมนคละขนาด มีการคัดขนาดไม่ดี ร่วมกับหินทรายขนาดเม็ดหยาบ การคัดขนาดไม่ดีและมีเศษชิ้นของหินภูเขาไฟในสัดส่วนที่สูง แปลความได้ว่าเกิดจากการสะสมตัวของธารน้ำไหลแบบแผ่ซ่าน บนพื้นที่ตอนต้นของเนินตะกอนน้ำพารูปพัด (stream flow deposits in proximal alluvial fan) ส่วนลักษณะปรากฏที่เกิดร่วมกันแบบบี ประกอบด้วย ชั้นหินทรายขนาดเม็ดละเอียดถึงปานกลางมีการคัดขนาดปานกลาง แสดงลักษณะโครงสร้างชั้นหินวางตัวขนานกันต่อเนื่องเป็นแนวยาว อยู่ร่วมกับชั้นหินทรายแป้งและหินโคลนโดยมีสัดส่วนของชั้นหินทรายแป้งและหินโคลนเพิ่มมากขึ้นในตอนบน จากลักษณะดังกล่าวแปลความได้ว่า เกิดจากการสะสมตัวของธารน้ำหลากแบบแผ่ซ่านบนพื้นที่ตอนปลายของเนินตะกอนน้ำพารูปพัด (unconfined to poorly confined sheet flow of down slope distal alluvial fan) ในส่วนของลำดับชุดหินชั้นบนประกอบด้วยลักษณะปรากฏที่เกิดร่วมกันแบบซี หินส่วนใหญ่ประกอบด้วยหินทรายชั้นหนาเม็ดหยาบ แสดงลักษณะโครงสร้างตะกอนแบบการวางชั้นเฉียงระดับ บ่งบอกการสะสมตัวแบบธารน้ำประสานสาย (braided stream)

การศึกษาทางด้านธรณีเคมีเพื่ออธิบายธรณีแปรสัณฐานขณะชุดหินสะสมตัว และแปลความแหล่งตะกอนต้นกำเนิด ใช้เทคนิคการแบ่งแยกโดยวิธีการพล็อตกราฟสัดส่วนค่าความเข้มข้น

ของ ธาตุออกไซต์หลัก (major elements) ธาตุร่องรอย (trace elements) และ ธาตุหายาก (rare earth elements) ผลการศึกษาบ่งชี้ว่าหมวดหินภูขัดสะสมตัวภายใต้ธรณีแปรสัณฐานแบบ passive margin และเมื่อนำไปประมวลร่วมกับผลการศึกษาทางด้านศิลาวรรณาที่พบว่าหมวดหินภูขัดมีต้นกำเนิดมาจากการพัดพาหลายรอบของตะกอน (recycled oregen) สามารถบ่งชี้ได้ว่าหมวดหินภูขัดมีแหล่งตะกอนต้นกำเนิดมาจากกระบวนการเปลี่ยนสภาพและยกตัวสูงขึ้นอันเป็นผลจากการชนกันของแนวเทือกเขา (deformed and uplifted sequence of the collision orogens) หรือจากกระบวนการการยกตัวสูงขึ้นของแนวหินคดโค้ง (the foreland fold and thrust belt) โดยที่แหล่งตะกอนต้นกำเนิดเป็นหินตะกอนร่วมกับหินภูเขาไฟหมู่เกาะรูปโค้งภาคพื้นทวีป (continental volcanic arc) จากธรณีแปรสัณฐานทางด้านตะวันตก (Nan-Uttaradit Suture Zone และ Sukhothai Zone) และหรือ ธรณีแปรสัณฐานทางด้านตะวันออก (Loei-Phetchabun Fold Belt) อย่างไรก็ตามผลจากการศึกษาอายุทางกัมมันตรังสีของธาตุยูเรเนียมและตะกั่วในแร่เซอร์คอน บ่งบอกอย่างชัดเจนว่า แหล่งตะกอนต้นกำเนิดมาจากธรณีแปรสัณฐานทางด้านตะวันตกเพียงแหล่งเดียวเท่านั้นซึ่งมีหินภูเขาไฟในช่วงอายุไทรแอสซิกตอนกลางถึงตอนปลาย

ผลการบูรณาการการศึกษา สามารถอธิบายวิวัฒนาการทางด้านธรณีแปรสัณฐานของพื้นที่นครไทยได้ว่า ขณะที่หมวดหินภูขัดสะสมตัวในพื้นที่นครไทยนั้น ธรณีแปรสัณฐานทางด้านตะวันตกเริ่มมีการยกตัวเป็นแหล่งจ่ายตะกอนหลักให้กับหมวดหินภูขัด โดยเป็นการยกตัวตามแนวโครงสร้างธรณีแปรสัณฐานเดิม ในช่วงประมาณยุคครีเทเชียสตอนปลาย (Maastrichtian) ในขณะเดียวกันธรณีแปรสัณฐานทางด้านตะวันออกกลับยังไม่มีการยกตัวเป็นแหล่งจ่ายตะกอนให้กับหมวดหินภูขัด จนกระทั่งสิ้นสุดการสะสมตัวของหมวดหินภูขัด หลังจากนั้นพื้นที่ทั้งหมดซึ่งประกอบไปด้วย ธรณีแปรสัณฐานทางด้านตะวันตก พื้นที่นครไทย และธรณีแปรสัณฐานทางด้านตะวันออก จึงมีการยกตัวขึ้นพร้อมๆกัน ดังจะเห็นได้จากระดับภูมิประเทศในปัจจุบันของทั้งสามพื้นที่อยู่ในระดับที่ใกล้เคียงกัน อันเนื่องมาจากการเคลื่อนที่เข้ามาของแผ่นทวีปอินเดีย (Greater India) ชนกับแผ่นทวีปยูเรเซีย (Eurasia) ในช่วงยุคพาลีโอจีนตอนต้น (Ypresian) และจากผลการแปลความดังกล่าวข้างต้นนี้ อาจกล่าวได้ว่าชุดหินภูขัดมีอายุของการสะสมตัว อยู่ในช่วงอายุระหว่าง Maastrichtian ถึง Ypresian

สาขาวิชาเทคโนโลยีธรณี ลายมือชื่อนักศึกษา__________

ปีการศึกษา 2557 ลายมือชื่ออาจารย์ที่ปรึกษา__________

ลายมือชื่ออาจารย์ที่ปรึกษาร่วม__________

PRADIT NULAY : FACIES CHARACTERISTICS OF THE LATE CRETACEOUS - PALEOGENE SEDIMENTS (PHU KHAT FORMATION) IN THE NAKHON THAI REGION : IMPLICATIONS FOR TECTONIC EVOLUTION. THESIS ADVISOR : ASST. PROF. AKKHAPUN WANNAKOMOL, Ph.D., 207 PP.

PHU KHAT FORMATION/ FACIES ASSOCIATION/PROVENANCE/U-Pb DETRITAL ZIRCON DATING/ GEOCHEMISTRY

The purposes of this study are to carry out detailed study of environmental deposition, provenance and tectonic setting of the Phu Khat Formation during deposition in the Late Cretaceous - Paleogene and discuss on geotectonic evolution by using facies study, petrography and the whole-rock geochemistry integrated with U-Pb detrital zircon dating. The facies study indicates that the Phu Khat Formation is underlain unconformably by aeolian sandstone of the Khao Ya Puk Formation (or the Phu Tok Formation). The formation can be roughly subdivided into two large sequences, i.e., the upper and lower sequences. The lower sequence is mainly characterized by the succession of alluvial fan facies consisting of facies association A and B. The facies association A is composed mainly of conglomerate and poorly sorted, coarse-grained sandstone of stream flow deposits in the proximal alluvial fan (the lower Phu Khat Formation). The facies association B is characterized by continuous even parallel bedded, medium- to fine-grained sandstone grading up into siltstone and mudstone which was deposited under unconfined to poorly confined sheet flow condition of the down slope distal alluvial fan environment (the middle Phu Khat Formation). The upper sequence comprises a succession of facies association C (the upper Phu Khat Formation) which is composed chiefly of thick-bedded, coarse-grained sandstone of the fluvial braided stream.

Geochemically, discriminant function plots of major, trace and rare earth elements have revealed the tectonic setting and the provenance of the Phu Khat Formation. The results indicate that the Phu Khat Formation was accumulated in the passive margin tectonic setting and the provenance of the Phu Khat Formation consists primarily of sedimentary rocks associated with continental volcanic arc rocks. The complementary petrographic study confirms the source was from the recycled orogen. The Phu Khat Formation could be derived either from the deformed and uplifted sequences of the collision orogens or the foreland fold and thrust belt either from the western (the Nan-Uttaradit Suture and Sukhothai Zone) or the eastern (the Loei-Phetchabun Fold Belt) continental terranes or both. However, the U-Pb detrital zircon dating provides a clear evidence that the provenance of the Phu Khat Formation was uniquely from the western terrane with igneous activity predominantly occurred in the Middle to Late Triassic time.

Tectonically, the result indicates that while the Phu Khat Formation was accumulated in the Nakhon Thai region, the western terrane was uplifted by reactivation of the pre-existing structure probably since the Maastrichtian time as the source of sediments. Meanwhile, the eastern terrane (mainly the Loei-Phetchabun Fold Belt) had not been uplifted probably until the accumulation of the Phu Khat Formation was terminated. Thereafter, the whole region began to uplift forming a high mountainous area since the Ypresian time when the Greater India collided with the Eurasia. Consequently, the depositional age of the Phu Khat Formation can be constrained as the Late Cretaceous (Maastrichtian) to not younger than the Early Paleogene (Ypresian).

School of Geotechnology — Student's Signature____________________

Academic Year 2014 — Advisor's Signature____________________

Co-Advisor's Signature__________________

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to Asst. Prof. Dr. Akkhapun Wannakomol, thesis advisor and Dr. Chongpan Chonglukmani, thesis co-advisor for their guidance, encouragement and valuable discussion as well as open the real world of geology for me. The Royal Thai Government is thanked for financial support.

Thanks are also extended to thesis committee, Prof. Dr. Kittitep Fuenkajorn, Assoc. Prof. Dr. Benjavan Ratanasthien and Asst. Prof. Dr. Mongkol Udchachon, for their critical comments and helpful suggestions.

I am greatly indebted to Prof. Dr. Qinglai Feng of State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences in Wuhan for the constructive advice, assistance and also support of the valuable laboratory work. This appreciation is extended to his family for their hospitality and assistance during I was in Wuhan, China.

I would also like to thank Prof. Dr. Andy Carter of the Department of Earth and Planetary Sciences, Birkbeck, University of London (UK) for his kindly providing U-Pb detrital zircon dating. Thanks are due to Dr. Assanee Meesook for helping with field work and served on the thesis committee and commented on the manuscript. Thanks also go to Dr. Heiner Heggemann for providing valuable papers in the geology of the Nakhon Thai region and discussion on the geology of the Phu Khat Formation. Grateful appreciation is due to the staffs and my Chinese friends (Nei Xiew Mei, Xin Qian and Gao Hai Long) at the State Key Laboratory of Geological Processes and

Mineral Resources, China University of Geosciences in Wuhan for their helping and supporting the analyses.

Thanks are also extended to Director General of Department of Mineral Resources for providing permission during the course of study. My friends at SUT, Boonnarong Arsairai, Hathaichanok Vattanasak, Namporn Wattanaton, Khongkeaw Jenjitpaiboon and Peerawat Khongurai are thanked for their helping with the field work and warm hospitality during I was in SUT.

Finally, I most gratefully acknowledge my family members: father, mother, sisters and my fiancé (Miss Katemanee Nilda), for all their support throughout the period of this research.

Pradit Nulay

TABLE OF CONTENTS

Page

TABLE OF CONTENTS (Continued)

Page

TABLE OF CONTENTS (Continued)

Page

TABLE OF CONTENTS (Continued)

Page

LIST OF TABLES

Table **Page**

LIST OF FIGURES

Figure **Page**

LIST OF FIGURES (Continued)

Figure **Page**

LIST OF FIGURES (Continued)

Figure **Page**

LIST OF FIGURES (Continued)

Figure **Page**

LIST OF FIGURES (Continued)

CHAPTER I

INTRODUCTION

1.1 General statement

The Late Cretaceous to Paleogene in Thailand and vicinity are well documented for the time of active tectonic which lead to the uplift and erosion of the sediments (Morlay, 2012). In Thailand extensive study of this time period have been conducted in the northern and southern Thailand as the time deposition of extensional and/or rift of the Tertiary basins (Uttamo, 1999; Nichols and Uttamo, 2005; Morley and Racey, 2011) which provides the succession of economical hydrocarbon deposit. Theses succession have also been mentioned to deposit in the Nakhon Thai region and vicinity as the Phu Khat Formation, however its depositional environment was not considered as under the same condition as extensional basin in northern and southern Thailand (Heggemann, 1994; Sattayarak and Polachan, 1990).

The Nakhon Thai region is located between two major tectonic lines which in the Nan-Uttaradit Suture Zone to the west and the Loei-Phetchabun Fold Belt to the east (Fig. 3.1a). The red beds sandstones sequence of the Phu Khat Formation in the Nakhon Thai region is the topmost units overlying on the Khao Ya Puk Formation (or the Phu Tok Formation) in the Indochina Block (Heggemann, 1994; Heggemann et al., 1994). It is interpreted to deposit more or less as a result of Himalayan Orogeny in the Latest Cretaceous-Early Paleogene. This tectonic event are believed to reactivate the movement of those pre-existing tectonic lines (i.e., Nan- Uttaradit Suture Zone and the Loei-Phetchabun Fold Belt) as the provenance supplying for the sediment of the Phu Khat Formation (Heggemann, 1994).

However, the interpretations of all above assumptions and the previous extensive study of the Phu Khat Formation (e.g. Kosuwan 1990; Heggemann et al., 1994; Meesook et al., 2002; Assavapatchara and Raksasakulwong, 2010) are principally based on surface mapping without insight detailed study of their facies characteristics, provenance and tectonic setting. Moreover, depositional age of the formation is still controversial and inconclusive. Therefore, the purpose of this study is to presents the integration of facies characteristic with petrography, the whole-rock geochemistry and the U-Pb detrital zircon dating in order to resolve the above problems of the Phu Khat Formation. The results of this study provide a better understanding on the Mesozoic stratigraphic sequences and the tectonic evolution of the Nakhon Thai region during the deposition of the Phu Khat Formation. In addition it further constrain depositional age of the Phu Khat Formation. Consequently, it will be a major contribution as the basis for future land-use planning and mineral resources development, especially for groundwater development and saline soil hazard mitigation which lead to the efficient use of land and mineral resources with minimum environmental impact.

1.2 Research objectives

The objectives of this study are to:

1. Assess lithostratigraphy, facies characteristic and define depositional environment of the Phu Khat Formation in the Nakhon Thai region.
2. Determine the provenance and geotectonic setting type of the Phu Khat Formation in the Nakhon Thai region.
3. Discuss on the tectonics evolution of the Nakhon Thai region during the Late Cretaceous to Paleogene.

1.3 Scope and limitations

The study areas are coved in the Nakhon Thai region. The predominant areas are located in Loei and Phitsanulok Provinces (Figure 1.1). There are five referent localities which were studied in details (Figure 4.1b). The depositional environment of the Phu Khat Formation was interpreted mainly from their lithostratigraphy and facies characteristic including lithology, geometry, sedimentary structures, palaeo-current pattern and palaeontology. The provenance and tectonic setting during deposition were determined and discussed based upon the modal frame-work grained component of clastic sandstones associated with the whole-rock geochemistry (major, trace and rare earth elements) and the U-Pb dertrital zircon age dating. The results all above were used to clarify and discuss with previous study on the topic of tectonic evolution.

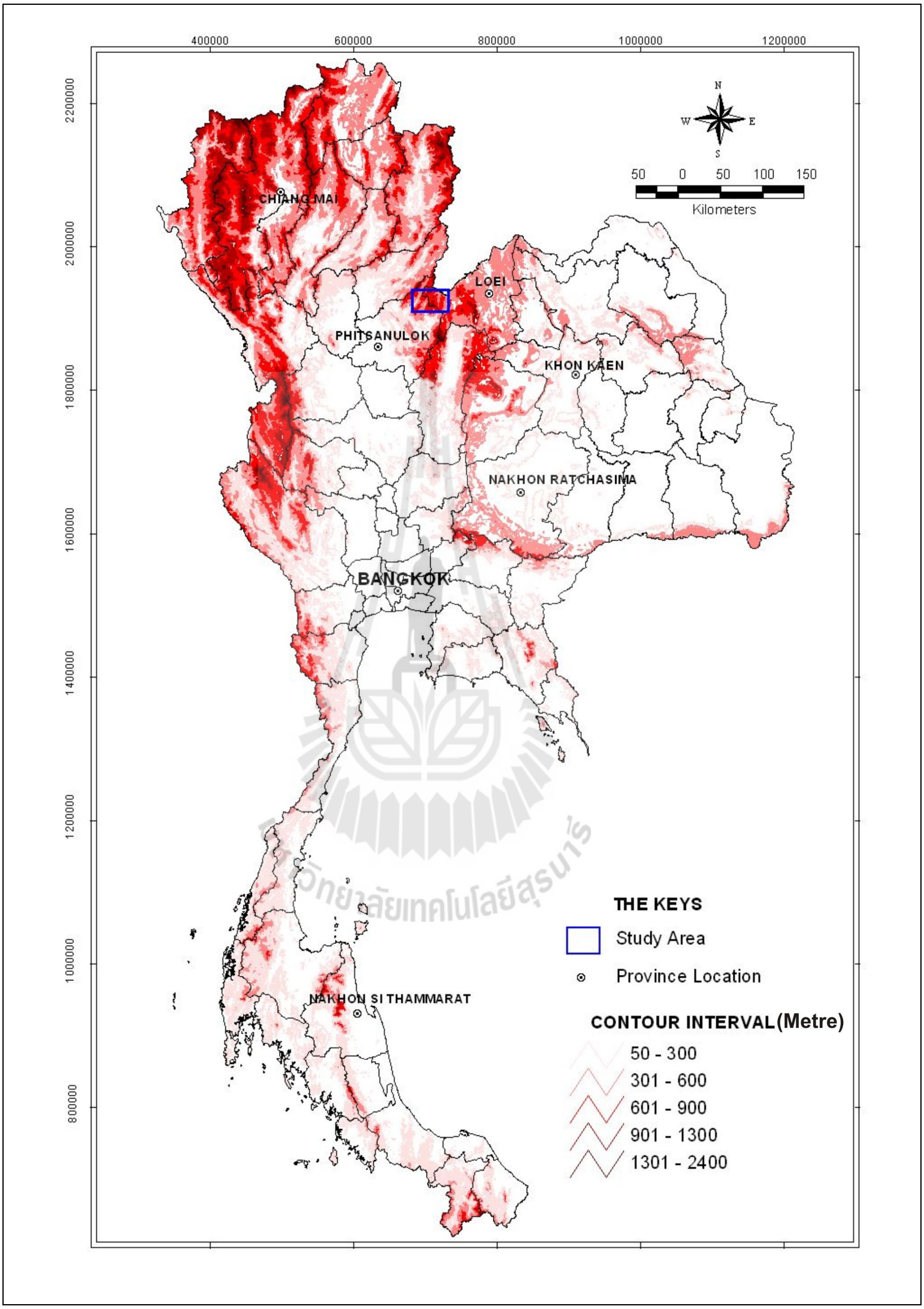


Figure 1.1 The location of study area

CHAPTER II

LITERATURE REVIEW

In this chapter the geological setting of Thailand is briefly described. The geology and the previous works in the study area and its vicinity are examined in more detail. In addition, the tectonic setting throughout Thailand and tectonic evolution of red beds of the Khorat Group are reviewed based mainly on previous studies.

2.1 Geologic setting

2.1.1 General geology of Thailand

The geology of Thailand has long been studied more than fourty years ago by Thai and foreign geologists based mainly on the surface mapping program of the Department of Mineral Resources (DMR). According to the geologic map of the DMR on the scale 1:2,500,000, Thailand has a long history of the rock unit since the Precambrian to the Quaternary period in which the regional stratigraphic correlation is presented in seven belts as shown in Figure 2.1. Details of each time-rock unit are briefly described as following.

2.1.1.1 The Precambrian

The high grade metamorphic rocks of amphibolites facies, orthogneiss, paragneiss, schist, cal-silicate, migmatite and mable are inferred as the oldest Precambrian rock in Thailand. The important evidence used to assign this age is based on the fact that these high grade metamorphic rocks are generally overlain by

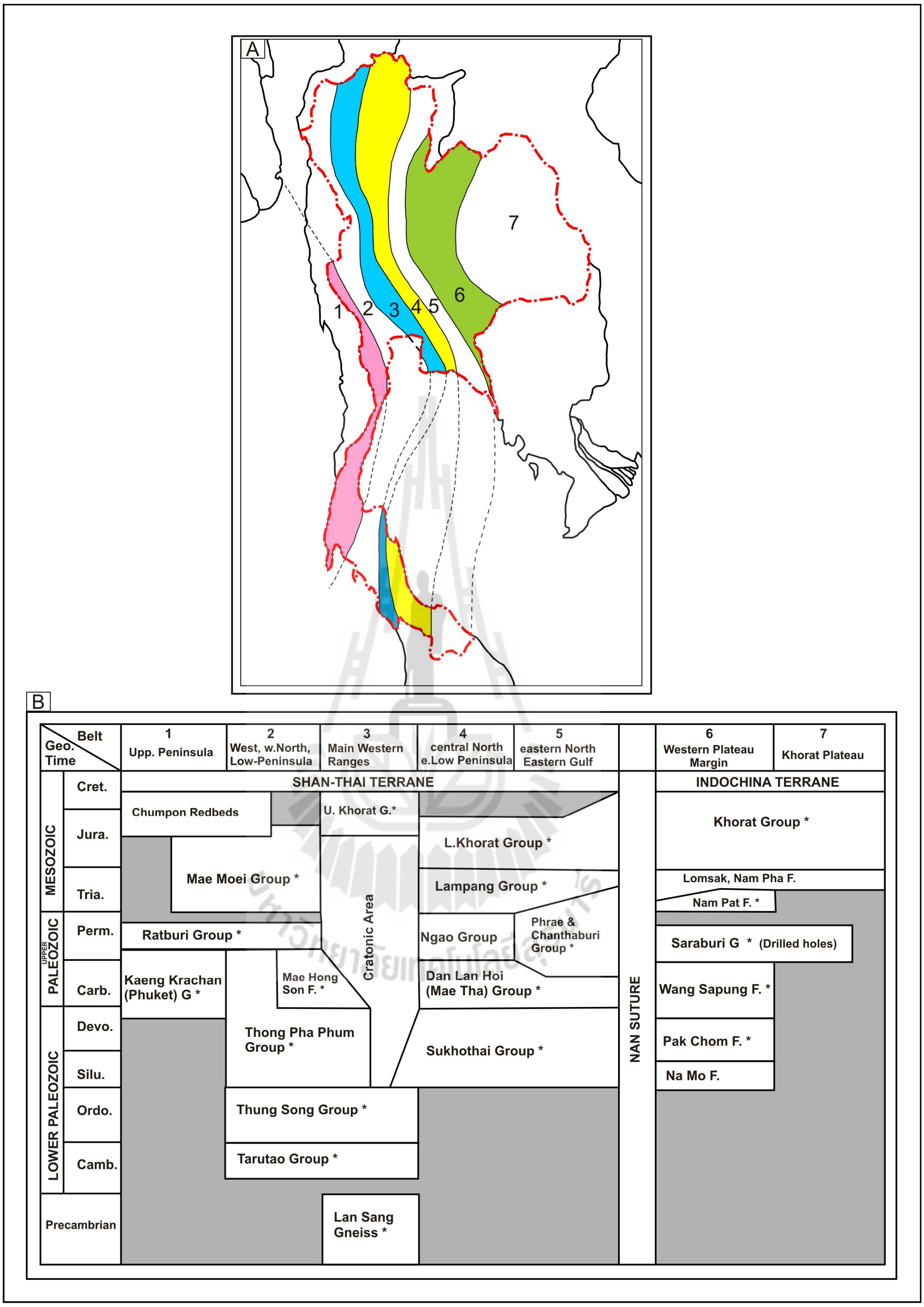


Figure 2.1 A) Regional seven stratigraphic belts of Thailand B) Generalized stratigraphic correlation of Thailand within seven belts. Name with (*) are used in DMR's 1:2,500,000 geologic map (after Bunopas, 1992)

sedimentary rocks containing the Cambrian fossils. It is believed that the regional dynamo-thermal is the main process producing these rocks. The rocks are well exposed in northern, western, southeastern and southern Thailand except for the northeast (the Indochina Block) (Figure 2.2). As stated by Mantajit (1997) these rocks may be correlated with the Ximen Group in southern Yunnan and Mogok Gneiss in Shan State of Myanmar. However, it should be kept in mind that the Precambrian age is only interpreted from stratigraphic relation. Recently, the geochronological study of the high grade metamorphic rocks indicates that the rocks have been deformed during the Triassic to the Late Oligocene (Hansen and Wemmer, 2011; Dunning et al., 1995; Ahrendt et al., 1993; Macdonald et al., 1993).

2.1.1.2 The Paleozoic

The Paleozoic rocks in Thailand can be subdivided into three rock units: the Lower, the Middle and the Upper Paleozoic. The Lower Paleozoic rocks are well exposed in the south and on the main western range (Figure 2.3). The rocks are divided mainly into two groups: the Tarutao Group and the Thung Song Group. The Tarutao Group is characterized by siliciclastic rocks, e.g., sandstone and shale of offshore shelf, barrier beach and a lagoonal marine (Lee, 1983) having its age as the Cambrian based on the occurrence of the Cambrian trilobites (Lee, 2006). The Ordovician Thung Song Group is entire sequence of limestone in southern Thailand. It overlies conformably on the Tarutao Group. The rocks comprise a thick-sequence of dark-gray argillaceous limestone, dolomites and calcareous shale which was interpreted to have been deposited in the shallow to deep carbonate ramp environment (Wongwanich, 1990).

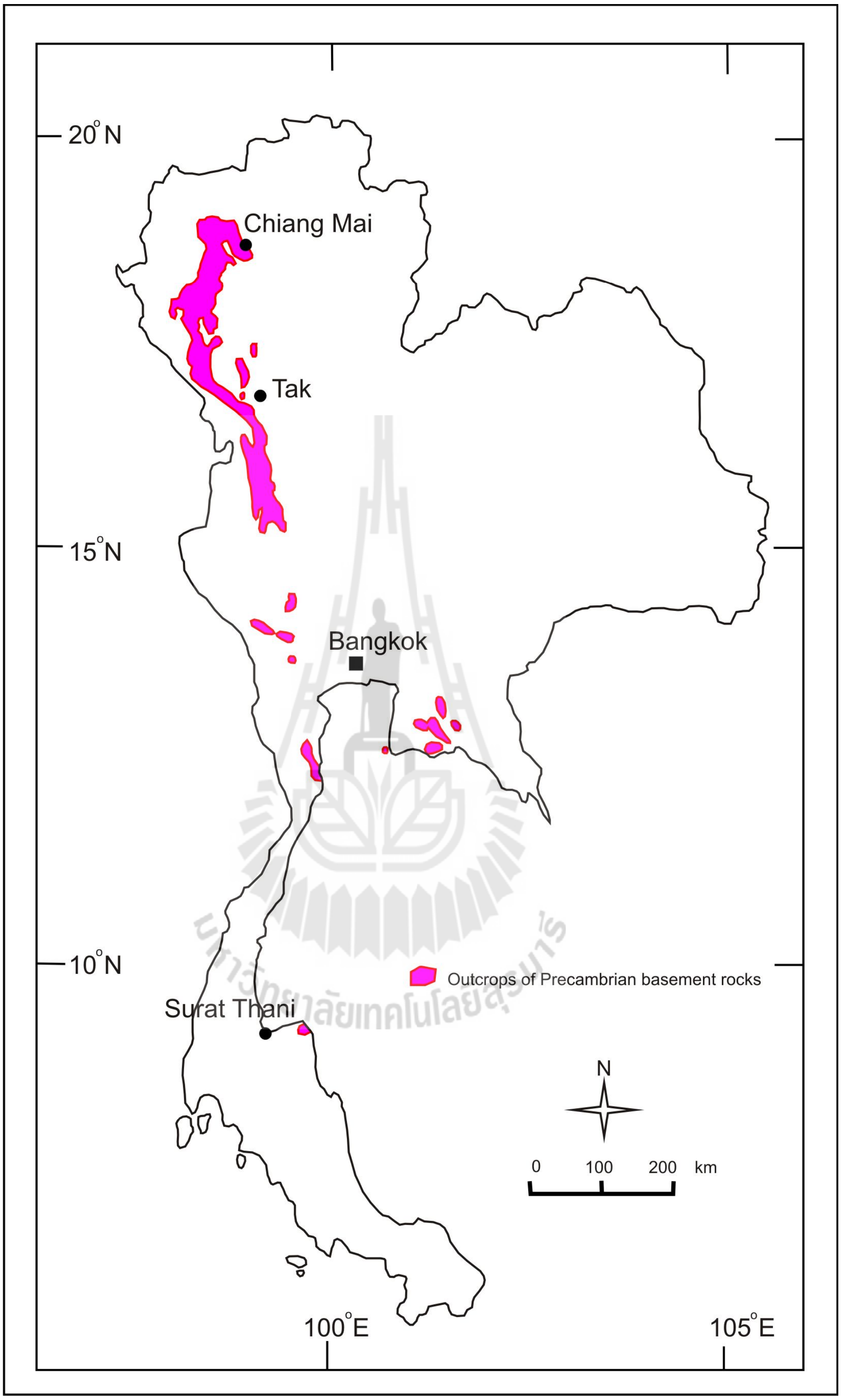


Figure 2.2 Distribution of the inferred Precambrian basement rocks in Thailand (after Hansen and Wemmer, 2011)

In western and northern Thailand the lateral equivalent Lower Paleozoic rocks have been subjected to low grade metamorphic rock comprising quartzite, schist and recrystalline limestone (Bunopas, 1981).

According to Mantajit (1997) and Bunopas (1994) the Middle Paleozoic rocks (Silurian-Devonian) of Thailand can be differentiated into three rock units throughout the country from the west to the east: the Thong Pha Phum Group in the western mountain range and peninsular Thailand, the Sukhothai Group in the north and the Na Mo and Pak Chom Formations in the northeast. The Thong Pha Phum Group is composed of mixed carbonate and silisiclastic shelf to basin facies. It comprises variegated nodule limestone, black graptolitic and tentaculitic shale, bedded chert with radiolarians, mudstone and sandstone. The group overlies conformably on the Ordovician Limestone and grades upward conformably into Carboniferous strata (Wongwanich and Boucot, 2011). The Sukhothai Group is characterized by low-grade metamorphic rocks, black graptolitic shale, chert and thin-bedded limestone. It is presumed to be overlain unconformably by the Carboniferous strata (Piyasin, 1972). The Na Mo and the Pak Chom Formations are possibly the oldest rocks in the northeastern region of Thailand. They are well exposed in a north-south mountain belt in the eastern border between Loei and Nong Khai, Udon Thani, Nong Bua Lam Phu Provinces. The Na Mo Formation is low-grade metamorphic rocks. It consists of phyllite, chlorite, politic schist, metatuff and quartzite which are overlain unconformably by the Devonian-Early Carboniferous Pak Chom Formation (Chairangsee et al., 1990). The Pak Chom Formation is composed mainly of shale, limestone, minor tuff and occasional chert in which radiolarian banded chert is a main constituent in the upper sequence. Paleontological study on radiolarian and coral indicates that the Pak Chom Formation is the Devonian-Early Carboniferous in age (Udchachon et al., 2011; Shasida et al., 1993; Saesaengseerung et al., 2008).

The Upper Paleozoic rocks (Carboniferous-Permian) are broadly exposed in all regions of the country. In the Carboniferous, the Kaeng Krachan Group is well exposed in southern Thailand. It consists of pebbly sandstone, intercalation of well bedded shale and pebbly shale containing Carboniferous bivalves, brachiopods and biozoans. The Kaeng Krachan Group is overlain conformably by the Middle Permian Ratburi Group (Bunopas, 1992). In the west and the north, the Thong Phu Phum Group is believed to continue from its upper most part of the Ordovician-Silurian-Devonian to the Carboniferous without a break (Bunopas, 1992). In the Mae Hong Son Province, Bunopas (1992) proposed the name Mae Hong Son Formation for the paralic red-bed with a strong continental environment. To the east of Chiang Mai Basin, Piyasin (1972) reported the exposure of the Carboniferous Mae Tha Group which is composed mainly of siliciclastic sedimentary rock. In the Sukhothai Province 200km SW of the Chiang Mai, the Dan Lan Hoi Group was reported by Bunopas (1992). The rocks overlie on the Silurian-Devonian Sukhothai Group. It is composed of tuffaceous sandstone, shale, quartzose sandstone and red siltstone which were interpreted to have been deposited in shallow marine condition (Bunopas, 1992). In northeastern Thailand, the Carboniferous Wang Saphung Formation was reported. It is composed mainly of sandstone, shale with some thin limestone beds and conglomerates. In the Permian period, the rocks in Thailand are predominantly limestone but their age and facies characteristics vary from place to place. The name Ratburi Group was widely used for the succession of all Permian carbonate rocks in the west and the peninsular Thailand. It consists mainly of restricted platform carbonate of the Middle Permian which overlies conformably on the pebbly mudstone of the Kaeng Khachan Group. Fossil assemblages are mainly fusulinids which indicate the Middle Permian to the Late Permian in age (Bunopas, 1992). In northern Thailand, the Ngao Group was reported to the Permian rocks in this region. The group consists of three formations from bottom to top, i.e., the Kiu Lom, the Pha Huat and the Huai Thak Formations (Piyasin, 1972). The Kui Lom Formation is characterized mainly by volcanic rocks (e.g. rhyolite, agglomerate, tuff and andesite). The Pha Huat Formation is characterized chiefly by massive beds of limestones containing brachiopods, corals and fusulinids. The Huai Thak Formation is the upper formation of the Ngao Group. It is dominated by siliciclastic sedimentary rock including shale, sandstone, interbedded with conglomerate. In central and northeastern Thailand, the Saraburi Group is restricted to the Late Carboniferous to the Middle Permian in which the rock unit varies from place to place. It overlies unconformably on the older rock and it is overlain unconformably by the Mesozoic rocks. The Permian rocks in this region can be roughly subdivided into three sub-regions, i.e., western carbonate platform (or the Khao Khwang Platform), a central mixed siliciclastic - carbonate basin (or the Nam Duk Basin) and an eastern mixed carbonate - siliciclastic platform (or the Pha Nok Khoa Platform).

2.1.1.3 The Mesozoic

The Mesozoic rocks are widely exposed in Thailand. It can be categorized into two main facies, i.e., marine and non-marine facies. The marine facies comprises the Lower Triassic to the Upper Jurassic rocks. They are widespread mainly in the west, the north, the southeast and the peninsula of Thailand. On the other hand, the non-marine facies consists of the Upper Triassic to the Upper Cretaceous rocks. It is broadly well exposed in northeastern Thailand since Late

Triassic to Late Cretaceous. While in the north and the peninsula, the non-marine facies begins in the Late Jurassic to the Late Cretaceous. In the Triassic time, Chonglakmani (2002: 2011) divided the Triassic rocks into four main facies according to its facies characteristics, i.e., continental facies, intra-arc facies, deep marine and oceanic facies and platform facies (Figure 2.4). The continental facies is entirely found in the northeastern Thailand on the Indochina Block. It is composed of the Huai Hin Lat Formation which is overlain by the Nam Phong Formation. The Huai Hin Lat Formation overlies unconformably on the Permian rocks and older strata. It is composed of five members in ascending order, i.e., the Pho Hai Member (mainly volcanic rock), the Sam Khaen Member (chiefly of conglomerate with some intercalations of finer sediment), the Dat Fa Member (gray to black carbonaceous shale), the Phu Hi Member (Clastic Sedimentary rock, mainly sandstone) and the I Mo Member (Clastic sedimentary rock associated with intermediate volcanic rocks). The Huai Hin Lat Formation was considered to be of the Late Triassic (Norian) on the basis of its faunal and floral assemblages (Chonglakmani, 2011). The Nam Phong Formation overlies unconformably on the Huai Hin Lat Formation in place and elsewhere the Permian or older rocks. It consists of conglomerate, carbonaceous sandstone, siltstone and mudstone. According to the subsurface geological data, the Nam Phong Formation can be separated into the lower member and the upper member, which are well defined by seismic profile (Booth and Sattayarak, 2011). In general, the Nam Phong Formation is considered to be the Late Triassic (Rhaetian in age) based on the occurrence of palynological evidence and prosauropod dinosaur bones associated with stratigraphic relation (Chonglakmani and Sattayarak, 1978; Buffetaut and Suteethorn, 1998; Racey et al., 1996).

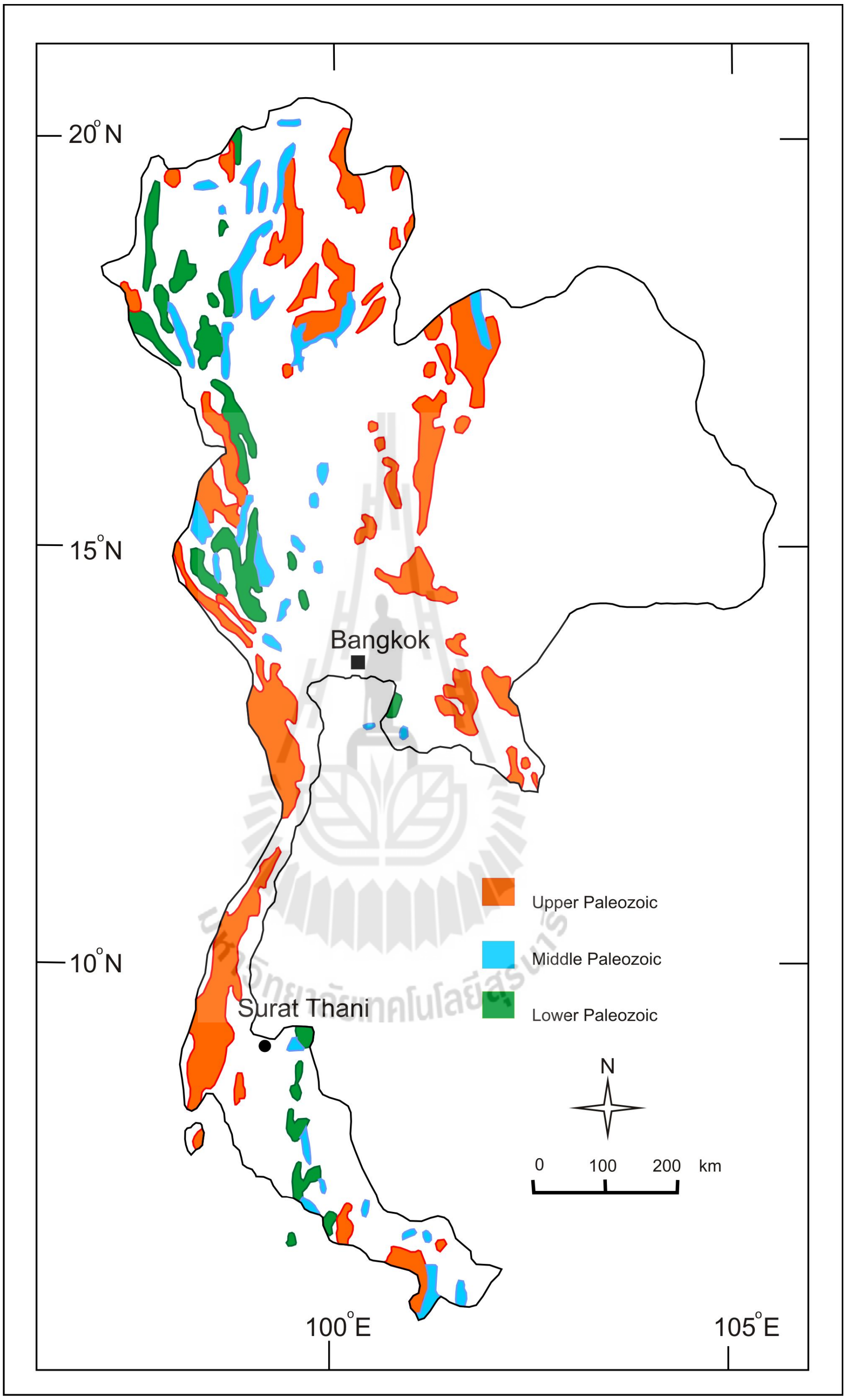


Figure 2.3 Generalized distribution of the Paleozoic rocks in Thailand (after Wongwanich and Burrett, 1983; Ueno and Charoentitirat, 2011).

The Intra-arc facies is distributed mainly in northern Thailand. It is composed of shallow marine siliciclastic and carbonate rocks, turbidites, rhyolitic and andesitic rocks. These sequences were deposited in the Lampang Basin as the Scytian- early Carnian Lampang Group and in the Phrae Basin as the Song Group in the Late Carnian-Norian (Chonglakmani, 2011). In the Uttaradit area, the Late Triassic alluvial fan was observed and the Nam Pat Group is given.

The Triassic continental platform facies is characterized by the shallow marine clastic and carbonate strata without volcanic rocks. This facies can be observed in the west and the peninsular Thailand. In the western part, it was deposited in the Mae Sariang and the Kanchanaburi Basins as the Lower Mae Moei and Si Sawat Groups. While in the peninsula, it is observed as the Sai Bon and Chaiburi Formations. The age of this facies ranges from the Early to the Late Triassic.

The Triassic deep marine and oceanic facies are mainly found in the northern part in the Fang and Chiang Dao areas and the name Fang chert was given. This unit could be traced southward through the Mae Sariang area as represented by the Mae Sariang Formation and southern peninsula in Songkhla Province as represented by the Nathawi Formation (Chonglakmani, 2011). The rocks are characterized by radiolarian chert, pelagic limestone and turbidites. Regarding to radiolarian biostratigraphy, this sequence ranges in age from the Devonian to the Late Triassic (Early Carnian) (Caridroit et al, 1993; Feng et al., 2004, 2005; Hara et al., 2010; Kamata et al., 2002; Sashida et al., 1993; Thassanapak et al., 2011; Wonganan and Caridroit, 2005).

In the Jurassic to the Cretaceous the rock sequences are mostly continental facies except in the most western part of Thailand where marine Jurassic rocks are well exposed in the Umphang, Mae Sot, and the Mae Hong Son areas named as the

Umphang Group, the Huai Fai Group and the Huai Pong Group respectively. The rocks are characterized by sandstone, conglomerate, mudstone, and limestone which contain abundant faunas including bivalves, gastropods, corals, ammonites, brachiopods and foraminifera indicating the Early to the Middle Jurassic in age (Meesook and Saengsrichan, 2011). In north and northeast of Thailand, the continental facies is widely observed in both regions. In the northeast a succession of rocks are represented by the red beds of the Khorat Group (Ward and Bunnag, 1964). The Khorat Group is composed of six formations of the alternated braided and meandering fluvial sandstone facies. It consists of the Nam Phong, Phu Kradung, Pha Wihan, Sao Khua, Phu Phan and Khok Kruat Formations (Racey and Goodall, 2009). The Khorat Group overlies unconformably on the Permian, Triassic Pre-Khorat and the older rocks. The thickness of the Group is approximately more than 4000 m (Ward and Bunnag, 1964). Traditionally, the Khorat Group has been intrpreted to be deposited since the Late Triassic to the Late Cretaceous without any breaking time (Ward and Bunnag, 1964). This age dating has been based on plant macrofossil and vertebrate studies. However, according to palynological evidence the Khorat Group was initiated to deposit not older than the Late Jurassic (the upper Nam Pong Formation) and continue to the late Early Cretaceous (Aptian age; the Khok Kruat Formation) (Racey and Goodall, 2009). Based on Racey and Goodall (2009), they proposed the hiatus in the Early to the early Late Jurassic in the northeastern part of Thailand. After the termination of the Khorat Group, the Maha Sarakham Formation began to deposit overlying unconformably on the top of the Khorat Group. It was considered as the Mid-Cretaceous (Albian - Cenomanian) (Sattayarak and Polachan, 1990) which consists of lower red-beds, lower salt, lower clay, middle salt, middle clay and upper salt units (Sattayarak and Polachan, 1990).

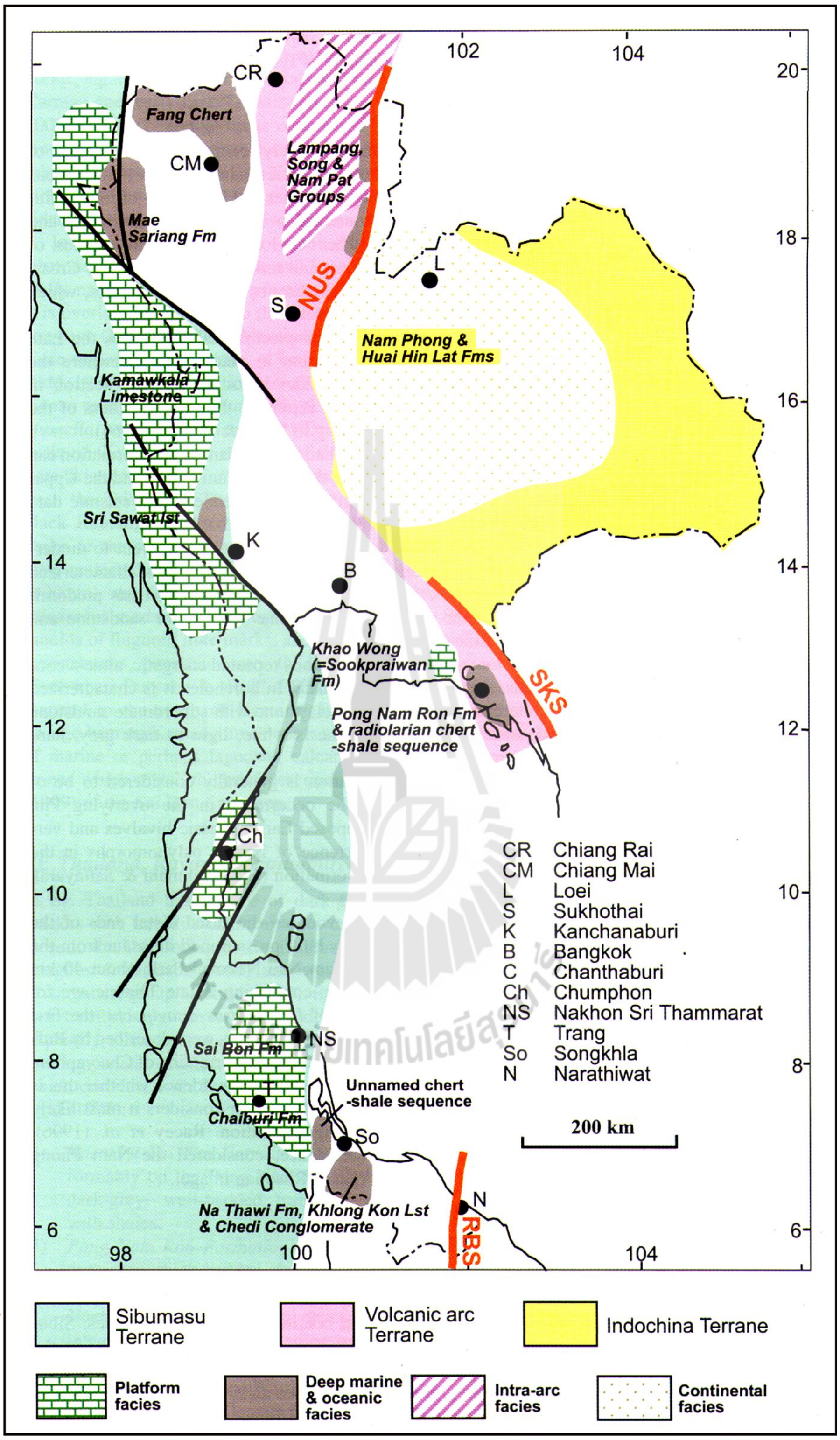


Figure 2.4 Generalized distribution of the Triassic rocks in Thailand (after Chonglakmani, 2011). NUS; Nan-Uttaradit Suture; SKS; Sa Kaeo Suture; RBS; Raub Betong Suture.

In turn the Maha Sarakham Formation is overlain conformably by the Late Cretaceous Phu Tok Formation (Raksasakulwong, 2002b). The Phu Tok Formation is composed of three informal members in ascending order; the Nawa (mainly claystone), Kham Takla (fine sandstone interbedded with siltstone and claystone) and the Phu Tok Noi (aeolian sandstone) (Meesook, 2011). In the Nakhon Thai region, an aeolian sandstone was named as the Khao Ya Puk Formation by Kosuwan (1990) rather than the Phu Tok Formation. Furthermore, Kosuwan (1990) and Heggemann (1994) reported the finding of conglomerate and sandstone sequences overlying on the Khao Ya Puk Formation. Kosuwan (1990) also proposed the new informal name for this sequence as the Phu Khat Formation. Due to the fact that the Phu Khat Formation overlies on the Khao Ya Puk Formation (or the Phu Tok Formation) it is, therefore, supposed to deposit in the Late Cretaceous to the Early Paleogene.

In Nan, Pha Yao and Phrae Provinces, northern Thailand, the succession of the Mesozoic rocks are divided into five informal formations namely (in ascending order), i.e., Ms1, Ms2, Ms3, Ms4 and Ms5 formations (Hahn, 1976). Drumm et al. (1993) reported that the Ms1 (alluvial fan facies) and Ms2 (acid to intermediate volcanic rocks) can be interpreted to have been deposited in the Late Triassic to the early Late Jurassic? on the basis of stratigraphic relation. The Ms3, Ms4, and Ms5 formations can be chonostratigraphically correlated equivalent to the Khorat Group including the Phu Kradung, Phra Wihan and Sao Khua Formations, respectively.

In peninsular Thailand, the Thung Yai Group was reported as the transitional zone of the marine to non-marine condition. It is composed of four formations, i.e., the Khlong Min, Lam Thap, Sam Chom and Phun Pin Formations in ascending order. The Khlong Min Formation is characterized by mudstone interbedded with limestone, siltstone and fossiliferous limestone, containing abundant fossils including estheria, ostracod, sporopollen and hybodont shark remains which indicate the Middle Jurassic in age (Teerarangsikul, 1999; Raksasakulwong, 2002a). The Khlong Min Formation overlies unconformably on the Triassic Chaiburi Formation and it was interpreted to have been deposited under lacustrine environment with gradually changing to fluviatile in the upper sequence (Teerarangsikul, 1999). The Lam Thap, Sam Chom and Phun Phin Formations are entirely non-marine environment. They are composed of the sandstone, siltstone, conglomerate and shale which are interpreted to have been deposited in fluviatile environment. The age of deposition ranges from the Late Jurassic to the Late Cretaceous based on the fossil assemblage and their stratigraphic relation (Teerarangsikul, 1999).

2.1.1.4 The Cenozoic

The Cenozoic rocks in Thailand are mostly developed in the Tertiary basins which are distributed in more than sixty basins within various parts of Thailand. They occur both on- and offshore which are generally associated with rift basins formed in extensional, transtensional or strike-slip settings (Morley and Racey, 2011). Commonly, the Thai rift basins display a half-graben geometry with sedimentary facies dominated by fluvial and fluvio-lacustrine facies in an initial stage; lacustrine facies in a main phase; and a final phase of fluvio-deltaic facies (Morley et al, 2001; Morley and Racey, 2011). These different depositional stages correspond to the structural development of the rift. Morley and Racey (2011) stated that the first stage of deformation started with relative low-displacement extension distributed on numerous faults and coarse clastics tend to infill the depression as a deposition of fluvial and fluvio-lacustrine facies. In the second phase the extensional rate increases and boundary faults become well established leading to the great subsidence. The subsidence rate exceeds the sedimentation rate and lake tends to be formed providing lacustrine sediment facies in this phase. In the final stage the extensional activity decreases toward the end of the rift and the sediment supply is greater than accommodation space which allows fluvio-deltaic facies to fill the entire rift. The Tertiary rift basins in Thailand are commonly diachronous younging from the east to west in Gulf of Thailand (Morley and Racey, 2011). Consequently, the oldest rift was commenced in the Late Eocene in the Krabi Basin in the south while the most rift basins in the northern Thailand were started in the Late Oligocene (Morley and Racey, 2011).

2.1.1.5 The igneous rocks

Granitic rocks

In general, granitic rocks in Thailand can be subdivided based upon their genesis, lithology and geochronology into three north-south trending belts including the eastern, central and western belts as shown in Figure 2.5 (Charusiri et al., 1993; Cobbing, 2011). The difference of geochronology and lithology of the granitic rocks reflects the geotectonic environment (Charusiri et al., 1993). The Eastern Granitic Belt is well exposed in the eastern Thailand through the edge of the Khorat Plateau to the northern Thailand. The largest body of the granitic rock in this belt is the Tak Batholith in Tak Province (Mahawat, 1984). The smaller plutons are in the area of Lampang, Loei, Chantaburi and Naratiwat Provinces. It is mostly characterized by coarse- to medium-grained equigranular hornblende-biotite varieties with subordinate porphyritic texture (Mahawat, 1984; Putthapiban, 2002). Geochemical study by using discrimination plot of Na_2O versus K_2O indicates that the Eastern Granitic Belt was originated from differential crystallization or partial melting from true magma and was classified as I-type affinity (Charusiri et al., 1993; Putthapiban, 2002). Radiometric dating studied by ^{40}Ar-^{39}Ar and U-

Pb zircon dating methods yields the age of the rocks at the Early- the Late Triassic (Charusiri et al., 1993; Khosithanon, 2008; Khin Zaw et al., 2014). The Central Granitic Belt covers the most area of granitic rocks in Thailand. It is well exposed in the area of Chiang Rai, Chiang Mai, Lampang and Lamphun Provinces in the north, Rayong Province in the east and Surat Thani, Nakhon Si Thammarat, Songkhla and Yala Provinces in the south. The granitic rocks in this belt are different from those of the Eastern Belt in both origin and geological environments. It is characterized by porphyritic coarse-grained, biotite-rich plutons. Feldspartic megacrysts are common while mafic mineral such as hornblende are rare (Charusiri et al., 1993). Geochemical data reveal that the rocks were originated from the partial melting of pre-existing crustal rocks and it was classified as the S-type granitic affinity based upon discrimination plot of Na_2O versus K_2O (Charusiri et al., 1993; Putthapiban, 2002). Radiometric dating studied by ^{40}Ar-^{39}Ar and U-Pb zircon dating methods indicates that the age of the rocks is the Late Triassic - the Early Jurassic (Charusiri et al., 1993; Khosithanon, 2008). The Western Granitic Belt covers a much smaller area than the other belts. It is well exposed as isolated granitic stocks in the western most part of Tak and Kanchanaburi Provinces and numerous plutons in Ranong, Phang Nga and Phuket Provinces. The granitic rocks in this zone are characterized by medium- to coarse-grained equigranular hornblende to porphyritic biotite-muscovite with megacrystic alkali-feldspar (Mahawat, 1984; Putthapiban, 1992). Geochemically, using the plot of Na_2O versus K_2O, the rocks were interpreted to have been formed by the partial melting of the pre-existing rocks within the crust which is more than 90 % of the granitic rocks in this belt are of S-type and subordinate I-type in some localities (Charusiri et al., 1993; Putthapiban, 2002). The geochronological data indicate that the rocks were formed in the Late Cretaceous-the Early Tertiary (Charusiri et al., 1993, Putthapiban, 1992).

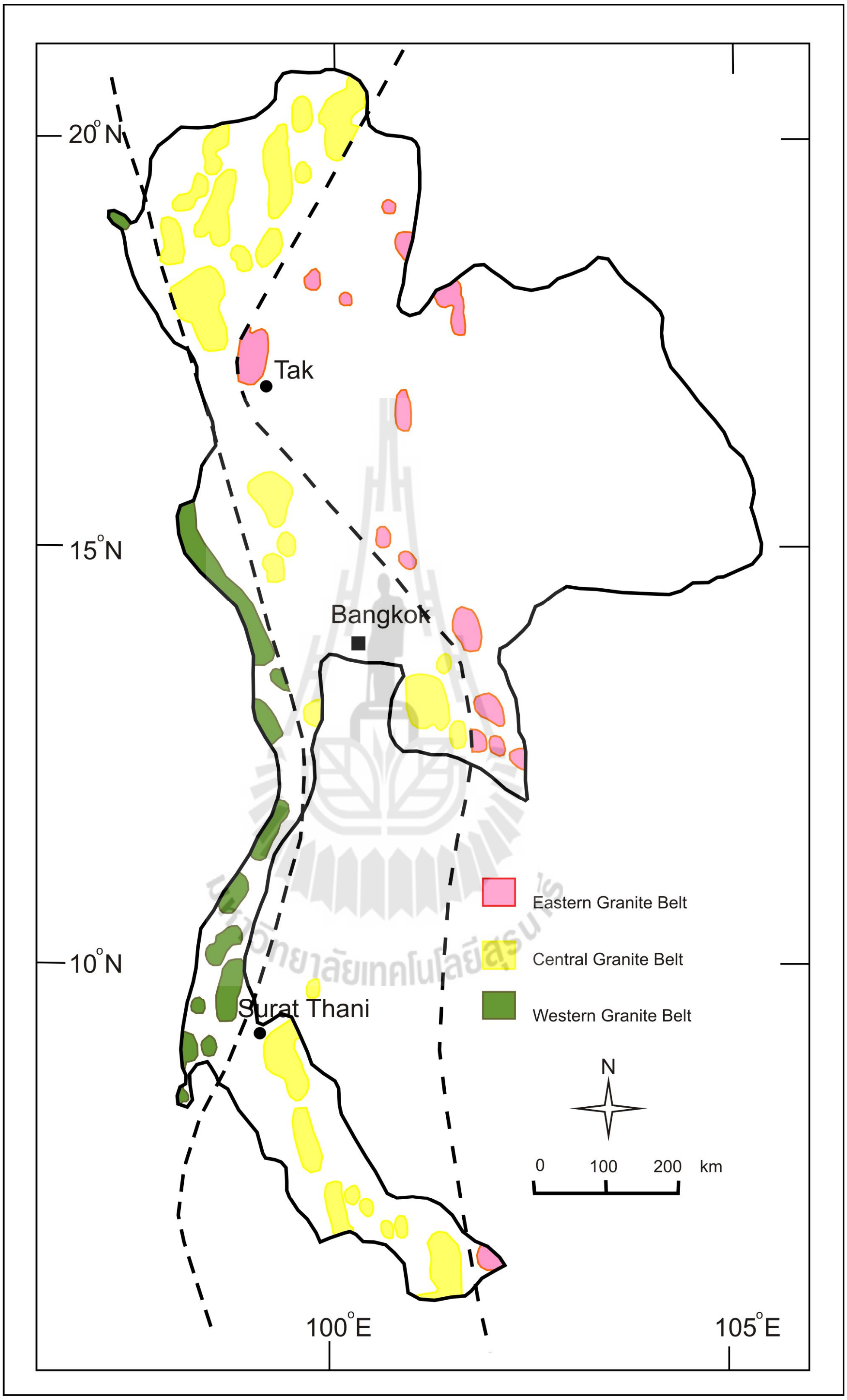


Figure 2.5 Distribution of granitoids rocks in Thailand (after Charusiri et al., 1993)

Volcanic rocks

The volcanic rocks are generally divided into three major clusters based on distinctive age of eruption (used is here); the Pre-Jurassic, Triassic-Jurassic and Cenozoic volcanic rocks.

The Pre-Jurassic volcanic rocks are mostly distributed in Thailand. It was categorized by Panjasawatwong et al. (1997; 2003) into four volcanic belts based on a regional compilation of occurrence, i.e., Chiang Mai-Chiang Rai, Tak -Lampang-Chiang Khong, Nan-Chantaburi and Loei-Phetchabun-Phai Sali volcanic belts (Figure 2.6). The Chaing Mai-Chiang Rai volcanic belt exposes approximately in the north-south direction from Chiang Rai through Chiang Mai to Li, Lamphun Provinces. They are composed of varying mafic volcanic rocks having equigranular, fine- to medium-grained texture, and consist largely of plagioclase, clinopyroxene and olivine. It is believed to have been erupted in the Carboniferous to the Permian time based on its stratigraphic relation (Barr and Charusiri, 2011). Geochemical study by Phajuy et al. (2005) on mafic volcanic rocks indicates that the rocks may have been formed in a major ocean basin rather than in a mature back-arc basin as interpreted by Barr et al. (1990). The Tak-Chiang Klong volcanic belt is exposed east of the Chaing Mai-Chiang Rai volcanic belt. It extends northward from Tak through Lampang and Phrae to Mae Khong River at Chiang Klong, Chiang Rai Provinces. It consists mainly of felsic volcanic rocks, e.g., rhyolite with subordinate intermediate and pyroclastic rocks. Geochemical study reveals that the rocks are formed in continental volcanic arc setting (Qian et al., 2013; Barr et al., 2000; 2006). U-Pb zircon dating indicates that the rocks were erupted at the Middle Triassic to the Late Triassic time (Qian et al., 2013; Khositanont, 2008, Srichan et al., 2008; 2009; Barr et al., 2000; 2006). The Nan-

Chanthaburi Suture Zone is located between the Tak-Chiang Klong volcanic belt and the Loei-Phetchabun-Phai Sali volcanic belt. In the Nan Suture Zone the volcanic rocks are composed of variable sizes of blocks embedded in serpentinite melange of the Carboniferous-Permian Pha Som Metamorphic Complex and the Late Permian to the Middle Triassic basaltic andisite Pak Pat volcanic rocks (Singharajwarapan, 1994). The Loei-Phetchabun-Phai Sali volcanic belt runs NE-SW from Loei through Phetchabun to Phai Sali, Nakhon Sawan Provinces. It is composed of lavas and pyroclastic rocks of a wide range of composition. In the Loei area the volcanic rocks are commonly divided into three sub-belts, i.e., eastern, central and western sub-belts. The eastern sub-belt is dominated by the rhyolitic rocks. It was interpreted to have been formed by crustal melting (Intasopa and Dunn, 1994). Geochronological study points out that the rocks were initially erupted in the Silurian time (Khin Zaw et al., 2014; Khositanont, 2008). The central sub-belt is dominated by basaltic rocks. It was interpreted as the mid-oceanic-ridge basalt and ocean island basalt which was erupted in the Late Devonian to the Early Carboniferous (Panjasawatwong et al, 1997; Intasopa and Dunn, 1994). The western sub-belt is dominated by the intermediate volcanic rocks e.g. andesite. The geochemical study shows that the rocks are formed in volcanic arc rocks an east dipping subduction zone (Khomkhan et al., 2013). The extensive study of U-Pb zircon dating indicates that the age of the volcanic rocks in the western sub-belt of the Loei and Phetchabun areas are constrained at the Late Permian to the Middle Triassic (Khin Zaw et al., 2014; Salam et al., 2014; Kamvong et al., 2014).

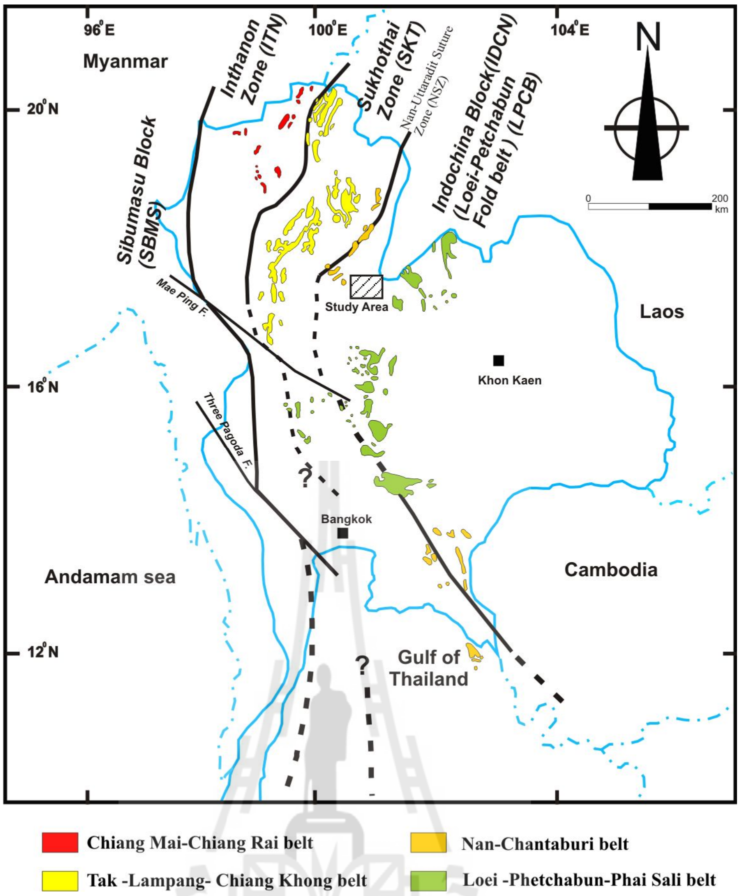


Figure 2.6 Distribution of the pre-Jurassic volcanic rocks in Thailand (after Panjasawatwong et al.,1997)

The Late Triassic to the Jurassic volcanic rocks exposes only in northern Thailand covering an area of Nan, Pha Yao and Phrae Provinces. The rocks, Ms2 formation (Drumm et al., 1993), are characterized by acid to intermediate volcanic rocks. There are no chemical and geochonological studies on the rocks. The age of the rocks is constrained on the basis of stratigraphic relation which are interpreted to have been erupted in the Late Triassic to the early Late Jurassic?.

The Cenozoic volcanic rocks, basaltic and rhyolitic, are associated with basaltic rocks scattering throughout Thailand but it is dominated in the eastern part of the country along the western and southern margin of the Khorat Plateau as shown in Figure 2.7. The rhyolitic associated with basaltic rocks are well exposed in the center of the country within Phetchabun, Lopburi and Saraburi Provinces. Geochronological study in basaltic rocks indicates that the igneous activity has begun since the Oligocene and continued until as recently as the Pleistocene (Barr and Cooper, 2013; Sutthirat et al., 1994; 1999; Intasopa et al., 1995). The rocks were interpreted in association with extensional basins formed during the Oligocene to the Late Miocene in response to complex regional tectonic stress related to the collision of India with the Eurasia (Morley, 2012).

2.1.2 Geologic setting of the study area and vicinity

Geographically of the Nakhon Thai region is dominated by a series of parallel mountain chains as the sequences of the Late Jurassic to the Cretaceous non-marine red beds of the Khorat Group and younger units (Racey, 2009; Racey et al., 1996) and forms a broad NE-SW trending synclinorium situated in the Indochina Block. These mountain chains are bounded by the series of the Paleozoic (pre-Khorat Group) of the Nan-Uttaradit Suture Zone to the west and the Loei- Phetchabun Fold

Belt to the east (Figure. 4.1a). As shown in the geologic map scale 1: 2,500,000 (Figure 4.1b) of the Department of Mineral Resource (1999) the red beds of the Khorat Group are well discovered in both regions; the Nakhon Thai region and the Khorat Plateau (Malila, 2005). There are the similar sequences dominated by the alternated beds of braided and meandering river systems (Meesook, 2000). Subsequently, the Khorat Group is overlain unconformably by the succession of rock salt beds of the Maha Sarakham Formation and aeolian sandstones of the Phu Tok Formation (Figure 4.2) (Sattayarak and Polachan, 1990; Lovatt Smith et al., 1996; Racey, 2009). However, in the Nakhon Thai region an aeolian? sandstone is named as the Khao Ya Puk Formation rather than the Phu Tok Formation, although they lithostratigraphy is identical (Meesook, 2011; Sha et al., 2012). Accordingly, the uppermost formations in the Nakhon Thai region are composed of the Khao Ya Puk (equivalent to the Phu Tok Formation) and the Phu Khat Formation whilst on the main land of the Indochina Block (the Khorat Plateau) only the Phu Tok Formation have been reported (Meesook et al., 2002). To the west of the Nakhon Thai region the Nan-Uttaradit Suture Zone has been interpreted as a remnant of a closed back arc basin (the Nan back arc basin) (Sone and Metcalfe, 2008; Ueno and Hisada, 2001) or small ocean (Yang et al., 2008). It is a narrow ophiolite zone predominated by the pre-Khorat Group of the Carboniferous to the Permian Pha Som Metamorphic Complex. It is overlain by fault contact with the Permo-Triassic? Pak Pat volcanic rocks and the Upper Triassic conglomerate of the Nam Pat Group (Singharajwarapan and Berry, 2000; Luddecke et al., 1991; Barr and Macdonald, 1987).

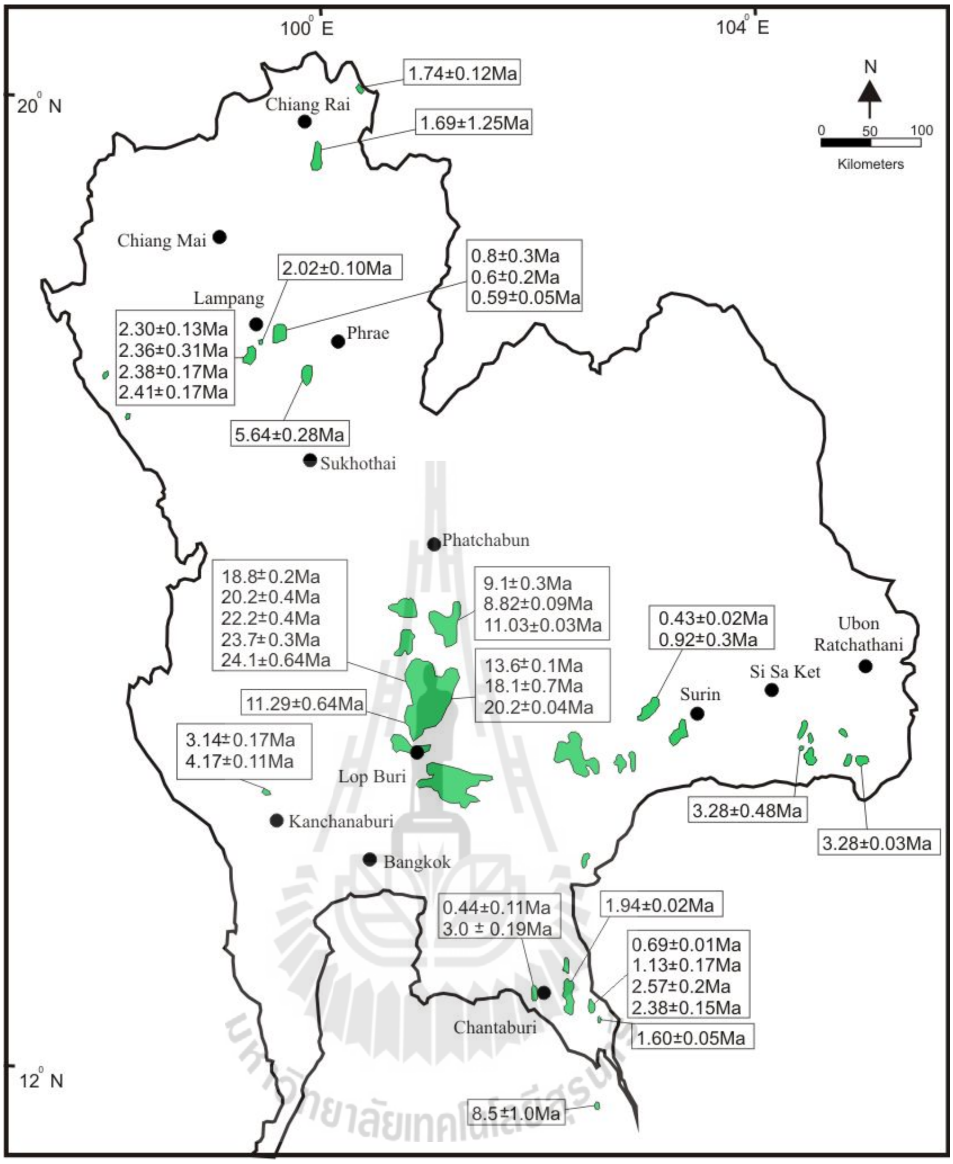


Figure 2.7 Distribution of the Cenozoic volcanic rocks in Thailand with age. (after Barr and Cooper, 2013)

To the east of the Nakhon Thai region, the pre-Khorat Group in Loei-Phetchabun Fold Belt is formed as a high mountain range in the western part of the Indochina Block. It comprises predominantly the succession of the Middle Paleozoic to the Early Mesozoic rocks which are composed of low-graded metamorphic rocks of the Silurian Na Mo Formation, the Devonian to the Lower Carboniferous Pak Chom Formation, the pre-orogenic, the synorogenic and the post-orogenic events of the Permian Nam Duk Formation, the platform Permian limestone of the Saraburi Group and the Fluvio-lacustrine of the Upper Triassic Huai Hin Lat Formation as well as the igneous rocks of a long range from the Silurian to the Tertiary in age. Details of each rock unit in the study area and its vicinity are briefly described as follows:

2.1.2.1 The pre-Khorat Group in the Nan-Uttaradit Suture Zone

The pre-Khorat Group in the Nan-Uttaradit Suture Zone is composed of the Pha Som Metamorphic Complex (the Pha Som Ultramafics and the Pha Som Group) of the probably the Permo-Carboniferous age, the Premo-Triassic Pak Pat Volcanic and the Triassic Nam Pat Group. Details of each rock units are as below.

The Pha Som Metamorphic Complex

The name of Pha Som Metamorphic Complex is used as a collective name of the Pha Som Ultramafics and the Pha Som Group. They have different lithology but similar structural history (Singharajwarapan, 1994). The Pha Som Ultramafics comprises mixed variety of rock, ranging from metavolcanic rocks, mafic-ultramafic plutonic rocks and amphibolites to metamorphosed pelagic-hemipelagic sedimentary rocks. It is characterized by block of various rock types in sepentinite matrix which was interpreted by Panjasawatwong (1991) as a serpentinite mélange. The age of ultramafic blocks was dated by the U-Pb zircon as the Late

Ordovician (Gibson, 2009) and the Late Devonian to the Middle Carboniferous (Yang et al., 2009) while the block of chert containing the radiolarian was dated at the Middle to the Late Permian. Based on these data the Late Permian age is suggested for the assembly of the Pha Som Ultramafics. The Pha Som Group is dominated by the low grade metamorphic rocks. Metagreywackes are the main rock type with subordinate phyllite. As suggested by Singharajwarapan (1994) the Pha Som Ultramafics unit is a tectonic contact rather than intrusive contact with the surrounding low-grade metagreywackes of the Pha Som Group. The thickness of the Pha Some Metamorphic complex is unknow due to the complex deformation style of the rocks.

The Pak Pat Volcanic

The Pak Pat Volcanic is composed of basaltic andesites and minor basalt, dacites and tuff. Geochemical characteristic indicated that the Pak Pat Volcanic rocks are oceanic island basalt (Singharajwarapan et al., 2000). In terms of composition, they are different from the Lampang-Phrae volcanic belt because of the contrasting lithological characteristic of these two volcanic suites. The volcanic rocks of the later group are dominated by felsic volcanic rocks (e.g. rhyolite and associated tuffs rather than basaltic andesite) while the Pak Pat volcanic is mainly of basaltic andesites. The thickness of the Pak Pat Volcanic was estimated from the outcrop width and the attitudes of the adjacent unit at 1500 m. They are fault contract with the Pha Som Group and is overlain unconformably by the Triassic Nam Pat Group (Singharajwarapan, 1994). There is no radiometric-age dating for the rocks unit but the age of the Pak Pat Volcanic was inferred from the stratigraphic relation as the Permo-Triassic age.

The Nam Pat Group

The Nam Pat Group was given name by Bunopas (1981) and described as the large turbidite fan. It consists of two formations, the Huai Lat Formation (lower unit as the proximal fan) and the Huai Bo Khong Formation (upper unit as more distal fan). The Huai Lat Formation is characterized by the volcaniclastic conglomerate with subordinate sandstone. The pebbles in conglomerate are of andesite, basalt, quartz, chert and limestone. The pebbles of limestone contain the Middle Triassic microfossil (Luddecke et al., 1991). The Huai Lat Formation is therefore considered as the Late Triassic in age. The thickness of the formation was estimated by Bunopas at 500 m but Singharajwarapan (1994) argued that is more than 1000 m from traverse section measurement. The Huai Bo Khong Formation conformably overlies the Huai Lat Formation. It is consists of greenish-gray turbiditic sandstone interbedded with shale and siltstone. The thickness of the formation is estimated more than 1500 m along the type section (Singharajwarapan, 1994). The Huai Bo Khong Formation is overlain unconformably by the Khorat Group.

2.1.2.2 The pre-Khorat Group in the Loei-Phetchabun Fold Belt

The pre-Khorat Group in the Loei- Phetchabun Fold Belt is composed of the long sequence of different rock types since the Early Paleozoic to the Late Mesozoic time. The details of each rock units are described as following.

The Na Mo and the Pak Chom Formations

These formations are possibly the oldest rock in the Northeast region. They are well exposed in a north-south mountain belt in the eastern border between Loei and Nong Khai, Udon Thani and Nong Bua Lam Phu Provinces. The Na Mo Formation is low grade metamorphic rocks. It consists of phyllite, chlorite, politic schist, metatuff and quartzite. The Na Mo Formation is overlain unconformably by the Devonian- the Early Carboniferous Pak Chom Formation (Chairangsee et al., 1990). The Na Mo Formation is therefore regarded as the Silurian in age. The Pak Chom Formation is roughly divided into two members, e.g., the lower and the upper members (Bunopas, 1992). The lower part is the Ban Nong member which is composed mainly of shale, limestone, minor tuff and occasional chert. The upper part is Pak Chom Chert member. It well exposed in the east of Loei Province. The radiolarian banded chert is a main constituent of the Pak Chom Chert member. Paleontological studies on radiolarian and coral fossil indicates that the Pak Chom Formation is the Devonian to the Early Carboniferous in age (Udchachon et al., 2011; Saesaengseerung et al., 2008; Fontain et al., 2003; Shasida et al., 1993). The Pak Chom Formation is overlain unconformably by the Saraburi Group which is evident by the Mid-Carboniferous Orogeny (Booth and Sattayarak, 2011).

<u>The Saraburi Group</u>

The Saraburi Group is restricted to the Late Carboniferous to the Middle Permian which the rocks unit varies from place to place. It overlies unconformably on the older rock and in turn it is overlain unconformably by the Mesozoic rocks.

The Late Carboniferous Wang Saphung Formation

The Wang Saphung Formation underlies conformably the massive Permian limestone. Generally, it has been informally called by petroleum geologists as the “Lower Clastics or the Si That Formation” of the “Saraburi Group” (Racey, 2011). It is delineated from the seismic profiles and occupies a section between the base of the massive limestone and the Mid-Carboniferous Unconformity (Booth and Satayarak, 2011). According to the subsurface seismic profiles, the base of the Wang Saphung

Formation is marked by a moderate -to-low angle unconformity above either the Pak Chom Formation or the basement (Booth and Sattayarak, 2011). The rocks are characterized by siliclastics (conglomerate, shale, and sandstone) interbedded with limestone and volcanic rocks. It is well exposed on the surface in the northwestern margin of the Khorat Plateau particularly in the Loei area which the rocks is overlies unconformably the Pak Chom Formation.

The Permian rocks

Wiclchowsky and Young (1985) divided the Permian rocks in this region into three main paleogeographic provinces based on the basis of facies characteristics, i.e., western carbonate platform (or Khao Khwang Platform), central mixed siliciclastic-carbonate basin (or Nam Duk Basin) and eastern mixed carbonate - siliciclastic platform (or Pha Nok Khoa Platform). The Khao Khwang Platform consists mainly of shallow marine fossiliferous limestone and dolomite. As state by Hintong et al., (1985), the Permian rocks in this region can be divided into six formations, namely as Phu Phe, Khao Khwang, Nong Pong, Pang Asok, Khao Khad, and Sap Bon in ascending order. In the Nam Duk Basin, the Nam Duk Formation is proposed by Chonglakmani and Sattayarak (1978) for the rocks sequence in this region. It is composed of the succession of pelagic sediment of deep marine in the lower part (e.g. chert, shale and allodapic limestone) grading up into flysh facies in the middle part (e.g. grawackes sandstone alternated with shale) and shallow marine molasses in the upper part (sandstone and shale) (Helmcke and Kraikhong, 1982). The Pha Nok Khoa Platform is composed of two main facies rocks including carbonate and silisiclastic. The Pha Nok Khao Formation is characterized by the massive bed of gray limestone facies with some nodular and lenticular chert. Fossils assemblages are included fusulinids and corals that indicate the Early to the Middle Permian in age (Ueno and Charoentitirat, 2011). The Hua Na Kham Formation is siliciclastic facies which is normally lying conformably on top of the Pha Nok Khao Formation. It is composed of sandstone, shale and thin bedded or lenses of limestone.

The Huai Hin Lat Formation

This formation was first given name by Iwai et al. (as cited in Chonglakmani and Sattayarak, 1978) as a basal unit of the Khorat Group. They described its type locality along the Huai Hin Lat in Chumpae District, Khon Kaen Province. Thereafter Chonglakmani and Sattayarak (1978) study the Huai Hin Lat Formation in more details which crop out at the NW of the Khorat Plateau and show that the formation comprise five member: (in ascending order) the Pho Hai, Sam Khaen, Dat Fa, Phu Hi and I Mo Member. The formation is interpreted as the non-marine sediment including conglomerate, black shale and grey sandstone of the Sam Khaen, the Dat Fa and the Phu Hi members with occasionally influenced by volcanic activity of the Pho Hai and the I Mo members under the fault bounded basin in humid to semiarid condition (Chonglakmani, 2011). The formation lies unconformably on the Permian and older rock as the result of the Indosinain I event and in turn it is overlain unconformably by the Nam Phong Formation of the Khorat Group as marked by the Indosinain II event (Booth and Sattayarak, 2011). As stated by Chonglakmani (2011) the Huai Hin Lat Formation can be assigned at the Early to the Middle Norian age based on the diverse and abundant fauna and flora.

2.1.2.3 The Khorat Group

The Nam Phong Formation

The Nam Phong Formation was given name by Ward and Bunnag (1964) as the type locality located in Wang Saphung District, Loei Province. Its stratigraphic successions are mainly of clastics sedimentary rock: consisting of red-brown micaceous sandstone, conglomerate, siltstone and mudstone. The environment of deposition is considered as fluviatile origin (Chonglakmani, 2011) which commence after the end of deformation event (Indosinain II) of half garben basin of the Huai Hin Lat Formation. The subsurface data indicated that the Nam Phong Formation can be divided in to two subunits; lower and upper Nam Phong member (Booth and Sattayarak, 2011). The lower Nam Phong member is rarely exposed at the surface. Consequently, it is essentially restricted to the central part of the Khorat Basin. The lower Nam Phong member is underlain unconformably by the Huai Hin Lat Formation (Indosinain II) and in turn overlain unconformably by the upper Nam Phong member (Indosinain III event) (Booth and Sattayarak, 2011). The age of the Nam Phong Formation is generally controversial. The evidence from the bivalve and vertebrate fossil indicated that the Nam Pong Formation should be the Triassic in age and the overlying sequence (The Phu Kradung Formation) is a Jurassic (DMR as cited in Meesook and Saengsrichan, 2011). In contrary, Racey and Gooddall (2009) gave a different age base on their palynological studies. They claim that the lower Nam Phong member is the Late Triassic (Rhetian) and the upper Nam Phong member is not older than the middle Early Jurassic and no younger than the Late Jurassic. As the result of these, Racey and Gooddall (2009) present the depositional hiatus between the lower and the upper Nam Phong members.

The Phu Kradung Formation

The Phu Kradung Formation was given name by Ward and Bunnag (1964) which the type section is located on the Phu Kradung Mountain in Loei Province. The rocks consist predominantly of maroon siltstone while sandstone and conglomerate are subordinate. As stated by Meesook and Saengsrichan (2011) the rocks show locally fining- thinning-upward sequence. Nevertheless, Booth and Sattayarak (2011) have shown the coarsening-upward sequence throughout the formation on the basis of subsurface study. The environmental deposition is considered as alluvial at the lower part and grade into fluvial in the upper part under meandering river system (Meesook and Saengsrichan, 2011; Boot and sattayarak, 2011; Racey et al., 1996). The Phu Kradung Formation lies conformably on the upper Nam Phong member and show gradational contact with the overlying formation (the Phra Wihan Formation). Racey and Gooddall (2009) assign the age of the Phu Kradung Formation at the Late Jurassic - the Early Cretaceous based on the basis of palynological evidence.

The Phra Wihan Formation

The Phra wihan Formation is composed entirely of white, coarse grained, well sorted texture, arkosic to othoquartzitic. It is rare of siltstone, mudstone and conglomerate (Meesook and Saengsrichan, 2011). Their thicknesses vary from 50 to 350 m, with tabular cross-bedding being observed in the sandstone beds (Racey et al., 1996). This dominant sandstone bed is interpreted to have been deposited by high energy, shallow braided stream with subordinate meandering stream (Racey et al., 1996). The Phra Wihan Formation is overlain conformably by the Sao Khua Formation and lie conformably on the Phu Kradung Formation with age constraint at the Early Cretaceous (not older than Berriasian) (Racey and Gooddall, 2009).

The Sao Khua Formation

The type locality of the Sao Khua Formation is located at Km35 on the Udon Thani - Nong Bua Lamphu road with 720 m thick (Ward and Bunnag_1964). The successions of the Sao Khua Formation are generally composed of an alternation of reddish-brown conglomeratic sandstone, siltstone and mudstone with calcrete and silcrete horizon at the base (Meesook, 2011). It was interpreted to have been deposited by low-energy of meandering stream and extensive flooding under warm and cool semiarid condition. According to Meesook (2011) the most vertebrate fossil that have been found in the Khorat Plateau have recognized in this formation. Previously, the age of the rocks had been assigned to the Upper Jurassic based on the basis of diverse vertebrate fauna (Racey et al., 1996). However, Racey and Gooddall (2009) suggested that the Sao Khua Formation should not older as the Jurassic age but it should be in the Berriasian-Barremian (the Early Cretaceous) based on the polynological data. The Sao Khua Formation overlies conformably on the Phra Wihan Formation, and is conformably overlain by the Phu Phan Formation.

The Phu Phan Formation

The Phu Phan Formation consists mainly of light-buff to brown, medium- to coarse-grained, well sorted sandstone with sub-rounded texture. It is rare of siltstone and mudstone but pebbly conglomerate with well-rounded quartz pebbles and subordinate mudstone intraclasts are severally found (Racey et al., 1996). Their thicknesses are 183 m at the type section on the Phu Phan Range (Ward and Bunnag, 1964). The dominant sandstone beds are interpreted to have been deposited by high energy of braided stream whilst subordinate fine-grained sediment represents floodplain deposit (Racey et al., 1996). The Phu Phan Formation is overlain conformably by the

Khok Kruat Formation, and lie conformably on the Sao Khua Formation with depositional age in the Barremian-the Aptian (Racey and Gooddall, 2009).

The Khok Kruat Formation

The Khok Kruat Formation consists mainly of thin- to thick-bedded of light gray to light brown, fine- to medium-grained micaceous or arkosic sandstone and often contain clay rip-up clasts. The sandstone beds are occasionally interbedded with siltstone and mudstone with subordinate conglomerate beds (Meesook, 2011). Subsequently, the sandstone beds generally show cross-bedding with some bi-directional cross lamination (Racey et al., 1996). As the result of that, the formation has been interpreted to be deposited by predominantly meandering stream and flood plain with occasional marine influence (Racey et al., 1996; Meesook, 2011). The Khok Kruat Formation is overlain unconformably by the Maha Sarakham Formation, and lies conformably on the Phu Phan Formation (Sattayarak and Polachan, 1990; Lovatt-Smith et al. 1996) with constrained age to the late Early Cretaceous (Aptian) (Racey and Gooddall, 2009).

2.1.2.4 The post-Khorat Group

The Maha Sarakham Formation

The Maha Sarakham Formation is rarely exposed on the ground surface. As the result of that, the studied have been done mainly on subsurface study. Normally, this formation is composed of three layers of evaporites and separated by reddish brown claystone scattered by anhydrite and some thin-bedded of fine-sandstone which in some place only two layers of evaporites are encountered (Booth and Sattayarak, 2011; Japakasetr and Suwanich, 1982). Potash horizons have also been reported at the lower evaporites layer (Racey et al. 1996; Japakasetr and

Suwanich, 1982). Utha-Aroon (1993) reported that the Maha Sarakham Formation was deposited in the continental setting based on the sedimentary scheme. This idea has been, subsequently, supported by the study of Racey et al. (1996) on the basis of sedimentological and diagenetic studies. They claimed that the Maha Sarakham Formation was deposited under hypersaline, land-lock lake within an arid continental desert environment. Hansen et al. (2002) and Sattayarak et al. (1991) pointed out that the depositional age of the formation is the Albian to the Cenomanian in age (the Mid-Cretaceous) based on the basis of radiometric dating and fossil assemblage. Additionally, an angular unconformity at the base of the Maha Sarakham Formation was reported as boundary between the Maha Sarakham Formation and the older formation by the Mid-Cretaceous inversion (Lovatt Smith et al., 1996). The formation is overlain conformably by the Phu Tok Formation. As the result of the different environment of deposition and the occurrence of an unconformity between the Maha Sarakham Formation and the underlying Khorat Group, the Maha Sarakham was suggested to exclude from the Khorat Group by Lovatt Smith et al., 1996 and Booth and Sattayarak, 2011.

The Phu Tok or the Khao Ya Puk Formation

The Phu Tok Formation is well exposed in the northern and central part of the Khorat Plateau. According to Booth and Sattayarak (2011) this formation has been completely removed by the Tertiary to the recent erosion in many places. However, the subsurface profiles of 2D seismic survey reveal that in the center of the basin the Phu Tok Formation was preserved more than 500 m thick (Booth and Sattayarak, 2011). In the Nakhon Thai Basin, Kosuwan (1990) reported the exposure of the Khao Ya Puk Formation which lies conformably on the older rock (the Maha Sarakham Formation). In addition, its lithostratigraphy can be correlated with the Phu Tok Formation in the Khorat Plateau (Meesook, 2011; Hasegawa et al, 2010; Heggamann, 1994).

As stated by Monjai (2006) and Meesook (2011) the complete succession of the Phu Tok Formation comprises three informal members: (in ascending order) the Nawa, the Kham Takha and the Phu Tok Noi members. The Nawa member is characterized by reddish brown claystone with disseminated gypsum at the base and calcite vugs in the upper part. The Kham Takha member consists predominant of fine-grained sandstone interbedded with siltstone and claystone. Desiccation cracks are a common sedimentary structure found in the Kham Takha member. The Phu Tok Noi member is composed of brick-red, fine- to medium-grained, thick-bedded sandstone with large-scale cross-bedding. In summary, coarsening upward is present throughout the sequence of the Phu Tok Formation.

The presence of disseminated gypsum at the base of the lower member and coarsening upward sequence throughout the formation indicated that the Phu Tok Formation had been transforming from evaporites lake deposit into shallower lake at the lower sequence (the Nawa member) and thereafter gradually change into fluvial system in the middle member (the Kham Takha member). Finally, the large-scale cross-bedding sandstone are evident an aeolian system in the Phu Tok Noi member with a semi-arid to arid palaeoclimate (Meesook, 2011; Booth and Sattayarak, 2011; Sattayarak and Polachan, 1990). Based on palynomorphs, it is considered to the Late Cretaceous in age (Lovatt Smith et al., 1996). It overlies conformably on the Mid-Cretaceous Maha Sarakham Formation which in turn it is overlain unconformably by the younger formation.

The Phu Khat Formation

The Phu Khat Formation consists of fine- to medium-grained lithicarenite of reddish brown to purple brown in colour. It is intrebedded with siltstone and conglomerate. The pebbles of conglomerate contain quartz, chert, sandstone, siltstone, volcanic and a few limestones. As reported by Kosuwan (1990) the Phu Khat Formation overlies conformably on the Khao Ya Puk Formation and it represents as the uppermost sequence of the red beds in the Nakhon Thai region. In contrast, the later study, e.g., Assavapatchara and Raksasakulwong (2010); Meesook et al. (2002) and Heggemann (1994) report the unconformity between the Phu Khat Formation and the older formation. Heggemann (1994) studied sedimentary evolution of the Khorat Group (the Upper Triassic to the Paleogene) in the Khorat Plateau and the northern Thailand. He found that the uppermost red beds formation in the Khorat Group is the Phu Khat Formation which it is accumulated only in the Nakhon Thai region. Based on the stratigraphic relation, the Phu Khat Formation was believed to be deposited in the Late Cretaceous to the Early Tertiary (Assavapatchara and Raksasakulwong, 2010; Meesook et al., 2002; Heggemann, 1994).

2.2 Tectonic review of Thailand

It is widely accepted that Thailand is divided into following four tectonic zones (from west to east) including the Sibumasu Block, the Inthanon Zone, the Sukhothai Zone and the Indochina Block (Figure 4.1a). The Indochina Block and the Sibumasu Block are two main continental blocks that believed originally derived from the Gondwana in the Devonian and the Permian respectively (Metcalfe, 2011; 2013; Sone and Metcalfe, 2008; Li et al., 2004; Ueno and Hisada, 2001). After a long time northward drifting, the Sibumasu Block collided and amalgamated with the Indochina Block in the southern Eurasia margin by closing of the Palaeo-Tethys in western Thailand during the Triassic time (Sone and Metcalfe, 2008; Feng et al, 2005; Chonglakmani, 2002; Ueno and Hisada, 2001). The Inthanon Zone has been considered as an extensive accretionary complex resulted from the closure of Palaeo-Tethys (Hara et al., 2009; Sone and Metcalfe, 2008). It is composed of various rock types range in age from the Devonian to the Triassic. The Sukhothai Zone or the Sukhothai Terrane of Barr and Macdonald (1991) and the Sukhothai Fold Belt of Bunopas (1981) was interpreted as a remnant of the Permo-Triassic island arc induced by subduction of the Palaeo-Tethys (Sone and Metcalfe). It is composed mainly of the fold and fault sequence of the Paleozoic - the Mesozoic sedimentary and igneous rocks. The Sukhothai Zone was divided from the Indochina Block by the Nan-Uttaradit Suture Zone to the east. The Nan-Uttaradit Suture Zone has been interpreted as a remnant of a closed back arc basin (the Nan back arc basin) (Sone and Metcalfe, 2008; Ueno and Hisada, 2001) or small ocean based on the basis of fauna diversity (Yang et al., 2008). It is a narrow ophiolite zone which is predominated by the Carboniferous to the Permian Pha Som Metamorphic Complex. The Pha Som Metamorphic Complex comprises basic and ultramafic igneous rocks, schists, meta-greywacke, serpentinite and bedded chert. It is overlain by fault contact with the Permo-Triassic? Pak Pat volcanic rocks (Singharajwarapan and Berry, 2000; Barr and Macdonald, 1987). The Nan back arc basin may start rifting during the Late Ordovician - the Early Carboniferous as evidenced by the U-Pb zircon dating age of the gabbro rocks (Yang et al., 2009; Gibson, 2009). It was closed and amalgamated with the Indochina Block in Permian-Triassic (Sone and Metcalfe; 2008;

Chonglakmani, 2002). Since the Triassic, the Indochina Block and the Sukhothai Zone has joined together as a one continent by the closure of the Nan-Uttaradit back arc basin (Chonglakmani, 2002).

In the Late Triassic the Indochina Block experienced an extensional phase which created the half garben basins with deposition of the fluvio-lacustrine Huai Hin Lat Formation (Chonglakmani, 2011; Chonglakmani and Sattayarak, 1987). While in the Sukhothai Zone the Triassic Lampang Group was deposited in marine environment (Chonglakmani, 2011). After the deposition of the Triassic sequence the continental red bed has blanketed in the Indochina Block and the Sukhothai Zone while in western of Thailand was still covered by the marine Jurassic sediments (Meesook and Seangseechan, 2011). In the Cretaceous Thailand is believed to be one continent and entirely covered by continental sediment. The deposition of the continental red bed is dominated in the Cretaceous (Racey and Goodall, 2009) which is known as the Khorat Group in the Khorat Plateau or the Indochina Block. The Khorat Group extends beyond the boundary of the Indochina Block to the Sukhothai Zone where is also to the Nakhon Thai region (part of Loei-Phetchabun Fold Belt) and to the Central Plain of Thailand (Morley, 2012). In the Mid-Cretaceous the inversion took place after the end of the Khorat Group accumulation (Racey, 2009; Lovatt Smith et al., 1996). The inversion in the Mid-Cretaceous leads to the restricted depositional basin of the red bed. Subsequently, the associated three rock salt layers of the Maha Sarakham Formation began to deposit under the hyper saline land-lock lake basin within an arid condition at the Mid-Cretaceous (Meesook, 2000; Racey et al., 1996). The basin was subsequently covered by the Phu Tok Formation in the Late Cretaceous under the arid desert environment (Meesook, 2011; Hasegawa et al, 2010; 2012). Finally, in the Late Cretaceous to the Early Paleogene the Southeast Asian region including Thailand was subject to strong deformation due to collision of the Greater India with the Eurasia (Morley, 2012).

2.3 Tectonic evolution of the red beds Khorat Group in the Indochina Block

Continental red beds of the Late Triassic to the Early Cretaceous in the Khorat Plateau and lateral equivalents are exposed over large areas of eastern Thailand, Laos, Cambodia and parts of Vietnam, southern Thailand, Peninsular Malaysia, the Yunan Basin and the Sichuan Basin in southern China (Racey, 2009; Figure 2.8). These are predominantly fluvial, alluvial and lacustrine facies (Racey and Goodall, 2009). Causes of different styles of basin evolution for the red beds in the Khorat Basin is generally poorly understood (Racey, 2009). Tectonic evolution model accounting for the deposition of the Khorat Group in NE Thailand have been proposed by a number of workers. In the recent review study, three proposed models are present as following:

1) The Khorat Group was the molasse sequence from the post-Indosinian Orogeny

This ideal concept was presented by Bunopas (1981) who claims that the Nan-Uttaradit Suture Zone is the main Paleo-Tethys located between the Shan-Thai (or the Sibumasu Block) and the Indochina Blocks. Bunopas (1981) stated that the two continental blocks were collided to each other in the Late Triassic which the Indochina Block trended to underthrust the Shan-Thai and form orogeny along the Nan-Uttaradit Suture Zone. After the collision, the erosions took place in the mountain and produced molasse deposited in the both sides of the suture. However, the most molasse sequences were developed in the Indochina Block since it forms as the underthrusting side. The molasse sequences had been deposited as a mega sequence of the non-marine, fluvial sandstone of the Khorat Group since the Late Triassic to Cretaceous as shown in Figure 2.9.

2) The Khorat Group was deposited in a thermal sag basin

This model was first presented by Cooper et al. (1989) who recognized the haft-garben basin developed in the lower Khorat Group (Huai Hin Lat Formation). Cooper et al. also demonstrated that the main Paleo-Tethys was located between the Shan-Thai and Indochina Blocks which run along the Nan-Uttaradit Suture Zone. However, as reported by Cooper et al. (1989) the collision of the two blocks was in the Early Triassic rather than the Late Triassic. After the collision, the Indochina Block was pulled apart obliquely due to the extensional collapse of the overthickened crust resulting from the orogen. Consequently, continental haft-garben basins were formed as the accommodation space for the Huai Hin Lat Formation to deposit in the Late Triassic. This process had been followed by a thermal cooling phase which was represented by a deposition of flat-lying of the mega sequence of the Mesozoic Khorat Group. The summation of this model is shown in Figure 2.10.

3) The Khorat Group was deposited in a foreland basin setting

This ideal concept has been presented by a group of workers who recognized the hiatus of the Khorat Group in the Jurassic (e.g., Lovatt Smith et al., 1996; Carter and Bristow, 2003; Racey, 2009). They reported that the Khorat Group has been mainly deposited in the Late Jurasic to the Early Cretaceous based on the basis of palynological study. They redefined the formation comprising in the Khorat Group only the six formations (in ascending order): the Upper Nam Phong, the Phu Kradung, the Pha Wihan, the Sao Khua and the Khok Kruat Formations which the lower and upper contacts are marked by the unconformity with the Upper Triassic Lower Nam Phong Formation and the Upper Cretaceous Maha Sarakham Formation respectively. They concluded that the provenances of the Khorat Group were derived from the Qinling Orogeny Belt of central China and some component of recycled inverted foreland basin sediments, both of which experienced the Late Jurassic to the Early Cretaceous deformation. This ideal model is supported by the palaeocurrent, sandstone petrography and the U-Pb zircon data which are consistent with a hinterland located within the Qinling Orogenic Belt (Carter and Bristow, 2003). Moreover, this point of view is also coincided with the paleomagnetic study in the Khorat Group which indicated that during the deposition of the Khorat Group (mainly the Late Jurassic to the Early Cretaceous) the Khorat Basin was close to the Qinling Foreland Basin (Charusiri et al., 2006). So based on these evidences, Carter and Bristow (2003) make the conclusion that the original position of the Khorat Basin during the deposition of the Khorat Group is closed to the Qinling Foreland Basin and the Khorat Group was deposited under the foreland basin associated with flexural subsidence as same as the Qinling Foreland Basin. Thereafter, the Khorat Basin or the Indochina Block was southward movement relative to the South China Block to the present location as the result of the left lateral displacement on the Red River Fault since the Late Cretaceous due to the Himalayan Orogeny. The proposed model of Carter and Bristow (2003) is shown in Figures 2.8 and 2.11.

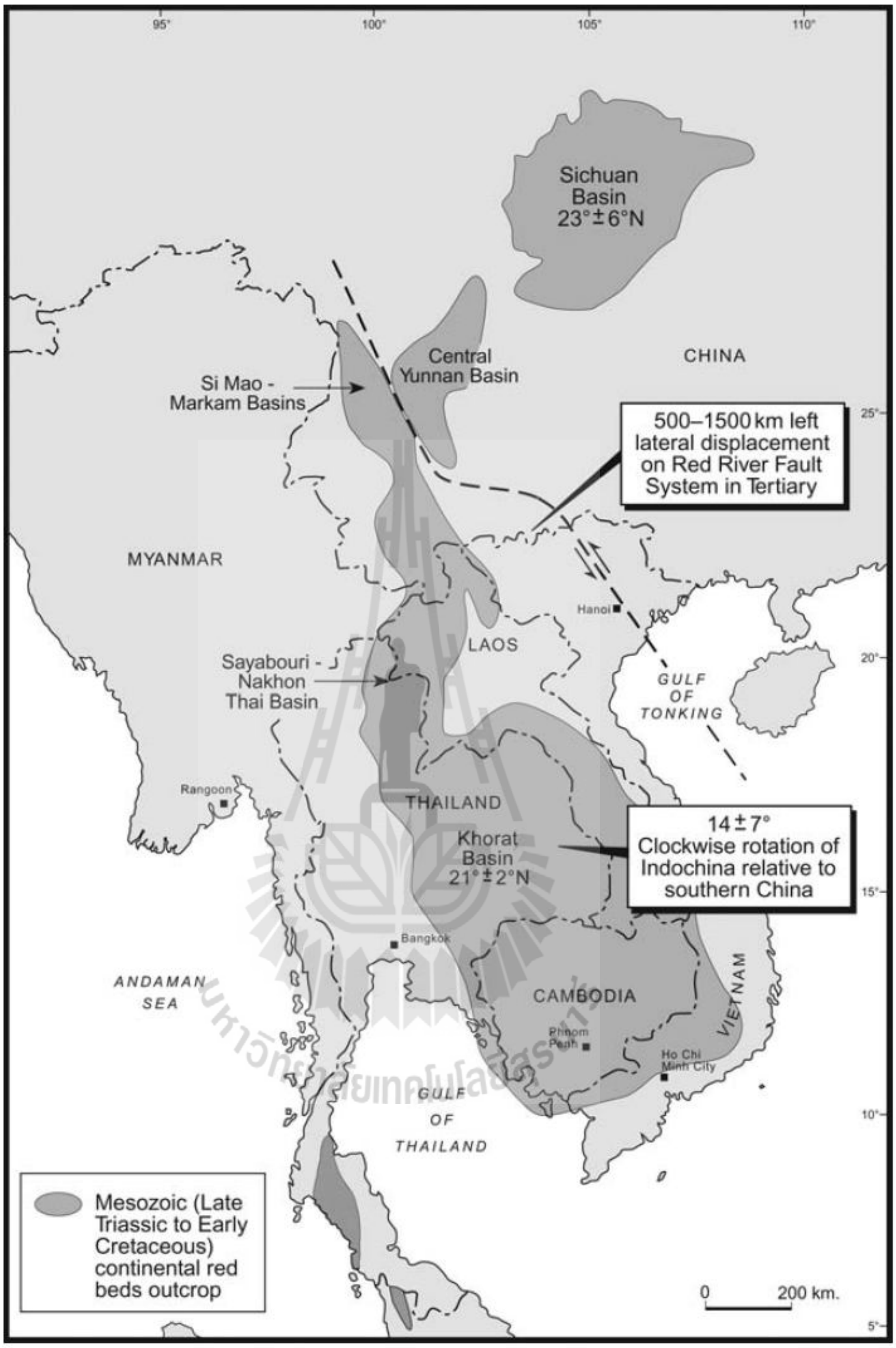


Figure 2.8 Distribution of Mesozoic red beds of the Late Triassic to the Late Cretaceous in Southeast Asia and South China with the effect of major lateral displacement along the Red River Fault System coupled with a clockwise rotation of the Indochina Block relative to southern China (after Racey, 2009).

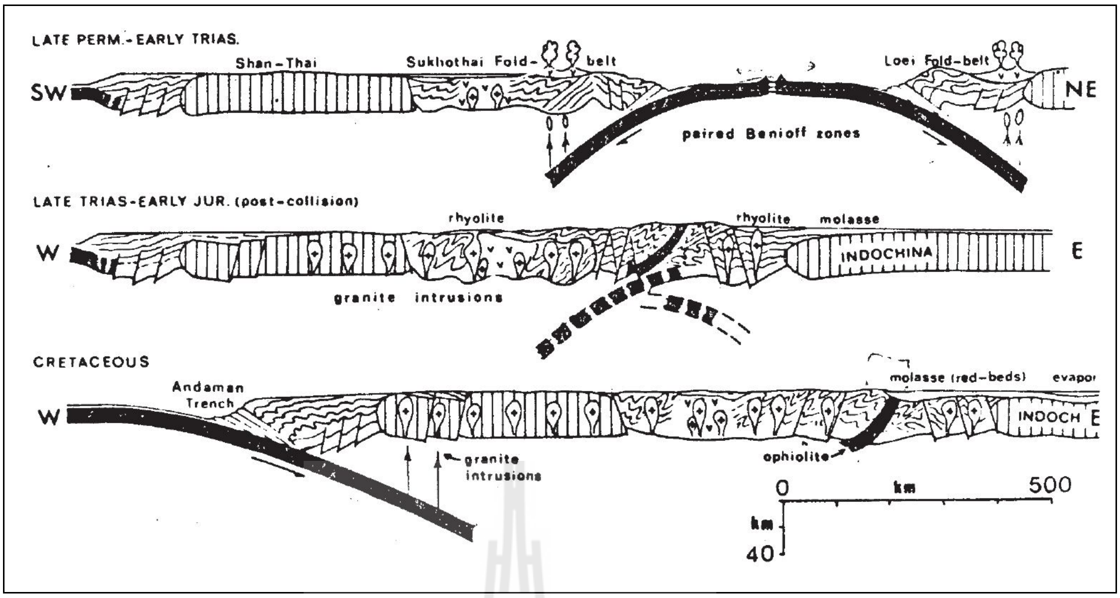


Figure 2.9 Tectonic model of Thailand since the Late Permian to the Cretaceous describing genesis of the molasse (red beds) in the Indochina Block (after Bunopas, 1981).

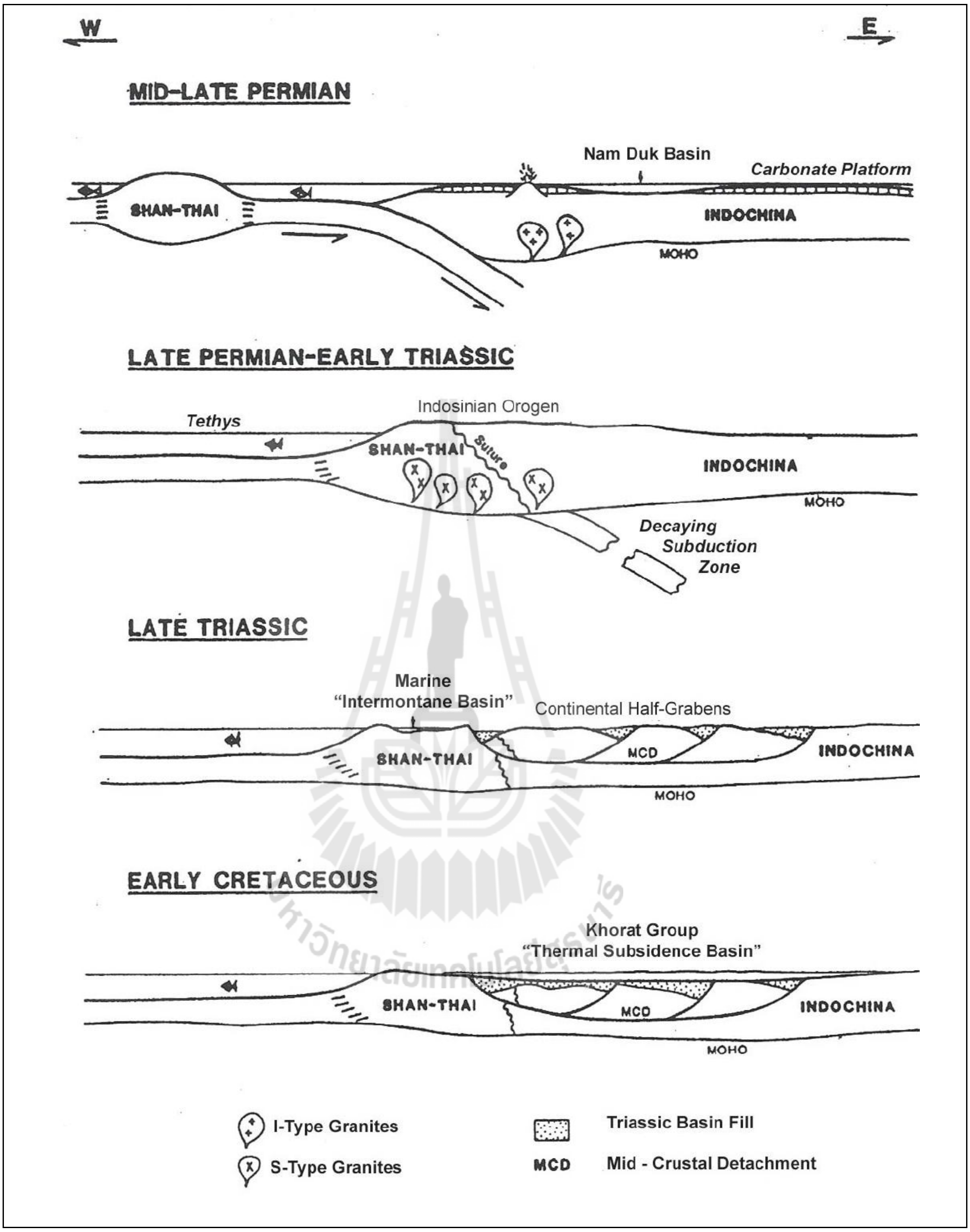


Figure 2.10 Tectonic model of Thailand describing evolution of the Late Triassic basins in the Indochina Block (after Cooper et al., 1989).

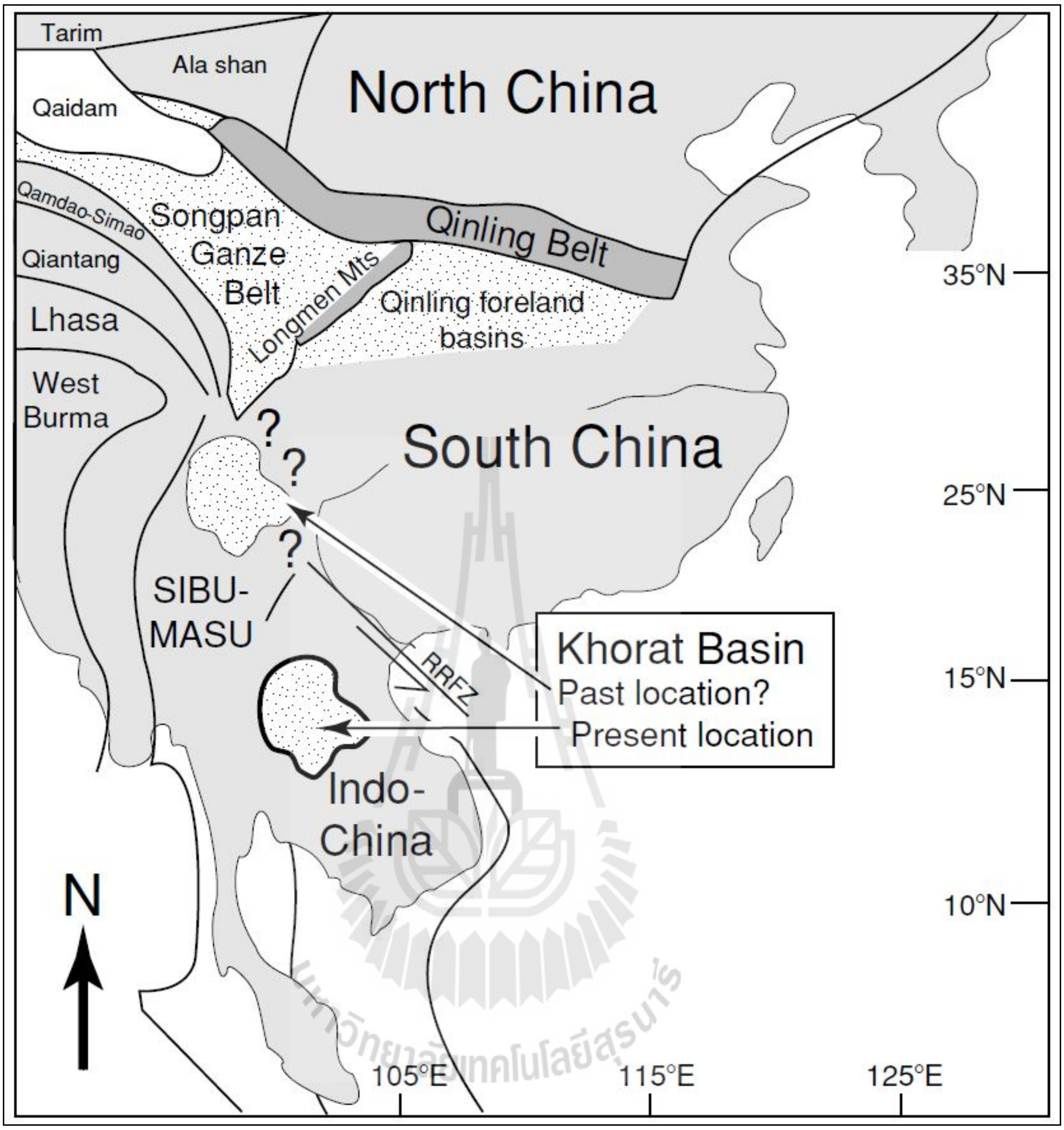


Figure 2.11 Proposed model of the location of the Khorat Basins in the past (the Late Jurassic to the Early Cretaceous) and the present location after lateral displacement along the Red River Fault System (after Carter and Bristow, 2003).

2.3 Previous work of the Phu Khat Formation

Chareonpravat et al. (1976) had conducted the regional geological map of the Thailand on scale 1: 250,000 in map sheet NE47-12 (Changwat Loei) which covered the Nakhon Thai region. They reported that the entirely area of the Nakhon Thai region was covered by the succession of the Cretaceous sandstone, shale and conglomerate which was undifferentiated. It was considered as the one formation included in the Khorat Group that was underlain conformably by the Phu Phan Formation. However, the study is mainly based on aerial photographic interpretation without detailed field survey.

Kosuwan (1990) had conducted the detailed geological map of the Nakhon Thai region on scale 1: 50000. He reported two new informal name formations: (in ascending order) the Khao Ya Puk Formation and the Phu Khat Formation. The two formations were interpreted as having been deposited by fluvial process in the Late Cretaceous and underlain conformably by the rock salt layers of the Maha Sarakham Formation. The Khao Ya Puk Formation consists mainly of three sequences, i.e., the lower, the middle and the upper sequences. The lower sequence is characterized by reddish brown claystone and shale, whereas in the middle sequence is composed of the fine-grained sandstone interbedded with siltstone. The sedimentary structure such as sand dyke, ripple mark and mud-crack are common. The upper sequence is coarse- to medium-grained, thick-bedded arkosic sandstone with large scale cross-bedding. Kosuwan (1990) suggested that the lithological sequence of the Khao Ya Puk Formation was probably correlated to the Phu Tok Formation in the Khorat Basin. However, the both two formation (the Khao Ya Puk and the Phu Tok Formations) were interpreted to deposit in different basin. As the result of this, it leads Kosuwan to establish the new name formation in the Nakhon Thai region instated of the Phu Tok name. The Phu Khat Formation consists of reddish brown to purple brown, fine- to medium-grained lithic arenite intrebedded with siltstone and conglomerate. The pebbles of conglomerate are composed of quartz, chert, sandstone, siltstone, volcanic and limestone. As reported by Kosuwan (1990) the Phu Khat Formation overlies conformably on the Khao Ya Puk Formation which is believed to be the uppermost sequence of red beds in the Nakhon Thai region.

Heggemann (1994) studied sedimentary evolution of the Khorat Group (the Upper Triassic to the Paleogene) in the Khorat Plateau and the northern Thailand. He concluded that the uppermost red beds formation of the Khorat Group is the Phu Khat Formation which is well exposed in the Nakhon Thai region. As stated by Heggemann (1994) the Phu Khat Formation is characterized by multi-stored and multi- lateral fanglomerate, with pebble clasts consisting of quartz, sandstone, chert, intermediate volcanic and claystones. The total thickness throughout the formation was estimated approximately 500 m. The formation was interpreted to have been deposited by alluvial fan environment in more or less the Late Cretaceous to the Early Paleogene while the underlying formation (the Khao Ya Puk Formation) was deposited by aeolian desert environment under arid climate rather than by fluvial process as presented by Kosuwan (1990). Owing to the imbrications direction of pebble clasts in conglomerate beds, Heggemann (1994) claimed that the provenance of the Phu Khat Formation was derived from the uplift of the western terrane (the Nan-Uttaradit Suture Zone and the Sukhothai Zone) together with the eastern terrane (the Loei-Phetchabun Fold Belt) (Figure 2.12).

Meesook et al. (2002); Meesook (2011); Assavapatchara and Raksasakulwong (2010) reported the unconformity contact between the Khao Ya Puk Formation and the Phu Khat Formation based on the presence of abrupt facies change. They interpreted that the Khao Ya Puk Formation had been deposited by occasional meandering river and by winds in semi- arid condition grading upward to arid desert in the Latest Cretaceous to the Early Cenozoic. In contrast, the Phu Khat Formation was interpreted to have been deposited by alluvial fan and meandering fluvial in the semi-arid condition. They proposed the age of the Phu Khat Formation more or less as same as the Khao Ya Puk Formation in the Latest Cretaceous to the Early Cenozoic.

In summary, the previous studies have made their conclusion from the regional study without detailed study of lithostratigraphy, facies characteristic, and provenance of the Phu Khat Formation. Subsequently, most of them propose the different ideas about the age, contact and depositional environment of the formation. Therefore, the detailed lithostratigraphy and facies characteristic as well as the provenance are more favoured in this study in order to gain more understanding on the depositional environment and the provenance of the Phu Khat Formation.

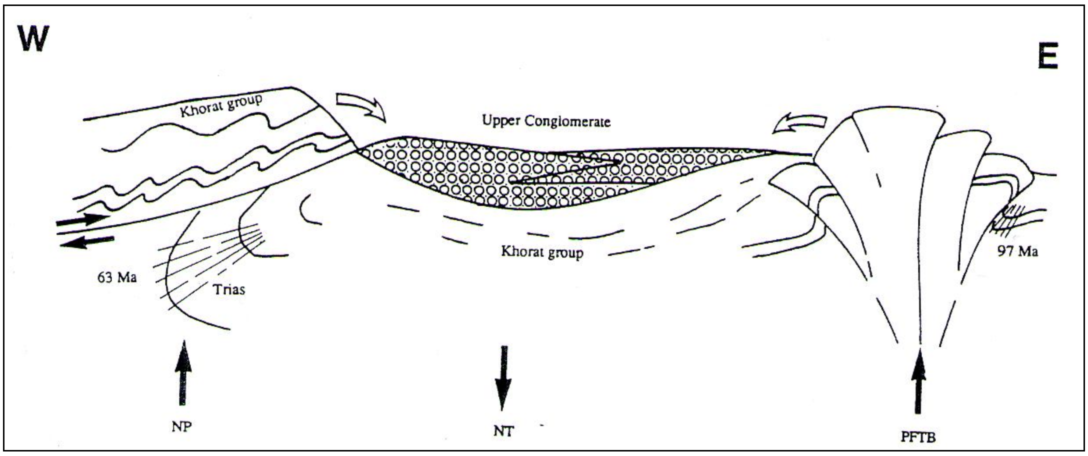


Figure 2.12 Proposed model for the provenance of the Phu Khat Formation (or Upper conglomerate) after Heggemann (1994). NP: Nam Pat, NT: Nakhon Thai and PFTB: Phetchabun Fold and Thrust Belt.

CHAPTER III

METHODOLOGY

In this chapter the methods of study are described. It is composed of three main strategies, i.e., desk study, field work and laboratory work. All three main works are carried out in order to achieve the objectives of the thesis. The details of each strategy are as following.

3.1 Desk study

The geological data and relevant previous study were collected through the published papers, text books and internet sources. All of these data were used as the based data to support and solve the problem.

3.2 Field works

Four time field work was undertaken in December 2012, March-April 2013, July 2013 and April-May 2014, using 1: 50,000 base topographic map series L7018 published by the Royal Thai Survey Department. Due to discontinuous nature and intense tropical weathering, a simple continuous stratigraphic section could not be obtained. Therefore, five reference locality sections were measured by tape measure and more than twenty of reconnaissance locations were investigated by visual estimation coving the provinces of Loei and Phitsanulok where the outcrops of the Phu Khat Formation are well exposed (Figure 4.1b). The collection and analysis techniques of field data were followed the suggestion of Tucker (1988; 2003) which criteria using for distinction were based on the facies analysis. The measured sections were presented as geographic column. Facies analysis were conducted and distinguished by using lithology, geometry, sedimentary structures and paleocurrent pattern following the suggestion of Selley (2000). In addition, palaeontology will also be employed where it is available. The description of the facies and facies code as well as the interpretation will be adapted from the lithofacies model and classification of Miall (1985; 1996), Collinson (1996) and Selley (2000). Results of field investigation were used to analyze facies characteristics and interpret the processes and environmental deposition of the sediments.

3.3 Laboratory works

3.3.1 Petrographic study

The thin sections of fresh sandstone sample were analyzed under the conventional microscope and cathodoluminescence (CL) at the China University of Geosciences (CUG) in Wuhan, People's Republic of China. The petrographic classification for siliciclastic rocks used throughout this study was based upon Folk (1974). The Gazzi-Dickinson (Dickinson & Suczek, 1979; Dickinson, 1985) point counting method was used on representative 51 sandstone sample (15 of the Khao Ya Puk and 36 of the Phu Khat Formation containing matrix less than 25%) in order to count grains (quartz, feldspar and rockfragment) that are larger than 60 μm. In each thin section 300 grain on average were point counted following the Gazzi-Dickinson method. The classification and symbols of grained types are shown in Table 3.1. The results of point-count data were used to plot triangular discrimination in concordance with the suggestion of Dickinson (1985) to evaluate the provenance of the sandstone sample. They were recalculated to 100 % for each of triangular discrimination. The QFL and QmFLt plots are main discrimination used in this study and the provenance can be classified into three main type, i.e., magmatic arc (undissected, transition and dissected), continental block (craton interior, transitional continental and basement uplift) and recycled orogen (subduction complex, collision orogen and foreland uplift) provenance (Dickinson, 1985).

3.3.2 The whole-rock geochemistry

The fresh rock samples of sand size were selected for analyses in order to reduce the variation of composition and to minimize secondary contamination due to weathering and alteration. The samples were carefully cleaned, crushed and powdered in a tungsten–carbide mill to less than 200 mesh. Fifteen samples consisting of 12 samples from the Phu Khat Formation and 3 samples from the Khao Ya Puk Formation were analyses for bulk-rock geochemistry. Major element analysis was conducted at the Geological Analysis Division, Department of Mineral Resources (DMR, Thailand) by an Axios Advance X-Ray Fluorescence (XRF) spectrometer. The basic concept behind the XRF technique is that when the sample is bombarded with high energy X-rays, secondary radiation is emitted, with wavelengths and intensities dependent on the elements present. Measurement of intensity of the characteristics radiation for a particular element give a value reflected its concentration in the sample. The concentration of element is finally calibrated by reference standard. For trace and rare earth elements, rock powders were first digested by HF + HNO3 in Teflon bombs as the solution and then were analyzed by an Agilent 7500a Inductively Coupled Plasma-Mass Spectrometry (ICP-MS) at the Wuhan Supervision and Test Centre for Mineral Resources of Ministry of Land and

Resources (Wuhan). The principle behind this technique is that the sample in acid-solution was nebulized to form an aerosol. The argon gas is used as carrier gas to bring the aerosol into torch. In the torch the high temperature is produced by a radio frequency generator in order to atomized and ionized the sample. Ions are then transmitted into the mass spectrometer in order to measure the concentration of the various elements present. Analytical precision is generally better than 5% for most elements. All geochemical data were plotted in discrimination diagram of Bhatia (1983, 1985), Bhatia and Crook (1986), Roser and Korsch, (1986, 1988), Floyd and Leveridge (1987) and McLennan et al. (1993) in order to determine the provenance and tectonic setting types. The basic concepts behind of these discriminations were based on observations made from geochemical characteristics of each suite of sandstones with known provenances and tectonic settings.

3.3.3 U-Pb detrital zircon dating

Three representative samples were selected for the U-Pb dating. One is from the upper part of the Khao Ya Puk Formation (Up-Kyp) and the other two from the lower part of the Phu Khat Formation (Low-Phk) and the middle part of the Phu Khat Formation (Mid-Phk). Zircons were separated using standard rock disaggregation and heavy mineral separation procedures, mounted in epoxy, and polished. Optical microscopy and cathodoluminescence (CL) images outline the morphology and internal structure of the grains. CL images were obtained on a JEOL JXA-8100 electron microprobe. All of three samples were analyzed by using Laser Ablation- ICPMS. The first two samples (Up-Kyp and Low-Phk) were conducted at the Department of Earth and Planetary Sciences Birkbeck, University of London (UK) and the last sample (Mid-Phk) was performed at the State Key Laboratory of Geological Processes and Mineral

Resources, China University of Geosciences in Wuhan. The $^{206}Pb/^{238}U$ ratio was used to determine ages where < 1000 Ma and the $^{207}Pb/^{206}Pb$ ratio for older grains. The age distributions are displayed as Kernel density plots (Botev et al., 2010; Vermeesch, 2012). Subsequently, the data were used to investigate the specific source area with known age dating. Finally, the results were integrated with the petrography, the geochemical data and the previous study to interpret and discuss on the provenance, tectonic setting type and tectonic evolution in the study area. Summarization of the thesis methodology is shown in Figure 3.1.

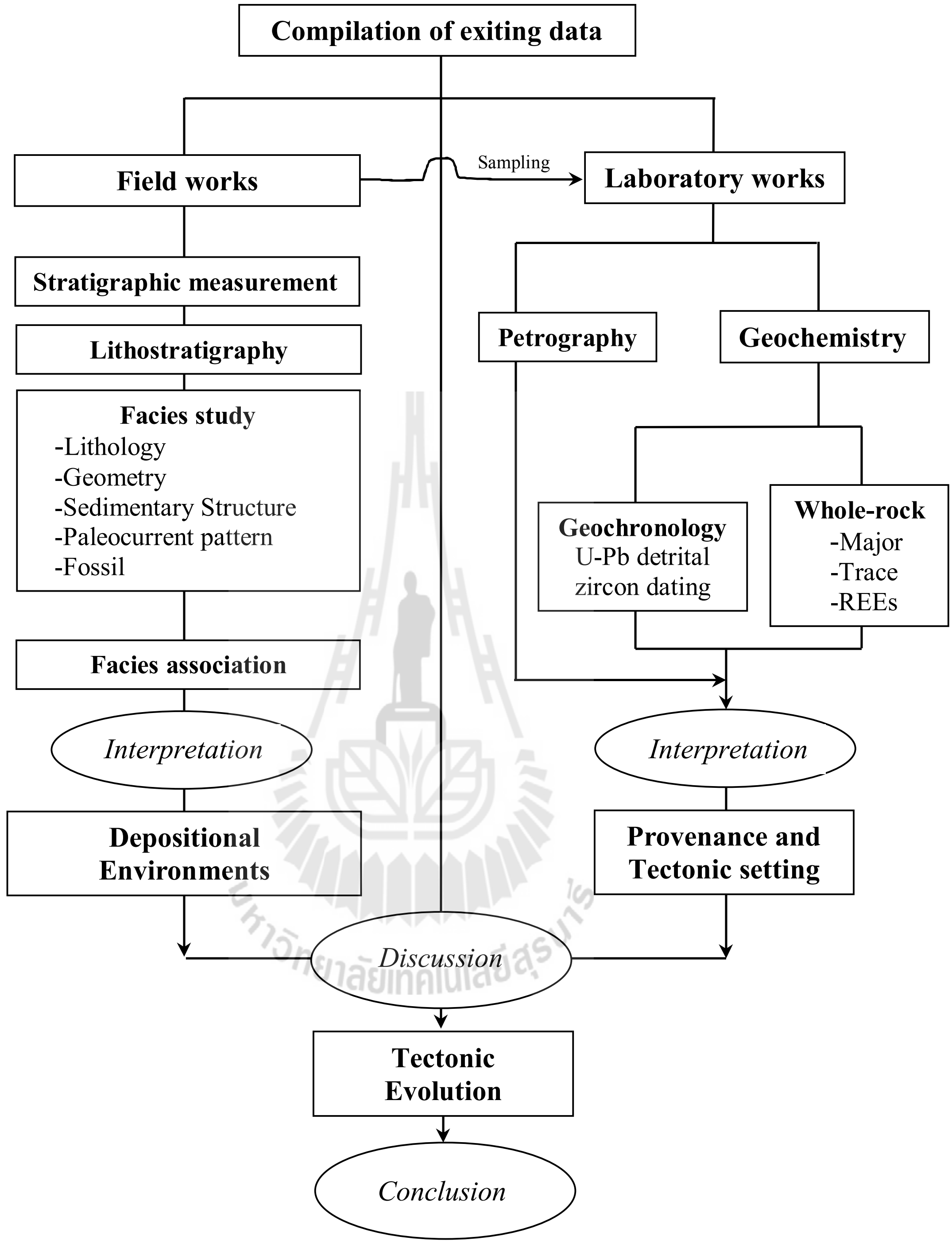


Figure 3.1 Research methodology

Table 3.1 Classification and symbols of grain types (after Dickinson, 1985)

A. Quartzose Grain (Qt = Qm + Qp)

Qt = total quartzose grains

Qm = monocrystalline quartz (> 0.62 mm)

Qp = polycrystalline quartz

B. Feldspar Grains (F = P + K)

F = total feldspar grains

P = plagioclase grains

K = potassium feldspar grains

C. Unstable Lithic Fragment (L = Lv + Ls)

L = Total unstable lithic fragments

Lv = Volcanic/metavolcanic lithic fragments

Ls = Sedimentary/ metasedimentary lithic fragments

D. Total Lithic Fragments (Lt = L + Qp)

Lc = Extrabasinal detrital limeclasts (not included in L or Lt)

CHAPTER IV

RESULTS

This chapter presents the results of the study. There are two main parts. The first is the results of the field work which consist of the lithostratigraphy and facies characteristics of the Phu Khat Formation. The second is the results of laboratory works including the petrography, the geochemistry and the U-Pb detrital zircon dating. Details of each result are as follows:

4.1 Lithostratigraphy and facies characteristics of the Phu Khat Formation

4.1.1 Introduction

The stratigraphy of the red bed in Thailand have long been studied by many geo-scientists especially the red beds of the non-marine Khorat Group in the Khorat Plateau since they are a potential for mineral and fuel resources. The sequence of the Khorat Group is also extends beyond the rim of the Khorat Plateau to the Nakhon Thai region (Sha et al., 2012; Booth and Sattayarak, 2011) where the two regions are separated by the succession of pre-Cretaceous rock in the Loei-Phetchabun Fold Belt (Figure 4.1a). However, the stratigraphy of the uppermost part of the red beds is mentioned only in the Nakhon Thai region as the presence of the Phu Khat Formation (Figure 4.2). Nonetheless, the Phu Khat Formation is still ambiguous and there is a paucity of details in terms of their lithostratigraphy and facies study. So the main objectives of this section are to establish the stratigraphic sequence of rock units of the Phu Khat Formation and then study the facies characteristics of the Phu Khat Formation based on its lithology, outcrop geometry, sedimentary structure, palaeocurrent pattern, and fossils in order to interpret the environmental deposition of the Phu Khat Formation. The study area is in the Nakhon Thai region where the Phu Khat Formation is well exposed. Five reference sections (Figure 4.1b) are selected for detailed study.

4.1.2 Lithostratigraphy of the Phu Khat Formation

4.1.2.1 Definition and type section

The Phu Khat Formation was first named by Kosuwan (1990). It was mentioned in geological map 1: 50,000 on the Royal Thai Survey Department topographic map series L7018 sheet 5143 I and II of Ban Nam Khum and Amphoe Nakhon Thai, the Nakhon Thai region. The formation was defined as a sequence of the rocks that are characterized by fine- to medium-grained sandstone with reddish brown to purplish brown in colour. It is interbedded with reddish brown siltstone. Conglomerate beds were also occasionally reported as intercalated beds. The clasts of conglomerate beds are composed of quartz, chert, sandstone, siltstone, volcanic and small pebble limestone locally. As mentioned by Kosuwan (1990) the sequence of the formation was conformably underlain by the thick-bedded, large-scale cross-bedded sandstone of the Khao Ya Puk Formation. The type section designated by Kosuwan (1990) is broadly located on the local road from Ban Nam Ton to Ban Nam Chaeng Phatthana (Phu Khat). It is represented by the Royal Thai Survey Department topographic map series L7018 sheet 5143 I and II in scale 1: 50,000. Unfortunately, this location was defined as the type section but it was not provided sufficient data, e.g., section locality and lithostratigraphic explanation. In this study, as a single complete exposure of the formation is nowhere exposed, five reference localities (Figure 4.1b) and reconnaissance sites are thus designated and measured to the west and the east of the type section of Kosuwan (1990). The successions of the Phu Khat Formation from various localities are illustrated diagrammatically in Figures 4.3 and 4.4.

Reference locality 1. Km 40+300 Road No 1237 (Amphoe Chat Trakan - Ban Bo Phak)

This section is along the road cut between Amphoe Chat Trakan and Ban Bo Phak. It is located at milestone KM 40+300 to KM 40+600 about two kilometers south of Ban Bo Phak which is represented by the Royal Thai Survey Department topographic map series L7018 sheet 5144 II in scale 1: 50,000 grid reference 693869E, 1938258N. The section is 300 m long and the total measured thickness of the formation is 85 m which represent the lower part of the Phu Khat Formation. Details of the section are illustrated in Figure 4.5.

Reference locality 2. Km 24 to Km23+600 Road No 1286 (Ban Lao Ko Hok - Amphoe Na Haeo)

This section is along the road cut between Ban Lao Ko Hok and Amphoe Na Haeo. It is located at milestone KM 24 to KM 23+600 about three kilometers east of Ban Lao Ko Hok which is going up on to the peak of the mountain. The road was cut through the escarpment of mountain perpendicular to the strike of the bedded rocks which shows eastward dipping. It is represented by the Royal Thai Survey Department topographic map series L7018 sheet 5143 I in scale 1: 50,000 from grid reference 702081E, 1934500N to 702872E, 1934027N. The section is about 800 m long and the total measured thickness of the formation is 80 m which represent the upper lower part of the Phu Khat Formation. Details of the section are illustrated in Figure 4.6.

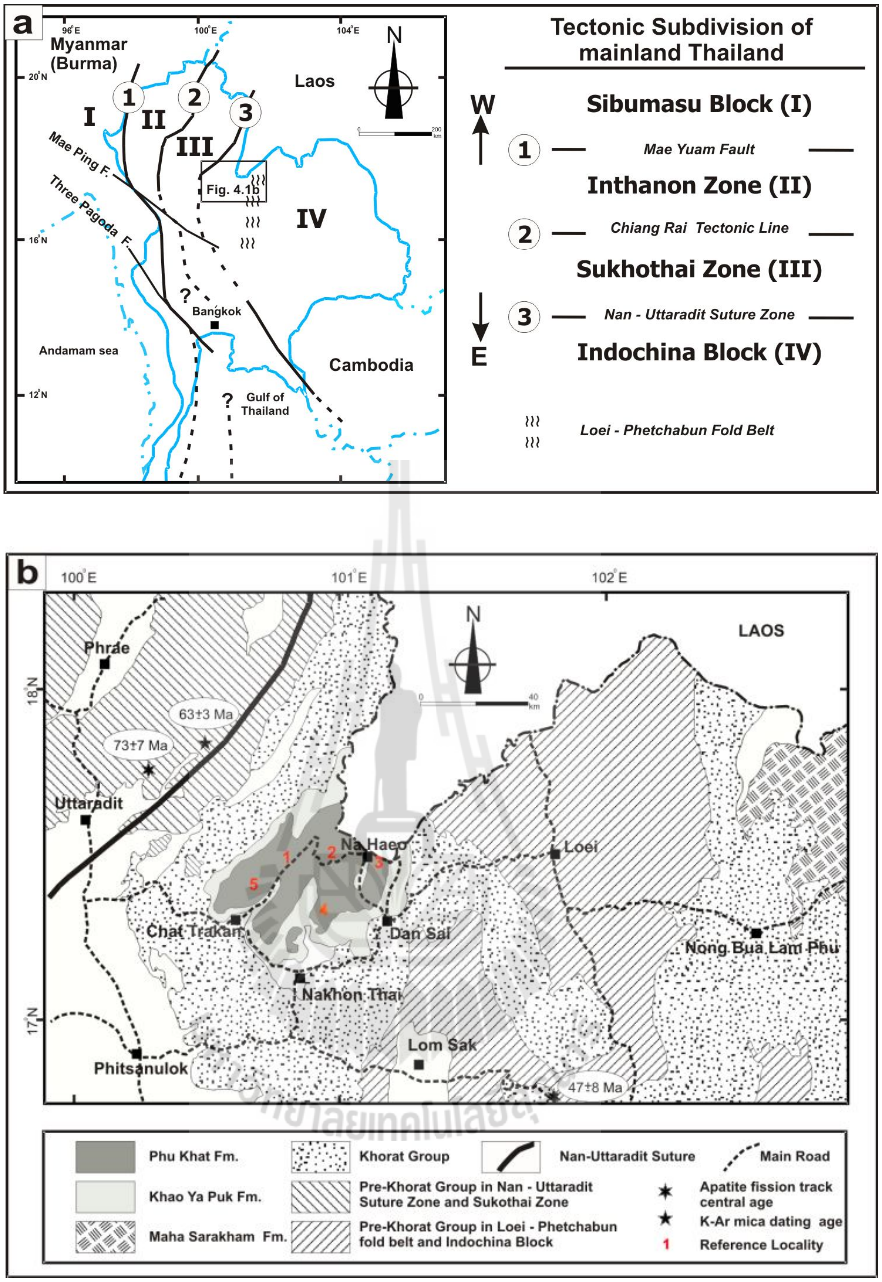


Figure 4.1-a) Geotectonic subdivision map of Thailand (after Barr and Macdonald, 1991; Ueno and Hisada, 2001). b) Simplified geological map of the Nakhon Thai region based on the Geological Map of Thailand (1:2,500,000) published by Department of Mineral Resources (1999). Apatite fission track age after Racey et al. (1997) and Upton (1999).The K-Ar mica dating age after Ahrendt et al (1993).

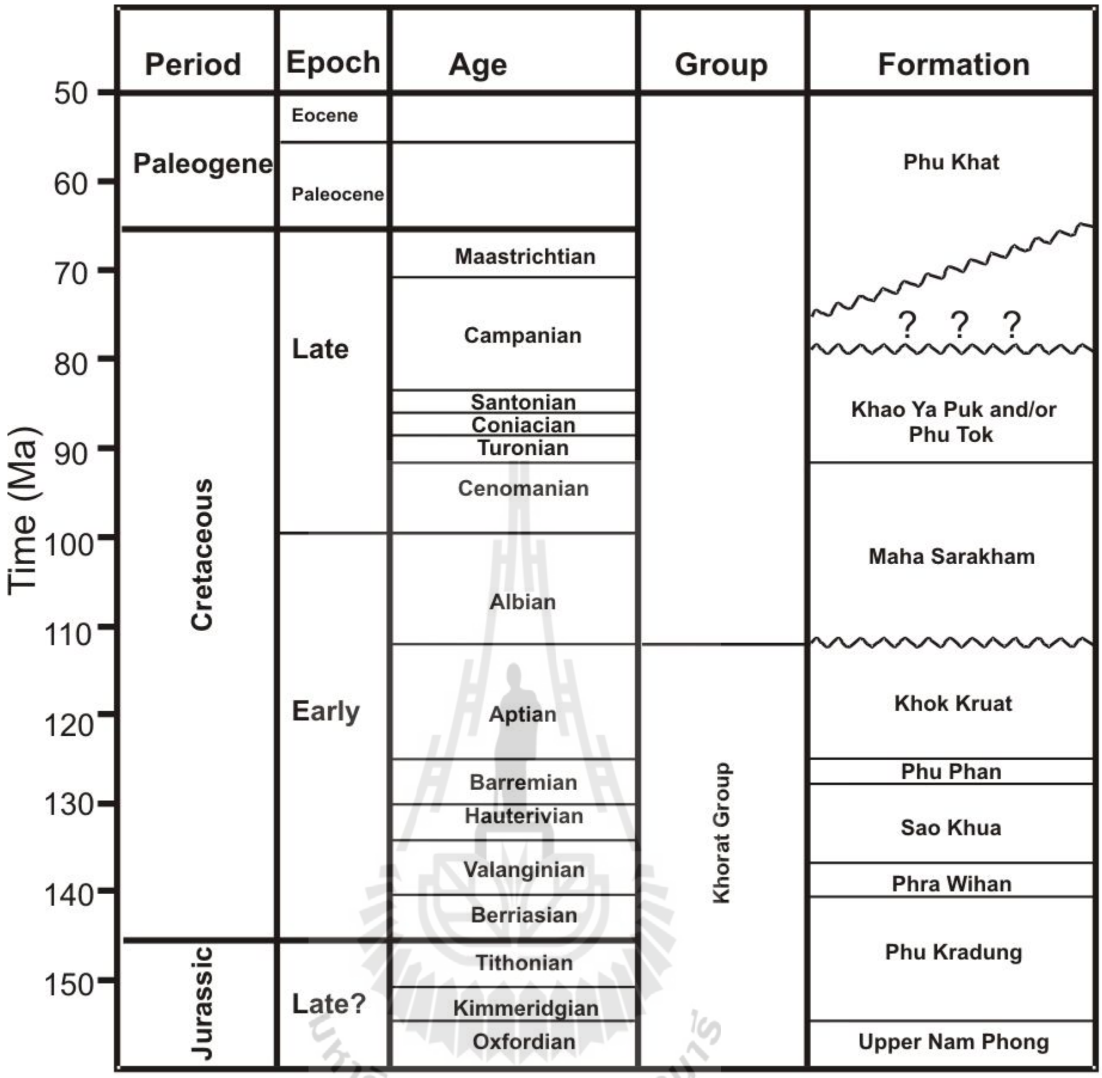


Figure 4.2 Schematic stratigraphic column of the Nakhon Thai region since the Cretaceous (modified after Racey et al., 1996; Racey, 2009; Assavapatchara and Raksasakulwong, 2010)

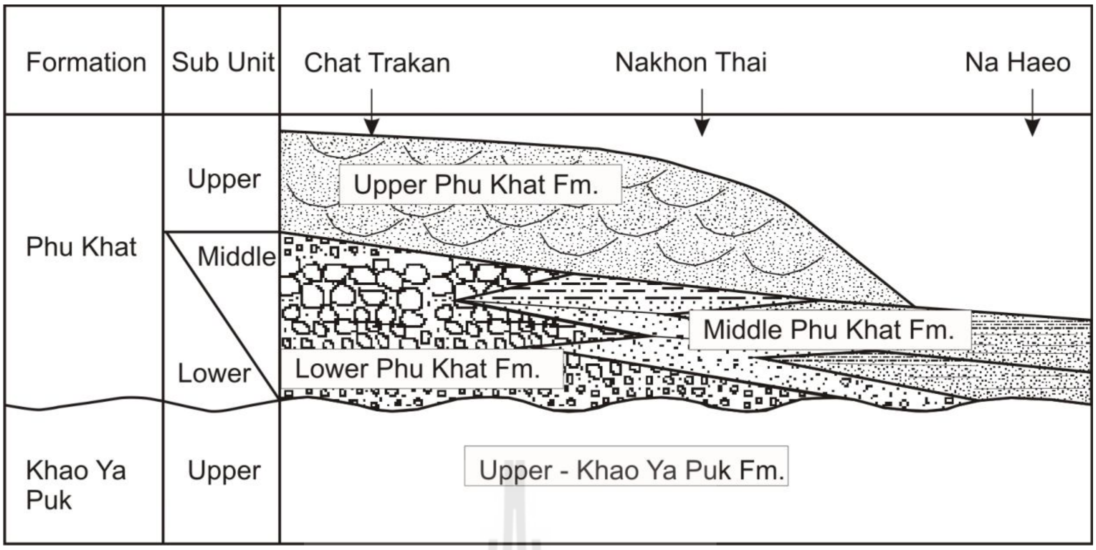


Figure 4.3 Succession of the Phu Khat Formation showing classification and facies relation of the various parts.

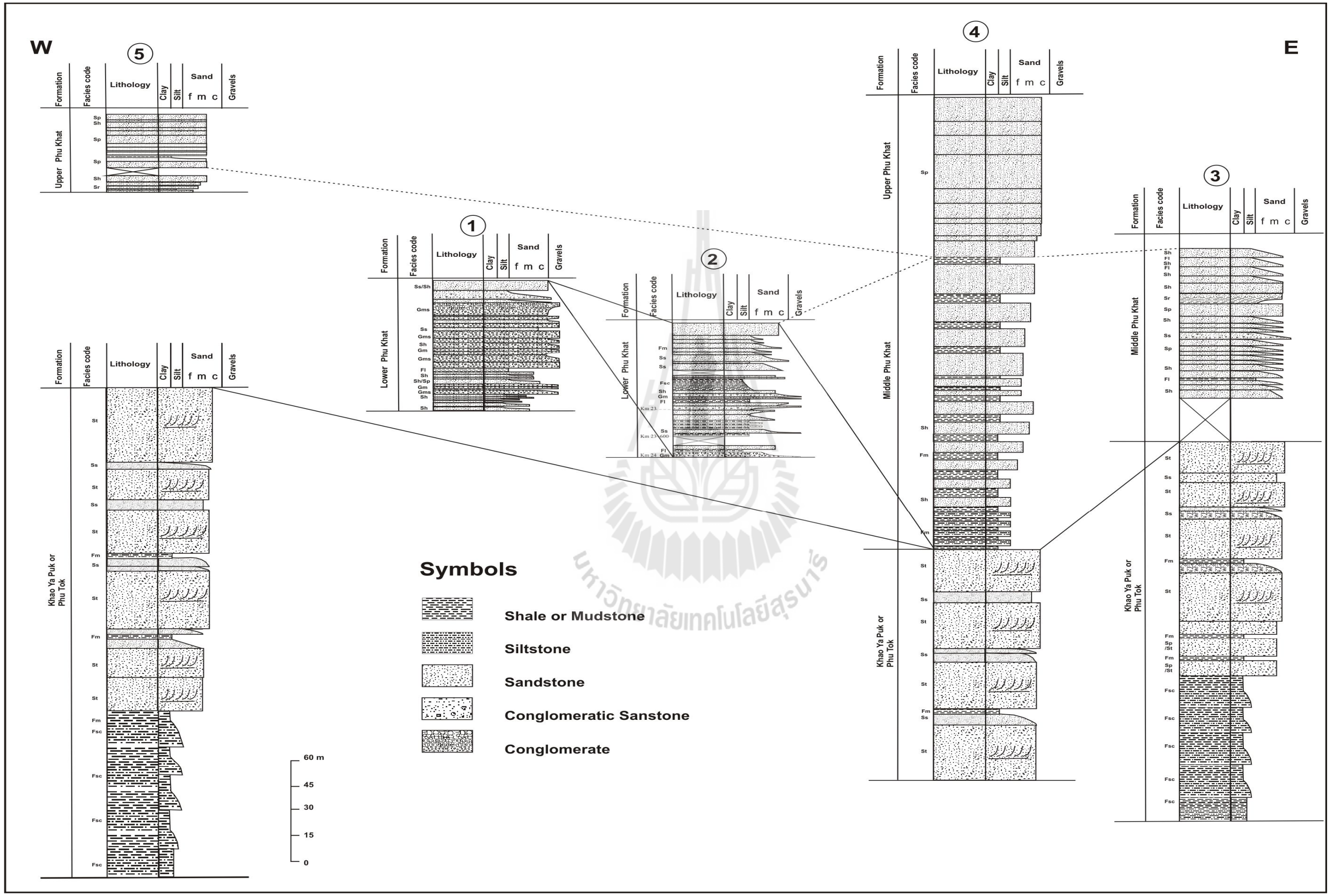


Figure 4.4 Lithostratigraphic correlation of the Phu Khat Formation in various study locations. For the location map see Figure 4.1b

Reference locality 3. Km 0 to Km 3+600 Road No 2195 (Amphoe Na Haeo - Ban Pak Man)

In this section two formations (the Khao Ya Puk and the Phu Khat Fm.) are observed in one section line along the road cut between Amphoe Na Haeo and Ban Pak Man. It is located at milestone KM 0 to KM 3+600. The road was cut perpendicular through the mountain which lies in N-S trending in the western flank of major syncline structure. It is represented by the Royal Thai Survey Department topographic map series L7018 sheet 5243 IV in scale 1: 50,000 from grid reference 720854E, 1935824N to 723495E, 1934991N. The section is about 3,600 m long and the total measured thickness of the two formation is 375 m including complete section of the Khao Ya Puk Formation about 265 m and the middle part of the Phu Khat Formation 110 m. Details of the section are illustrated in Figure 4.7.

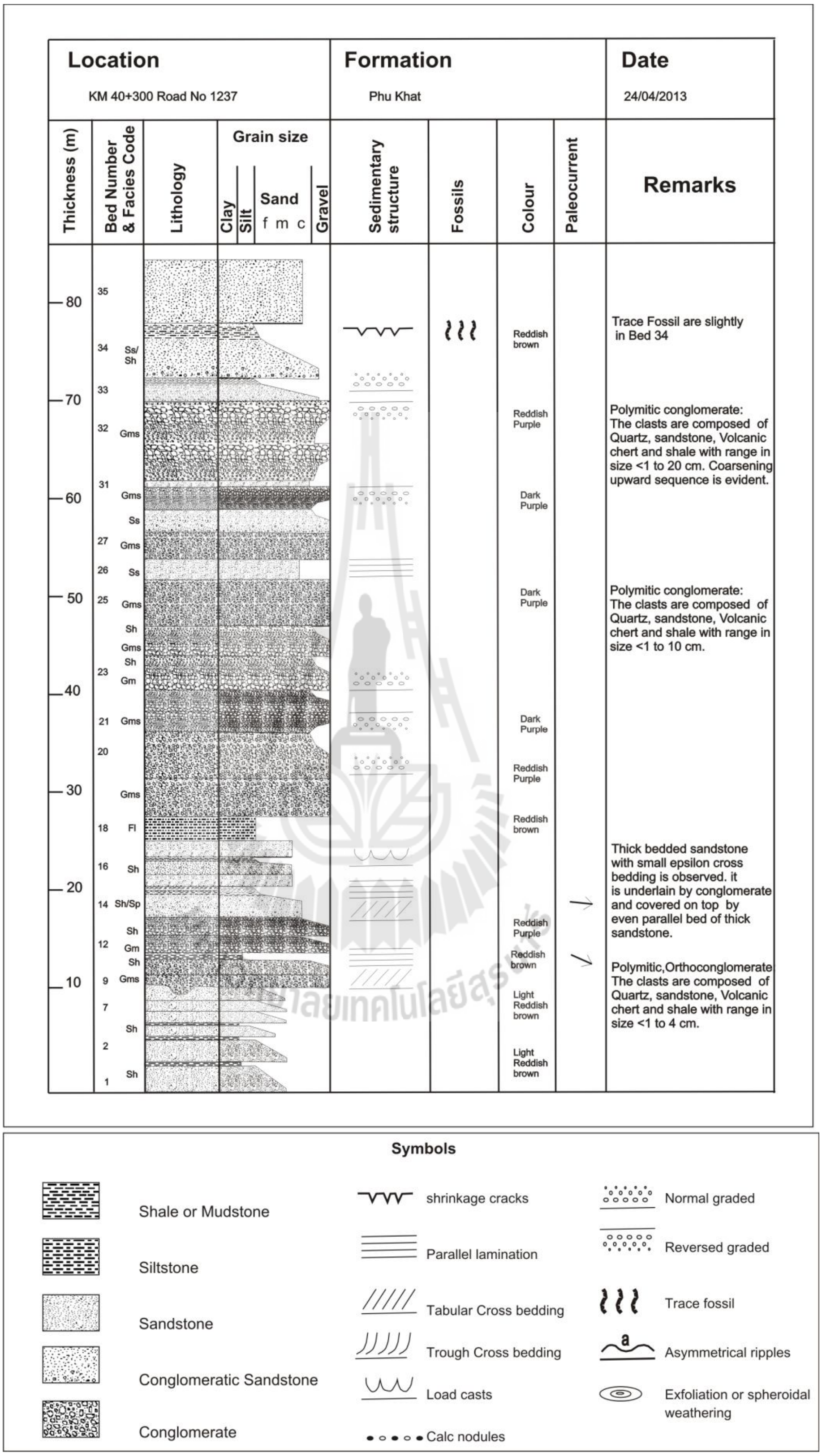


Figure 4.5 Lithostratigraphic column of the locality 1. Facies codes follow Miall (1985).

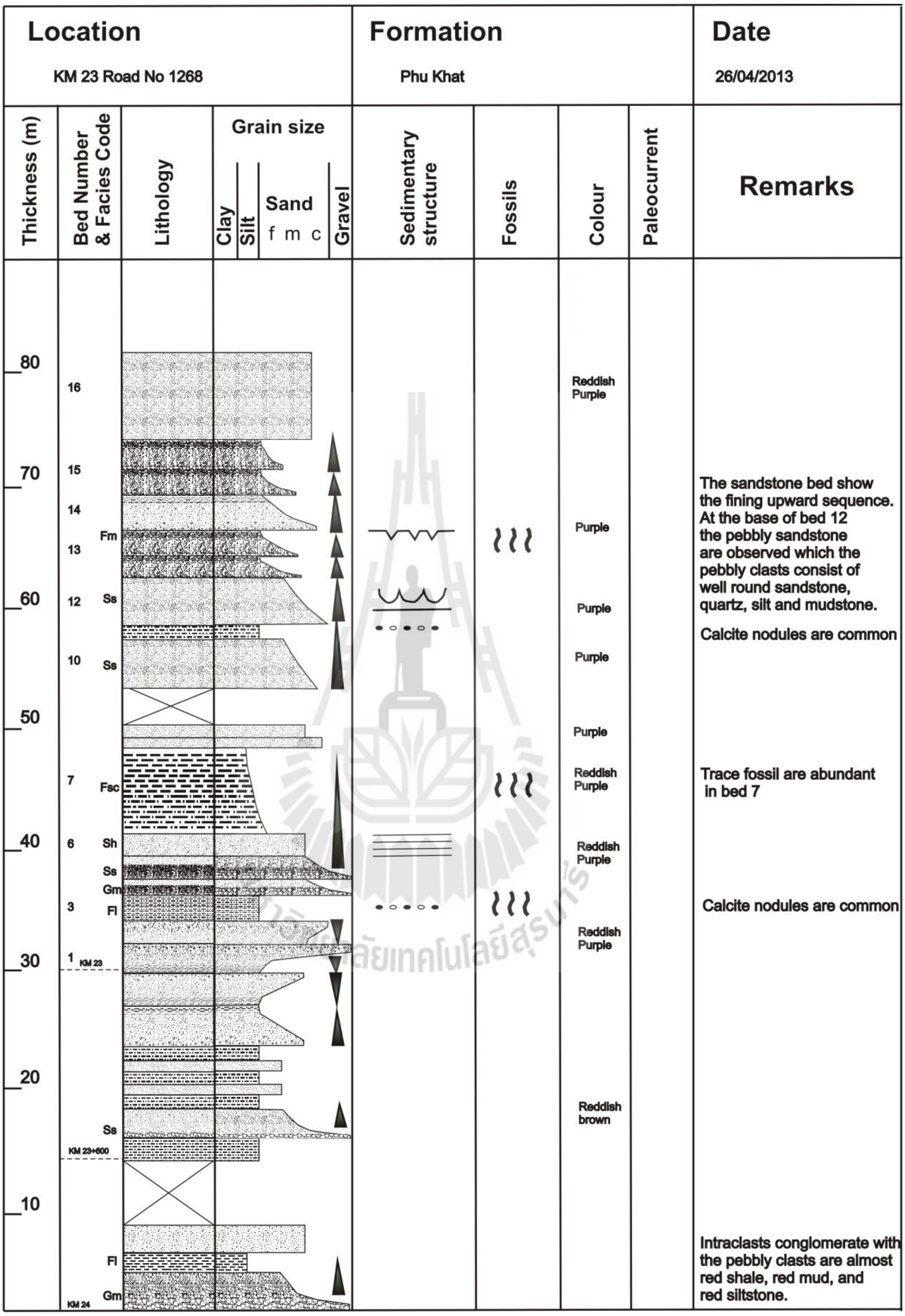


Figure 4.6 Lithostratigraphic column of the locality 2. For symbols see Figure 4.5.

Reference locality 4. Ban Nam Ton to Ban Nam Chaeng Phatthana (Phu Khat)

This section is along the road which is going up to the top of the Phu Khat Mountain from Ban Nam Ton to Ban Nam Chaeng Phatthana (Phu Khat). The detailed section was measured at the well exposed outcrop. The section was begun to measure at the upper part of the Khao Ya Puk Formation going upward continuously to the Phu Khat Formation. It is represented by the Royal Thai Survey Department topographic map series L7018 sheet 5143 II in scale 1: 50,000 grid reference 70246E, 1904884N. The section is 3,000 m long and the total measured thickness is 495 m including the upper part of the Khao Ya Puk Formation (165 m), and the middle and upper parts of the Phu Khat Formation (330 m). Details of the section are illustrated in Figure 4.8.

Reference locality 5. Dat Juang Waterfall

This section is located at six kilometers north of Ban Khok Phak Wan. The detailed section was measured from the waterfall namely Dat Juang. In this locality the outcrop of thick-bedded, cross-bedded sandstone are well exposed showing horizontal dipping. It is represented by the Royal Thai Survey Department topographic map series L7018 sheet 5143 IV in scale 1: 50,000 grid reference 676387E, 1920590N. The total measured thickness is 50 m which represent the upper part of the Phu Khat Formation. Details of the section are shown in Figure 4.9.

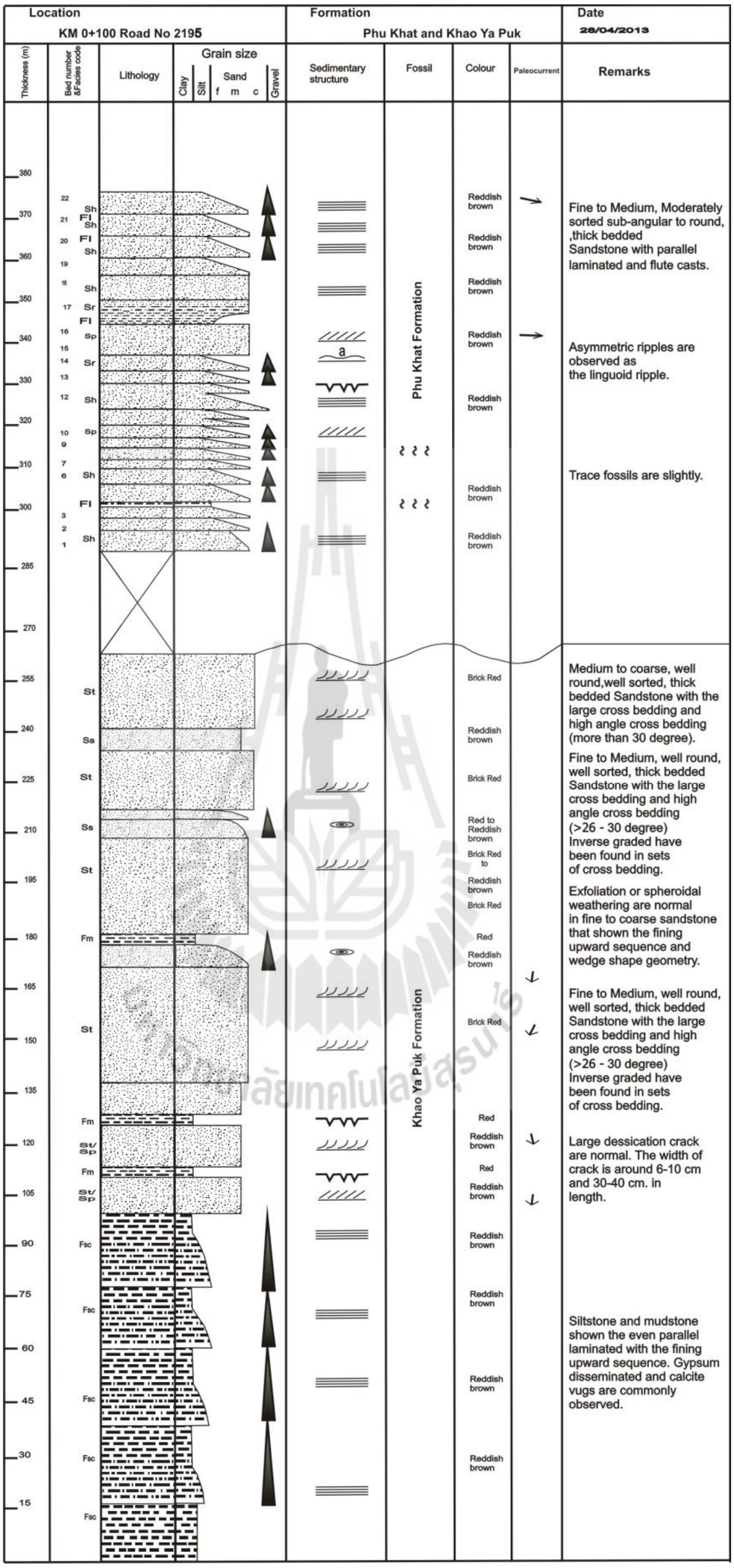


Figure 4.7 Lithostratigraphic column of the locality 3. For symbols see Figure. 4.5.

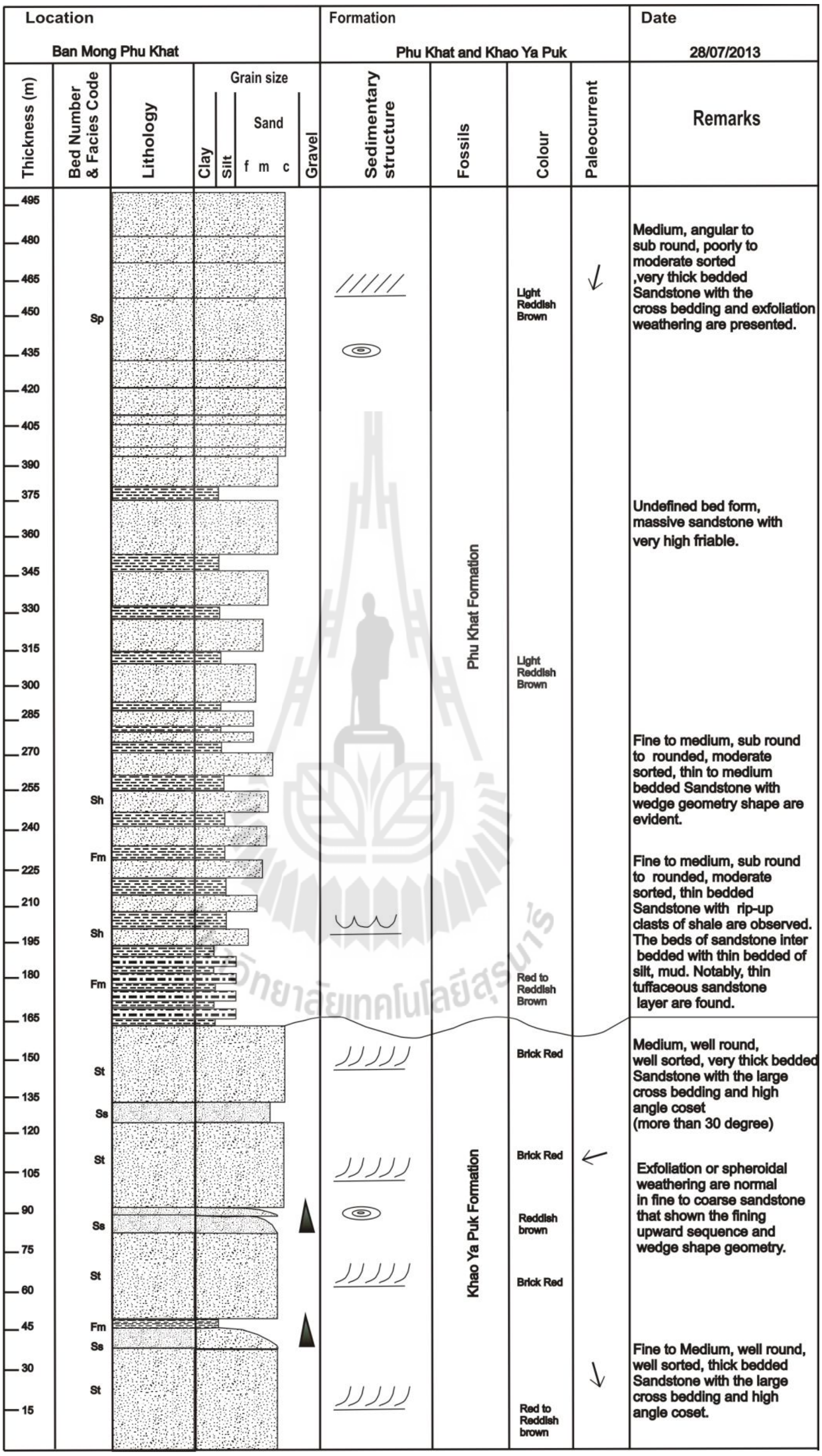


Figure 4.8 Lithostratigraphic column of the locality 4. For symbols see Figure 4.5.

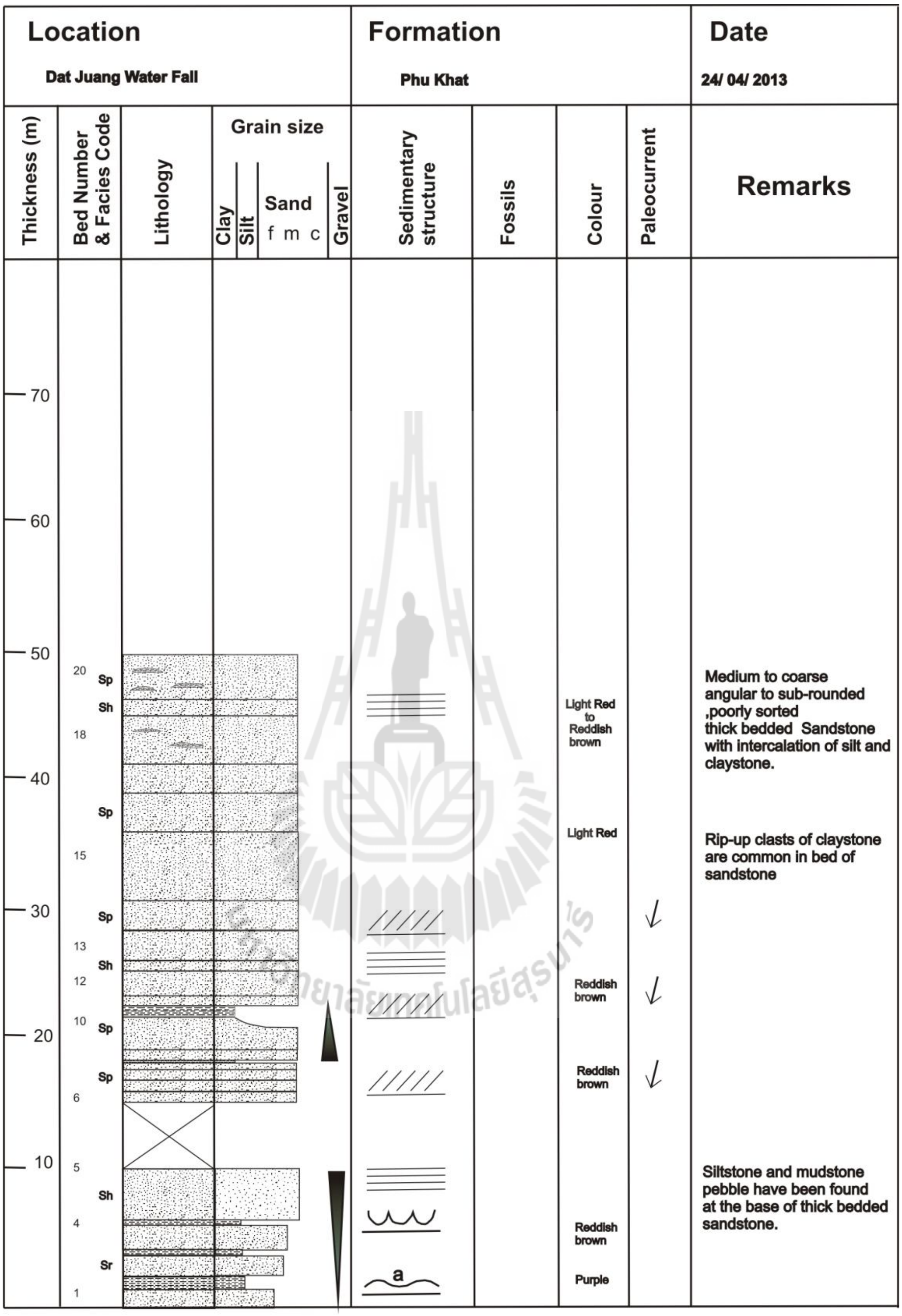


Figure 4.9 Lithostratigraphic column of the locality 5. For symbols see Figure 4.5.

4.1.2.2 Contact

Lower contact

Even though the contact of lower part of the Phu Khat formation in the field have not been found in this study, the unconformable contact either disconformity or paraunconformity are favoured based on the following features:

(I) The presence of polymictic conglomerates at the lower part of the formation. The lower part is characterized by the sequence of polymictic, conglomerates showing coarsening upward sequences in some beds together with cross-stratified, thin bedded sandstone. These features are likely to indicate the sub-aerial fan environment (Stanistreet and McCarthy, 1993; Miall, 1996). The cobble mudstone and siltstone clasts are observed in the conglomerates beds. They are more or less derived from the older formation (probably from the Khao Ya Puk Formation) presumably as resulted from tectonic uplift.

(II) The presence of abrupt facies change between the Phu Khat Formation and underlying the Khao Ya Puk Formation is observed. Only one section at reference locality 4 has found the contact between the Phu Khat Formation and the older formation (Khao Ya Puk). It seems to be somewhat conformable bed of the upper part of the Khao Ya Puk Formation grading up to the Phu Khat Formation. However, this locality is only the middle part of the Phu Khat Formation whilst the lower part is absent. Additionally, sedimentary structures of the Phu Khat Formation, e.g., cross-bedding, rip-up clast, channel structure, are apparent and indicate characteristic of fluvial process environment in semi-arid to more humid environment. It is clearly contrast with the underlying Khao Ya Puk Formation in which sedimentary structures represent typical of the aeolian sand dune deposit in more arid environment, e.g., large-scale cross-bedding, high angle foresets cross-bedding (29^0-33^0) with tangential base contact, very well sorted texture and super textural maturity as well as coarsening upward sequence of thin bedded sandstones (Pye and Tsoar, 2009; Tucker, 2003; Swezey, 1998; Pye, 1995). Consequently, all of these features provide the evidences that the Khao Ya Puk Formation may have been formed by aeolian dune in desert palaeoclimate (Meesook, 2011; Hasegawa et al, 2010; 2012) obviously contrasting with the Phu Khat Formation. The presence of abrupt facies change from arid climate in the Khao Ya Puk Formation to semi-arid and more humid in the Phu Khat Formation may be due to the climate change and/or tectonic uplift in the Late Cretaceous.

(III) Lack of structural dipping in the Phu Khat Formation. The Phu Khat Formation shows structural beds dipping with a few degrees especially in the sandstone beds of the upper part of the formation. They show dipping angle about 5 to 10 degrees which differs apparently from those underlying sandstone beds of the Khao Ya Puk Formation that show high angle dipping (25-30 degree on the average) within continuous section. This feature is interpreted to support evidence for an unconformable contact.

(IV) The contrasting detrital zircon age cluster between the Phu Khat and the Khao Ya Puk Formations. One notable difference between the Phu Khat and the upper Khao Ya Puk Formations is distribution of detrital zircon age (see more detail in section 4.2.5). Such a difference of provenance ages across the boundary of the two formations may imply the presence of a tectonic event or a major erosional event (post the deposition) of the Khao Ya Puk Formation.

In summary based on these mentioned features, the unconformable contact between the Phu Khat Formation and the Khao Ya Puk Formation was preferred in the interpretation.

Upper contact

According to all reference sites, the upper contact of the Phu Khat Formation has not been found in the Nakhon Thai region. The reason for an absence of the contact in the upper part of the Phu Khat Formation may be due to the Phu Khat Formation is the uppermost part of the red bed sequence in this region which is consistent with the conclusion of Heggermann et al. (1994).

4.1.2.3 Lithology

In this study the lithology of the Phu Khat Formation can be sub-divided into three parts, i.e., the lower, middle, and the upper parts. The lower part is chiefly and characteristically conglomerate, conglomeratic sandstone, litharenite. The middle part is dominated by alternate beds of sandstone, siltstone and mudstone with occasional trace fossils in calcareous mudstone. While the upper part, the thick-bedded litharenite and calcareous sandstone with tabular cross-bedding are dominant. The formation contains a variety of rock types and commonly underlies an area of high relief or being formed as high mountains in the Nakhon Thai region. Details of lithology in each part are as follows:

The lower part

Conglomerate; The conglomerates beds are well exposed and dominated in the reference locality 1 rather than in the reference locality 2, with varying composition and texture. In the reference locality 1 the pebble and cobble are generally rounded to subangular which is composed of quartz, chert, sandstone, volcanic clastic, mudstone, siltstone and small pebble limestone. The amount of resistant pebble (quartz+chert+sandstone) is 70 % with common red cherts, volcanic clastic (22%), and mudstone and siltstone (8%). The conglomerate beds in the locality 1 can be considered as polymictic conglomerate. These conglomerates, 50 cm to 8 m thick, are matrix- to clast-supported. Clasts range in size from 2-14 cm in average. The matrix is sandy to siltly having purple to reddish purple in colour. Subsequently, the coarsening upward sequences can be found in several conglomerate beds with structureless frabric in matrix-supported beds. In the locality 1 the conglomerate beds are generally intercalated with thin-bedded litharenite having some cross-stratifications observed in sandstone beds. The contact between conglomerate and sandstone are normally shown as channel erosion (Figure 4.10).

The conglomerate in the reference locality 2 is slightly different from the reference locality 1. Clasts in locality 2 are smaller than the locality 1 ranging from 0.5 cm to 4 cm in average. The clasts consist mainly of quartz, chert, sandstone, volcanic, mudstone and siltstone which show more roundness than those of the locality 1. The matrix is siltly to sandy having purple in colour. Subsequently, conglomerate beds, 1-2 m thick, in this locality are thinner than the locality 1.

In summary, the conglomerate from two sites are identical with respect to their clasts composition. Both of them contain mainly of quartz, chert, sandstone, volcanic, mudstone and siltstone. However, the thickness and clast size tend to decrease from the locality 1 to the locality 2 but the roundness index increases from the locality 1 to the locality 2.

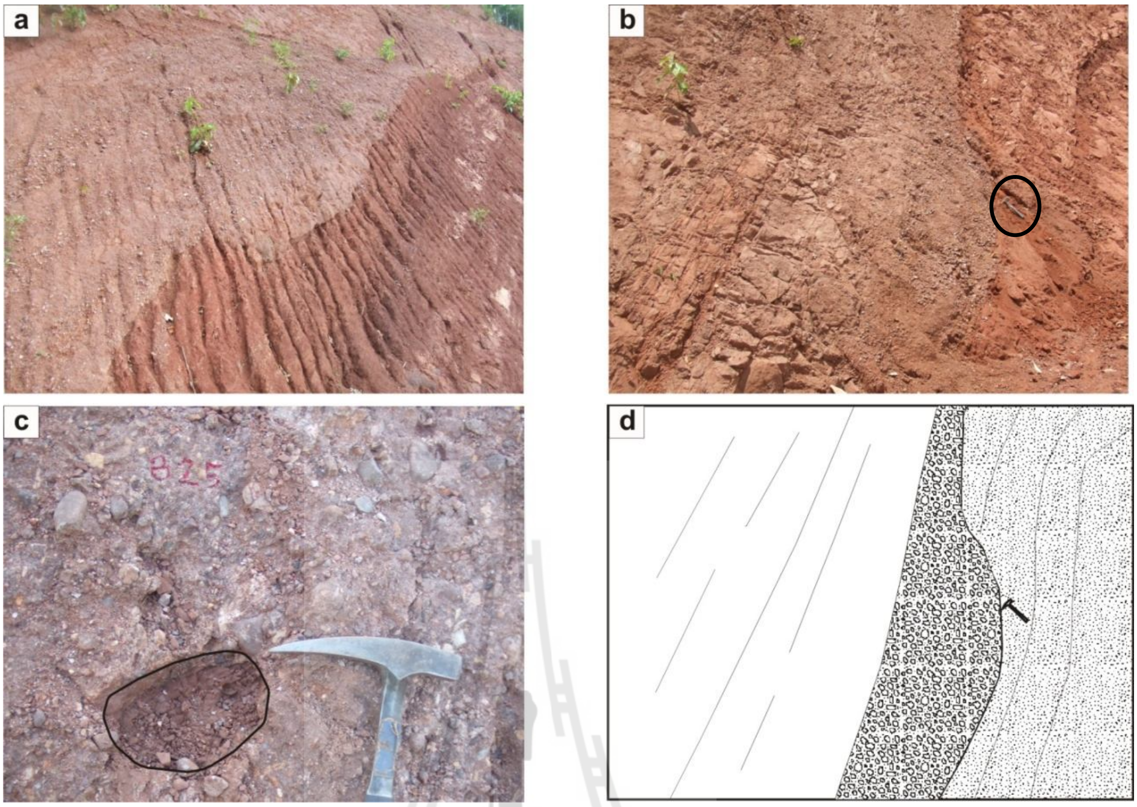


Figure 4.10 Photographs of conglomerate of the Phu Khat Formation. a and b) Polymictic conglomerate filled in the channel of the locality 1. Hammer within the black circle is scale. c) Closed up view of the polymictic conglomerate. Left of the hammer head is a siltstone cobble. d) Sketch of the channel conglomerate in Figure 4.10b.

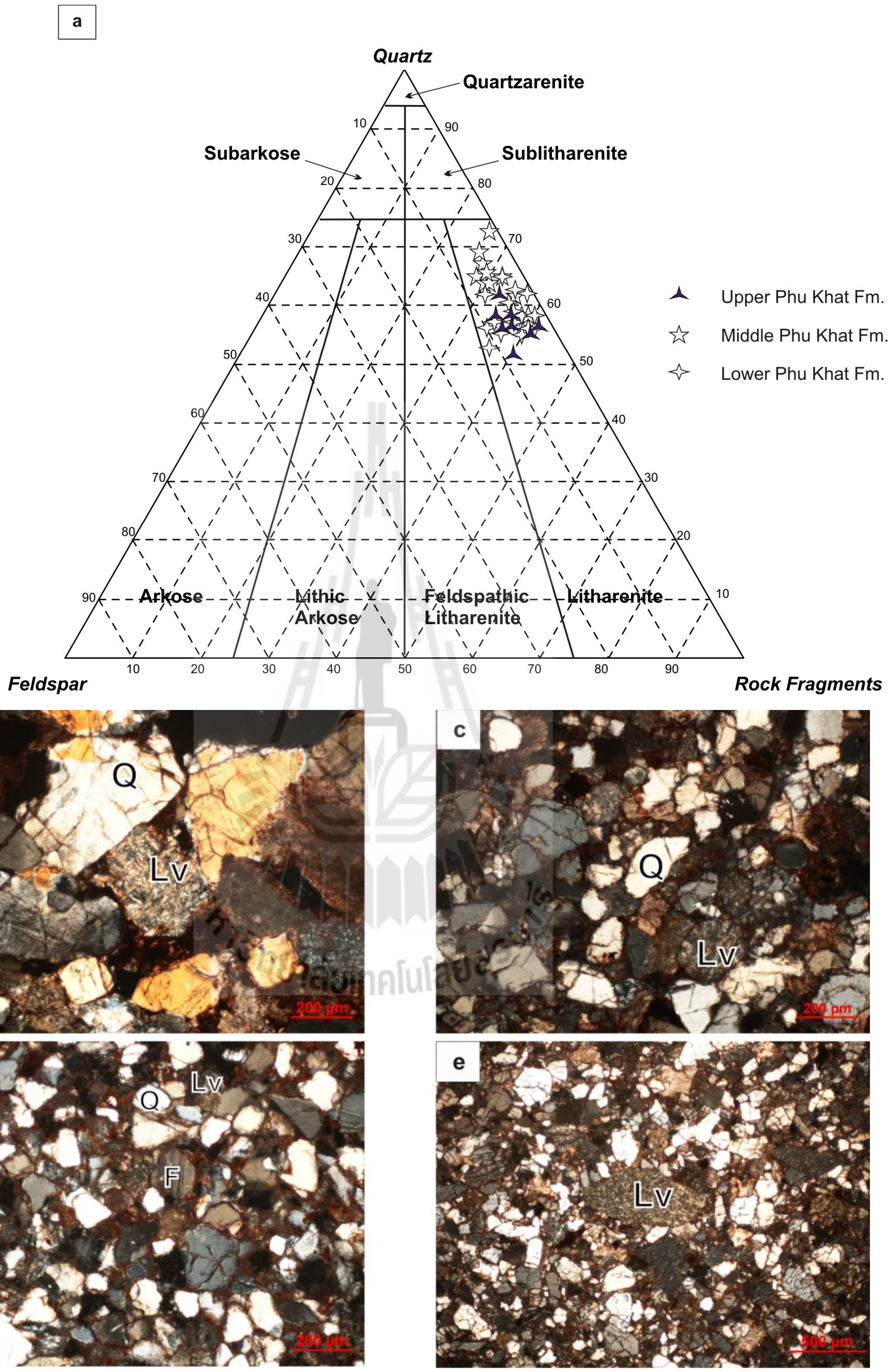


Figure 4.11 Sandstone classification and photomicrographs of clastic sandstone of the Phu Khat Formation.

a) Sandstone classification of the Phu Khat Formation after Folk (1974).

b) Poorly sorted litharenite of the locality 1.

c) Medium-grained, poorly sorted litharenite of the locality 2.

d) Moderately sorted litharenite of the locality 3.

e) Poorly sorted litharenite of the locality 5. All photographs were under cross-polarized.

Q: Quartz, F: Feldspar,Lv: Volcanic lithic fragment.

Sandstone; the sandstone beds are well exposed in both localities (1 and 2) but they tend to be a main sequence in the locality 2 whereas the locality 1 sandstone are a minor sequence interbeded within the predominant conglomerate beds. In the reference locality 1 the sandstones are chiefly litharenite having quartz 58% , feldspar 6% and rock fragment predominated by volcanic 36% (Figure 4.11a). The rocks are generally very fine- to very coarse-grained, poorly sorted texture. It is reddish brown to reddish purple in colour with angular to sub-rounded grains. The beds are ranging from medium- to very thick-bedded and capped commonly by fine-grained sediments which in turn these beds are cut through by the conglomerate beds (Figure 4.10b). Some beds show lenticular laminated beds within the conglomerate beds. Cross-stratifications are generally found in sandstone beds such as: parallel laminated and some small tabular cross-bedding (Figure 4.12). Moreover, complete polygons of mud-cracks with V-shape also have been found in some sandstone beds (Figure 4.13a).

In the reference locality 2 the sandstones are also litharenite sandstone following the classification of Folk (1974) (Figures 4.11a and c). Their components are similar to the reference locality 1 with quartz, feldspar and rock fragments contain 58%, 4% and 38 % respectively. Their grained sizes are ranging from fine- to coarse-grained with poorly- to moderately-sorted texture and grained shapes are angular to rounded grains. Some sandstone beds are conglomeratic sandstone containing rounded pebbles about 1 cm to 2 cm of volcanic rocks (Figure 4.14a). The thickness of beds ranges from thin to very thick. Generally, these beds are capped by fine-grained siltstone and mudstone with fining upward sequence. The sandstone to fine-grained siltstone and mudstone ratio is likely to be more than 3 with rare conglomerate.

Red siltstone and shale; These lithologic types are found as either interbedded or intercalated beds within the conglomerate in the locality 1 and sandstone beds in the locality 2. Some parts are shown as the capped bed on the top of the sandstone beds in the locality 2. Siltstone and shale are thin- to massive-beds ranging from 1cm to 2m thick. They are composed predominantly of siliceous cement with calcareous in some parts particularly in the locality 2. Subsequently, borrow trace fossils are normally observed within the thick-bedded calcareous shale and calcareous siltstone in the locality 2 (Figure 4.14b). Some calcareous nodules are observed in locality 2 (Figure 4.6).

The middle part

The middle part of the Phu Khat Formation is mainly characterized by reddish brown sandstone and reddish brown siltstone and shale. They are observed in the reference locality 3 and 4 which the fining-upward sequence is commonly observed throughout the section. Generally, in the both localities the middle part of the Phu Khat Formation have been found somewhat overlie unconformably on top of the older formation (the Khao Ya Puk Fm.). The details of their lithology are as following.

Sandstone; the sandstone are identical to the lower part which predominantly belong to litharenite with quartz contain 65% , feldspar 3% and rock fragment 32% on the average(Figures 4.11a and d). Nevertheless, the sizes of famework grains seem to be smaller than the lower part and show more textural maturity. They are generally very fine- to medium-grained sandstone with moderate sorting. It is generally reddish brown in color which grained shape range from sub-angular to rounded grains. Some sandstone beds are conglomeratic containing rounded pebble of sedimentary rock about 1cm to 2cm in size within the beds of sandstone (Figure 4.14c). The beds are ranging

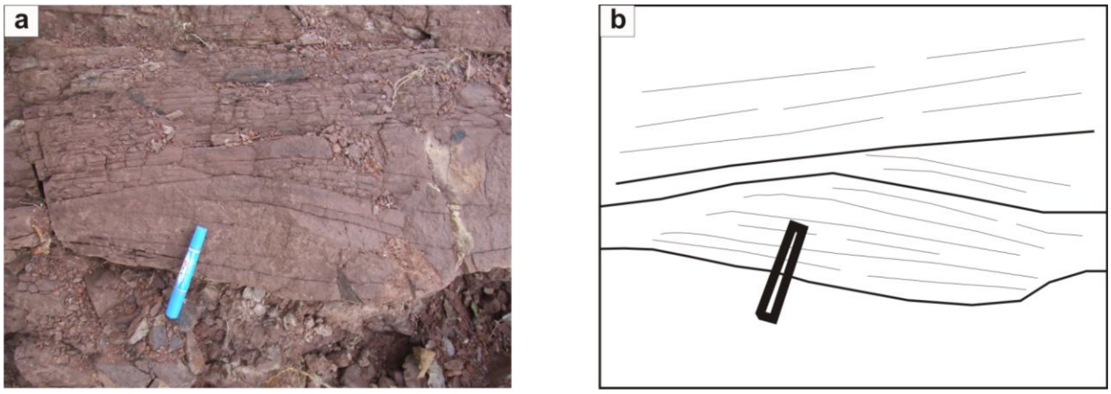


Figure 4.12 Photographs of cross-stratified sandstone in the locality 1 of the Phu Khat Formation. a) A tabular cross-bedding covered by parallel laminated sandstone. The structure probably reflects flows close to the dune-plane bed transition. Pen is scale (12cm). b) Sketch of the Figure 4.12a.

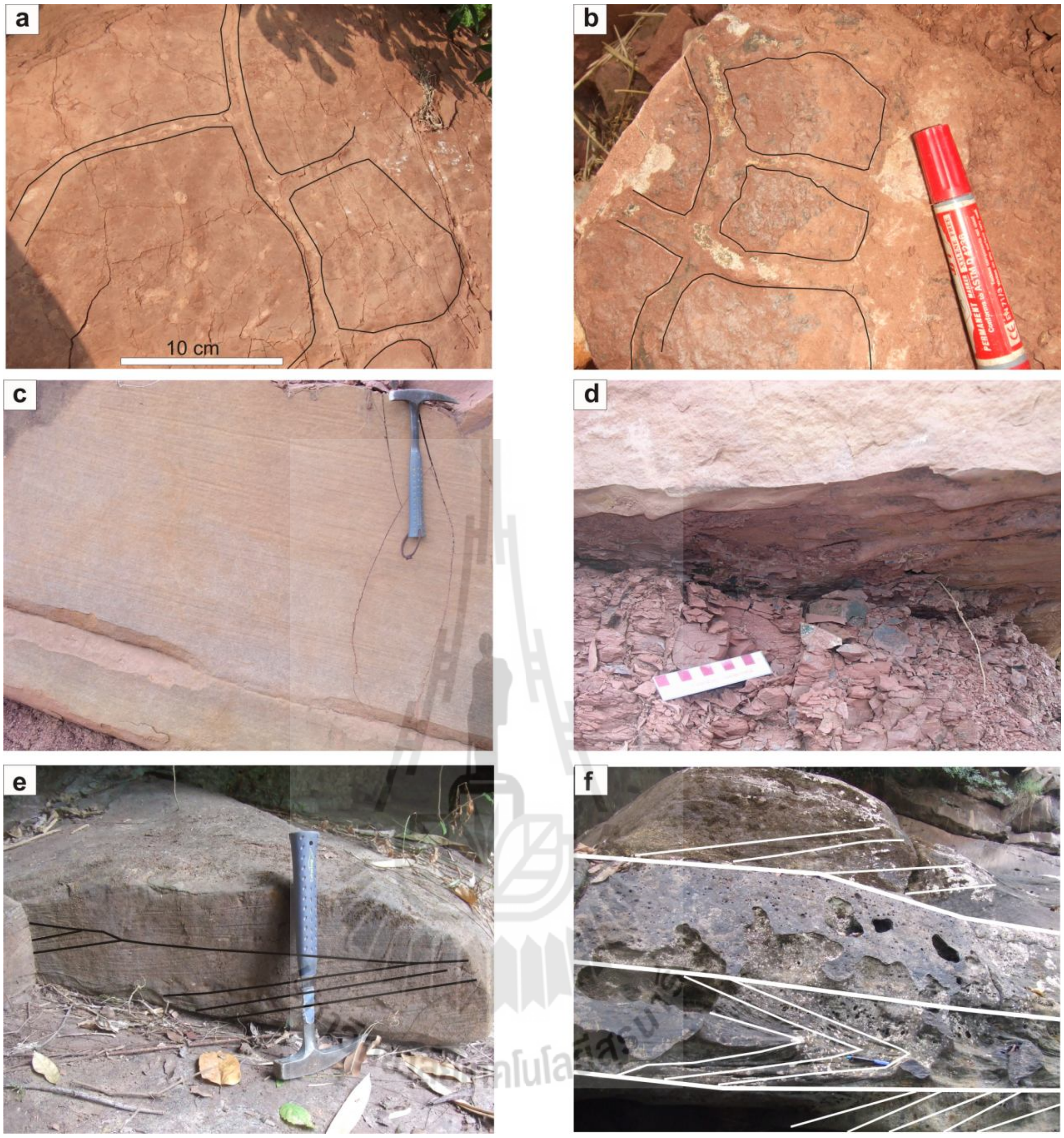


Figure 4.13 Photographs of sedimentary structures in sandstone beds of the Phu Khat Formation. a and b) Polygonal desiccation cracks in the locality 1 and 3 respectively . Pen is scale (12 cm). c) Parallel laminated in the locality 3. d) Load-casts in the locality 3, scale bar 10 cm. e) Tabular cross-bedding in the locality 5. Hammer is scale 30 cm. f) Overturn foreset cross-bedding of the upper part Phu Khat Formation.

from medium- to very thick-bed but in general the thickness decrease up into the upper sequence and capped commonly by fine-grained sediment showing continuous, even, parallel beds with fining and thinning upward sequence. The contacts between beds are sharp planar without erosion and scoured contact. Cross-stratifications are also generally found. It is chiefly by planar bedding, cross-laminated and some tabular cross-bedding as well as ripple mark with linguoid crest in some beds. Complete polygonal of mud-cracks and load-casts are also observed locally (Figures 4.13b, c and d). Consequently, the paleocurrent obtained from cross-stratified structures have shown SEE ward flow direction (Figure 4.16a).

Siltstone and shale; In general theses lithologic type are characterized by siltstone and shale which are interbedded with sandstone beds. They are reddish brown to reddish purple in color. The sandstone to siltstone and shale ratio ranges from 3:1 to 1:1 from the lower sequence to the upper sequence. Siltstone and shale are thinly- to thick- beds which its thickness gradually decreases from the lower to the upper sequence.

The upper part

The upper part of the Phu Khat Formation is mainly composed of thick-bedded sandstone with cross-stratification. They usually expose on the high mountainous area with elevation more than 1000m above mean sea level and show scarp of the mountain. The well exposure out crop is in the reference locality 5 which they have formed as the waterfall. The rocks are characterized by fine- to coarse-grained, poorly- to moderate-sorted sandstone with predominantly reddish brown to light red in color. Their lithology belong mainly to litharenite with quartz contain 56%, feldspar 6% and rock fragment 32% on the average (Figure 4.11a and e). Regarding textural maturity, they are generally showing less textural maturity than the middle part but are quite similar to the lower part with grained shape ranging from angular to sub-rounded grains. The beds are ranging from thick- to very thick-bedded with 1m - 4m thick on the average (Figure 4.15). The sharp erosional contact and pebbles lag are also evident. It is calcareous in some beds but the most are siliceous. The carbonaceous bed of siltstone and mudstone are observed as intercalated beds. Cross-stratification is generally found in sandstone beds especially tabular cross-bedding with overturn foreset (Figures 4.13e and f). Subsequently, asymmetry ripple marks are also observed. All cross-stratified structures indicate SSW ward palaeocurrent direction (Figure 4.16b).

In summary

The lithology of the Phu Khat Formation is composed of three main parts (Figure 4.17). The lower part consists mainly of the polymictic conglomerates, conglomeratic sandstone and poorly sorted litharenite. The polymictic conglomerates are matrix to clast-support within the matrix of sand. They are lacking of structural fabric but some part, in sandstone and clast-support conglomerates, the cross-stratified structures are recognized which indicate SEE ward palaeoflow direction. In the middle part, it is characterized by the tabular geometry of sandstones, siltstone and shale with fining upward sequence. Their compositions are quite similar to sandstone in the lower part. Furthermore, their palaeocurrent are also identical with SEE ward palaeoflow direction. But the sandstone in the middle part is shown more textural maturity than the lower part. The upper part is also predominated by poorly sorted litharenite. Most of them are chiefly shown thick-bedded, cross stratified sandstone that clearly indicated fluvial process system with palaeocurrent perpendicular to both former parts.

Figure 4.14 a) Photographs of conglomeratic sandstone in the locality 2. b) Trace fossils in siltstone beds in the locality 2. Pen is scale 10cm. c) Pebble clasts in sandstone beds in the locality 3. Pen is scale 12cm.

Figure 4.15 Thick-bedded sandstone at the locality 5. The man is scale 180cm height.

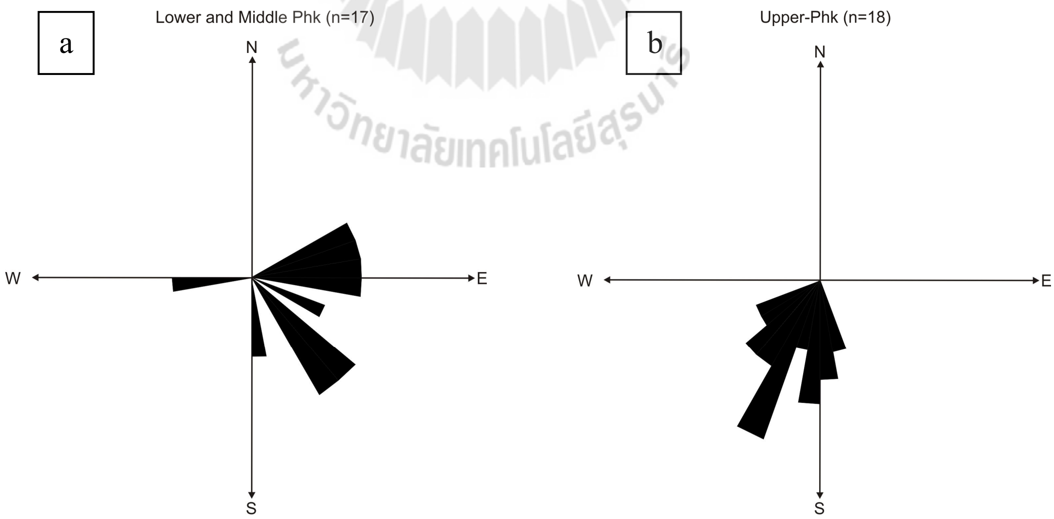


Figure 4.16 Rose diagrams showing paleocurrent pattern of the Phu Khat Formation after tectonic tilt correction. a) The lower and the middle Phu Khat Formation. b) The upper Phu Khat Formation.

4.1.2.4 Thickness and extent

The Phu Khat Formation is present throughout the area of this report and extends somewhat northeast to the north into Uttaradit Province and probably beyond the Thai border into the Ken Thao area in Laos which is bounded by the Nan-Uttaradit Suture Zone to the west and the Loei- Phetchabun Fold Belt to the east. In the report area the formation exposes in Chat Trakan and Nakhon Thai Districts of Phitsanulok Province and Na Haeo and Dan Sai Districts of Loei Province. The rock sequence are generally gently folded into broad synclines and anticlines which NE-SW trending parallel to the trending of the Nan-Uttaradit Suture Zone.

Firstly, Kosuwan (1990) given the name of the Phu Khat Formation but he did not mention the thickness of the formation at the type section. Thereafter, Heggermann (1994) suggest that the thickness of the Phu Khat Formation was about 500m which coincides with Meesook et al. (2002) who state that the Phu Khat Formation was 150 - 500m in range. In this study the thickness of the Phu Khat Formation was measured throughout the three parts and it indicate following Walther'law that total vertical thickness of the formation is 490m thick.

4.1.2.5 Age and correlation

<u>The age</u>

Due to a paucity of fauna and flora, the age of the Phu Khat Formation has been generally inferred by the stratigraphic correlation from several researchers. Heggermann (1994) explained the occurrence of the Phu Khat Formation as a result of the intense deformations in the Upper Cretaceous and the Paleogene during the collision of the Indian with the Eurasian Plates. Consequently, the thrust fault zone along the Nan- Uttaradit Suture Zone were reactivated and eastward thrust over the younger red bed of the Mesozoic Khorat Group. As the same time Heggermann et al. (1994) stated that the Khorat Basin had subsiding experience which is restricted to the Nakhon Thai area and formed the restricted accommodating basin for the alluvial fan sediment at the front of thrust fault zone. The sediments were fed by the thrust fault zone and offered the thick succession of alluvial fan deposited in the Nakhon Thai area. So, based on the assumption above, Heggermann (1994); Heggermann et al. (1994) point out that the age of the Phu Khat Formation is the Late Cretaceous (Campanian - Maastrichtian). This given age is similar with Meesook et al.(2002) and Meesook (2011) who suggest that the age of the Phu Khat Formation is more or less the Late Cretaceous - the Tertiary based on its lithostratigraphic relation that overlies the Late Cretaceous Khao Ya Puk Formation (Assavapatchara and Raksasakulwong, 2010).

In this study, the age of the Phu Khat Formation cannot be indicated directly from absolute age due to a lacking of fossils. However, the relative inferred age which is considered from tectonostratighaphic and detrital zircon dating favor the maximum deposition age of the Phu Khat Formation, which should not older than Campanian and not younger than Ypresian age (See more detailed discussion in chapter V).

Correlation

Based on the lithostratigraphy and stratigraphic position, the Phu Khat Formation can be correlated with the Phu Soay Dao formation in Laos (Assavapatchara and Raksasakulwong, 2010). The rocks in both regions contain similar lithology. In Laos, the Phu Soay Dao formation is composed mainly of brown to maroon sandstone, siltstone and claystone with conglomerate in place. Moreover, its stratigraphic position is identical to the Phu Khat Formation where it is underlain unconformably by the Say Som Boun Formation in which its lithostratigraphy equivalent to the Khao Ya Puk Formation (Assavapatchara and Raksasakulwong, 2010).

4.1.3 Facies characteristics of the Phu Khat Formation

The exposure of the Phu Khat Formation in the Nakhon Thai region has allowed sedimentary logging and revealed stratigraphic sequence. Based on the stratigraphic logging throughout the formation, the facies study was carried out in terms of lithofacies and facies association. The term of lithofacies is defined as the individual facies that emphasized on lithology of the rock that related to environmental process which may not specific environmental deposition. The facies associations are defined as a group of facies that occur together which are considered to be genetically or environmentally related to specific environmental deposition (Pirrie, 1998). So, in order to determine the environmental deposition of the Phu Khat Formation, the facies study including individual lithofacies and facies associations were carried out in details.

4.1.3.1 Lithofacies

The Phu Khat Formation in the Nakhon Thai region consists of nine individual lithofacies. There are deduced from the five reference localities and can be summarized in Table 4.1. The salient characteristics are as following:

Massive, matrix to clast supported conglomerate (facies Gms)

This facies consists of matrix to clast-supported conglomerate. The clasts are composed of quartz, chert, sandstone, siltstone, mudstone and little limestone. They are sub-angular to rounded and range in size from 2 to 14cm. The matrix is mainly purple in color, poorly-sorted sandstone.

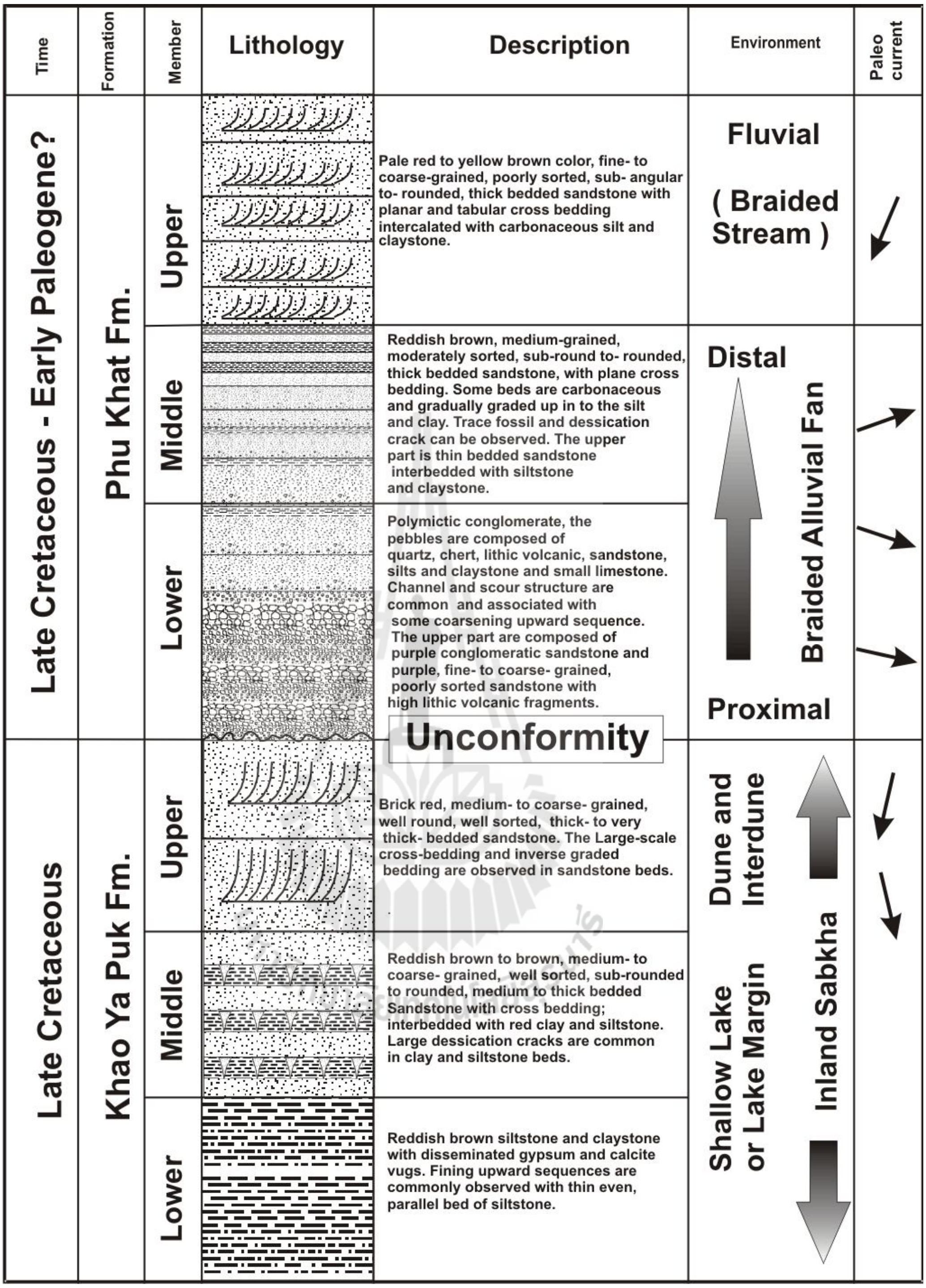


Figure 4.17 Schematic composite stratigraphic column of the Khao Ya Puk and the Phu Khat Formations. The Khao Ya Puk Formation modified after Monjai (2006) (Not to scale). For environmental deposition of the Phu Khat Formation see more detailed interpretation in section 4.1.3.2.

They generally occur as the massive beds and are usually associated with horizontal bedded sandstone. The bodies may display either sheet or lenticular geometries. Their lower boundaries are sharp contact above erosional surface where the upper boundaries are either sharp or graded up in to sandstone facies (Figure 4.18).

Massive or crudely bedded gravel (facies Gm)

This facies is dominated by clast-supported conglomerate. It generally occurs as the thick-beds above erosional surface where it grades up in to sandstone facies, as either lenticular or channel shape (Figure 4.19). Clasts are generally rounded and are mainly quartz, chert and sandstone. Sedimentary structures are rare in this facies.

Sand, coarse-grains with some pebbles (facies Ss)

This facies is characterized by medium- to coarse-grained sandstone. It is poorly sorted textures with angular to sub-rounded grains. Beds have either graded or erosive bases contact and are commonly underlain by beds of conglomerate facies (facies Gms and Gm) and fine-grained facies (facies Fl and Fm) (Figures 4.19 and 4.20). It is generally formed as medium- to very thick-beds with structureless. Occasionally, some beds display cross-stratification.

Sand, fine- to coarse- grains with planar lamination (facies Sh)

Facies Sh sandstone is characterized by very fine- to coarse-grains. It is poorly- to moderately-sorted texture with sub-angular to rounded grains. They generally display planar laminated structure and form unit ranging from 0.2-4m thick. The beds are characterized by sheet geometries with sharp boundary or erosional contact (Figure 4.21).

Sand, medium- to coarse-grains with planar cross-bedding (facies Sp)

This facies is dominated by medium- to coarse-grained sandstone. It is moderately- to poorly-sorted texture with sub-angular to rounded grains. The tabular cross-bedding are the main sedimentary structure in this facies which the foreset dip between 10^0 and 25^0 (Figure 4.22). The thicknesses of bedded set are medium to very thick. They are sharp contact with the lower and the upper beds. In general, the beds of medium-grained sandstone with moderately sorted texture are alternated with fine-grained, horizontally bedded sandstone of facies Sh.

Sand, fine- to medium-grains with cross-lamination (facies Sr)

Sandstone in this facies is characterized by fine - to medium-grains with moderately-sorted texture. The cross-laminations are the main sedimentary structure in this facies which were associated occasionally with horizontal lamination (Figure 4.23). The beds are characterized by sheet-like geometries and show sharp boundary contact with the fine-gained facies Fl and Fm. Generally, thickness of the beds range from thin- to thick-bedded.

Sand, silt, mud with fine lamination (facies Fl)

This facies is dominated by siltstone and mudstone associated with minor unit of fine- to very fine-grained sandstone. The sandstone beds are thin bedded while the siltstone and mudstone are formed as medium- to thick-bedding and display sheet-like geometries (Figure 4.24a). The main sedimentary structures are fine-lamination that has been found in siltstone and mudstone. However, in some locations the facies Fl was found as the unique unit and was not associated with thin bedded sandstone. In this scheme the facies has either sharp or gradational contact with the lower unit of facies Sh and in turn it was overlain by erosive contact of facies Gms, Gm or Ss (Figure 4.24b).

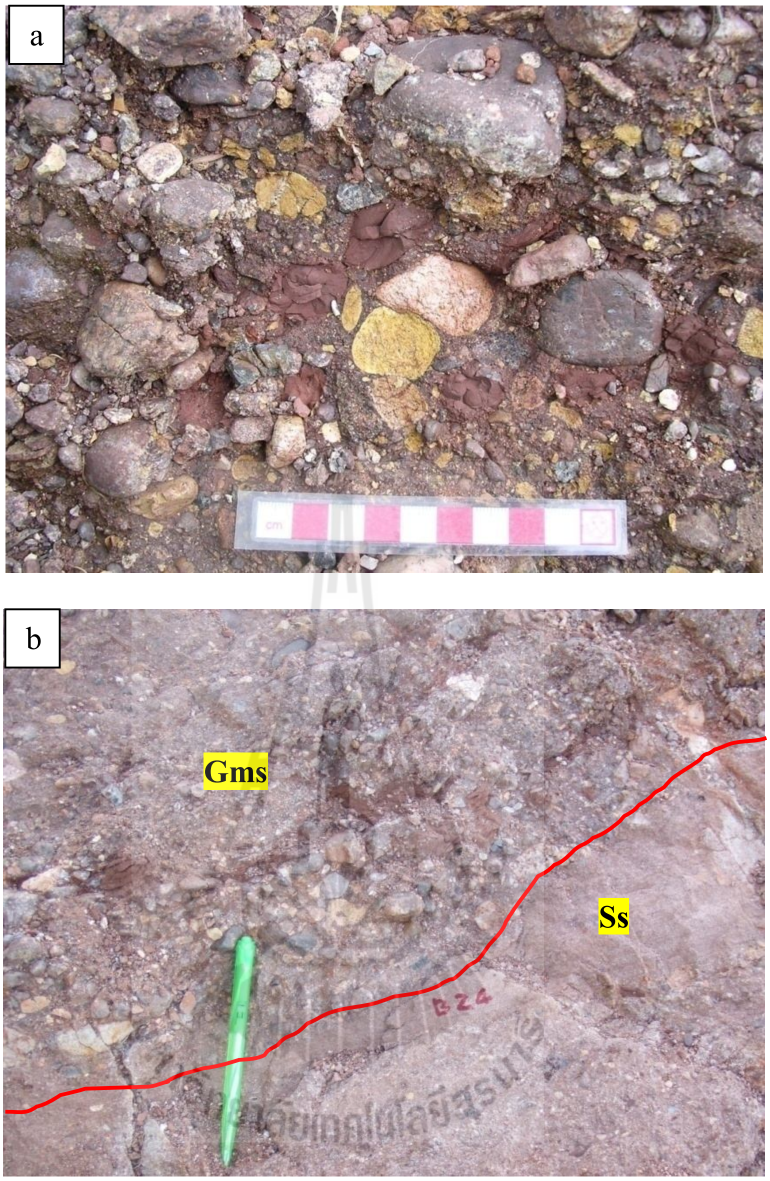


Figure 4.18 Photographs of facies Gms a) Matrix to clast-supported, polymictic conglomerate of facies Gms. b) Erosional contact between facies Gms and Ss. Both a and b are in the locality 1.

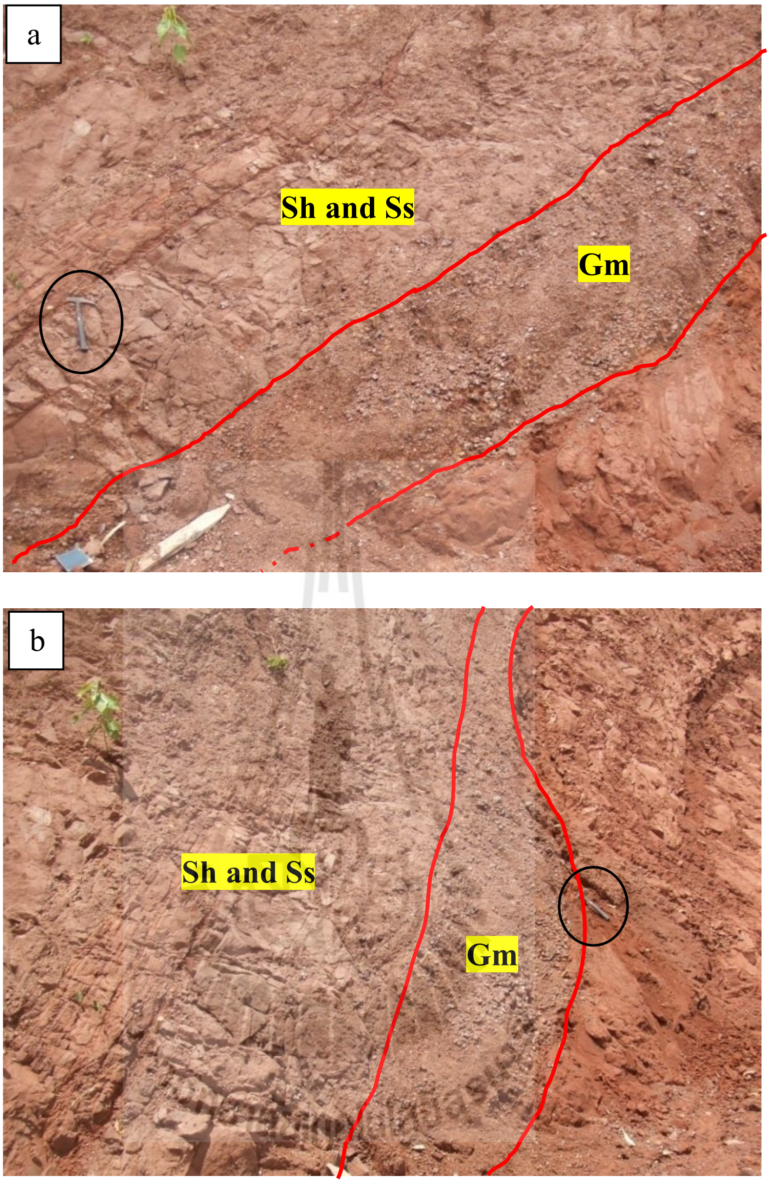


Figure 4.19 Photographs of facies Gm in the locality 1 a) Facies Gm is overlain by sandstone of facies Sh or Ss b) Channel geometry of facies Gm. Hammer within the black circle is scale 30 cm long.

Figure 4.20 Photographs of facies Ss a) Conglomeratic sandstone of facies Ss in the locality 1 b) In the locality 2. Hammer is scale 30 cm long.

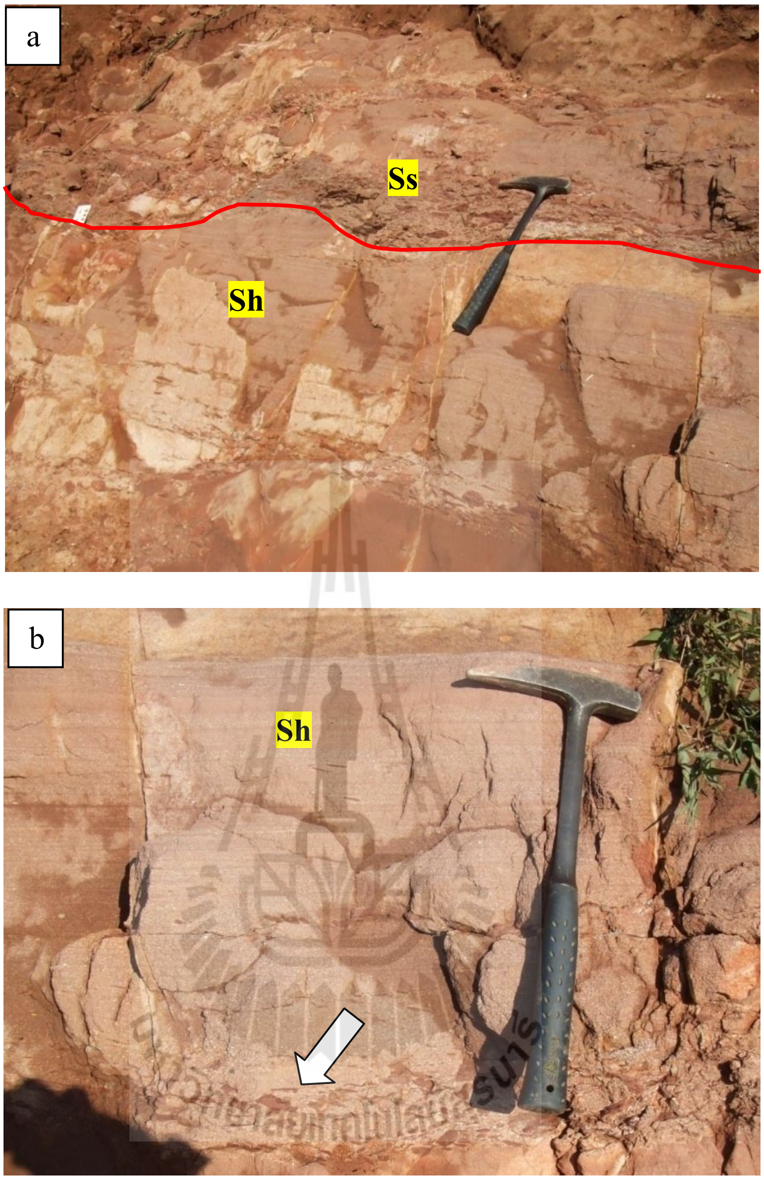


Figure 4.21 Photographs of laminated sandstone of facies Sh. a) The conglomeratic sandstone of facies Ss cuts the facies Sh. b) Rip-up clasts (arrow) are at the base of facies Sh. Hammer is scale 30 cm long. Grid referrence 697020E, 1945374N Map Sheet 5144II (Ban Bo Phak), Series L7018

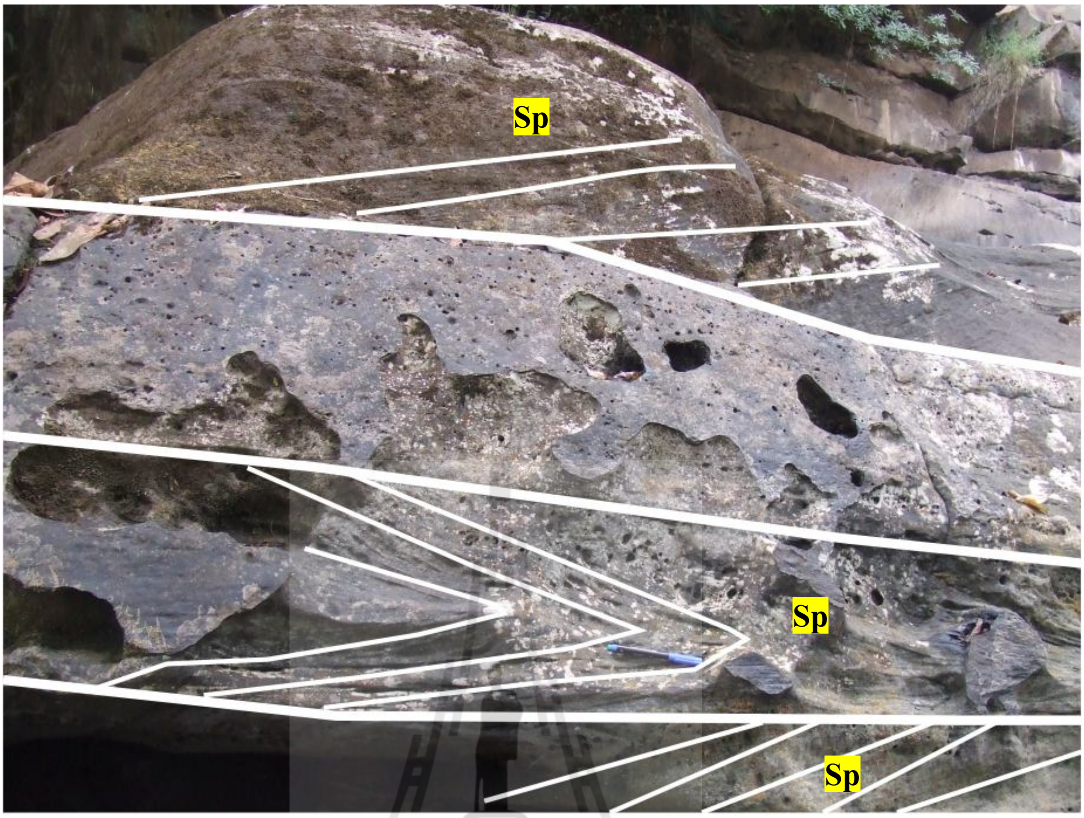


Figure 4.22 Thick bedded sandstone with tabular and overturn foreset cross-bedding of the facies Sp. Pen is scale 10 cm long. Grid referrence 711397E, 1943152N Map Sheet 5144II (Ban Bo Phak), Series L7018

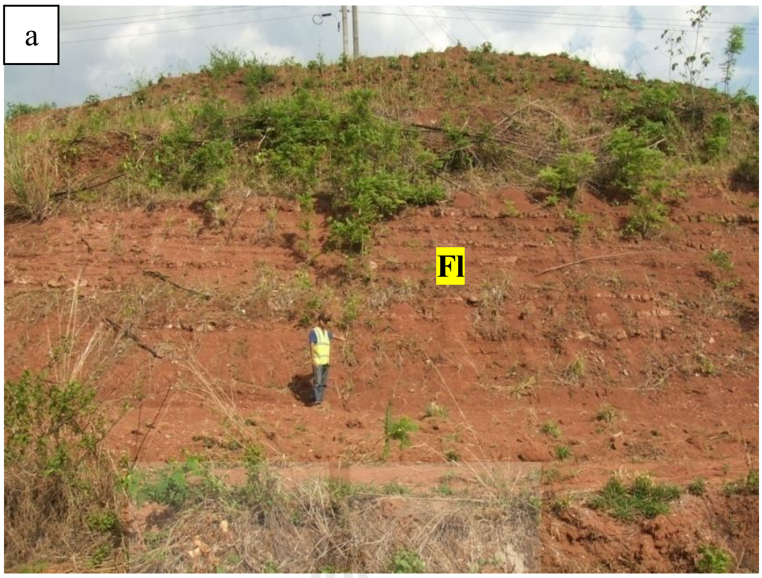
Figure 4.23 Cross-laminated sandstone of the facies Sr. Both a and b are in the locality 3.

Silt and mud with lamination to massive (facies Fsc)

This facies is characterized by massive-bedded siltstone and mudstone. Mudstone is dominant unit while the siltstone is minor. In general, it is more than 4m thick with structureless. Trace fossils are often found in this facies. It overlies sharply on the medium- to coarse-grained, poorly sorted sandstone of facies Ss or Sh.

Mud and silt with desiccation cracks (facies Fm)

This facies is dominated by a thin-bedded mudstone and siltstone that desiccation cracks have been often found in this facies (Figure 4.25). It is sharp to gradational contact with the lower unit of medium- to fine-grained sandstone with moderately- to well-sorted texture of facies Sh or Ss. In turn, it is overlain sharply by coarse-grained sandstone with poorly-sorted texture of the facies Sh or Ss.



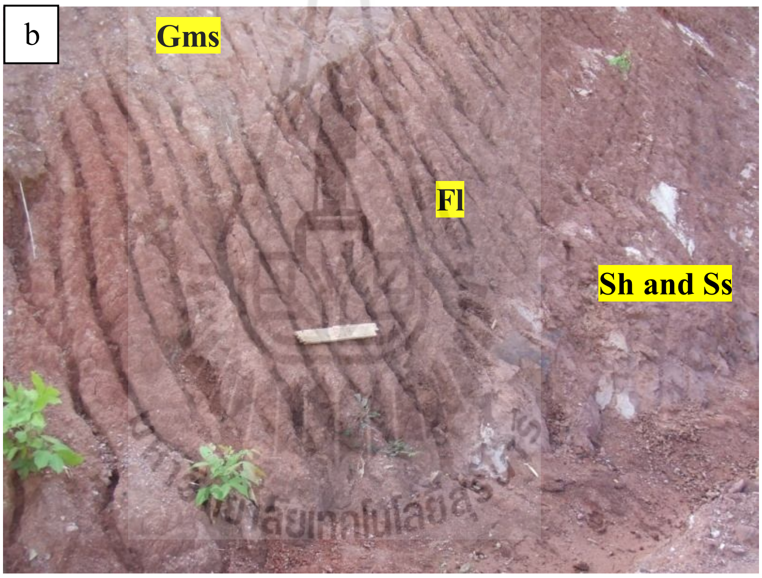


Figure 4.24 Photograps of facies Fl a) Down slope flood plain deposit or overbank of facies Fl in the locality 3. b) Waning flood deposit of facies Fl in the locality 1.

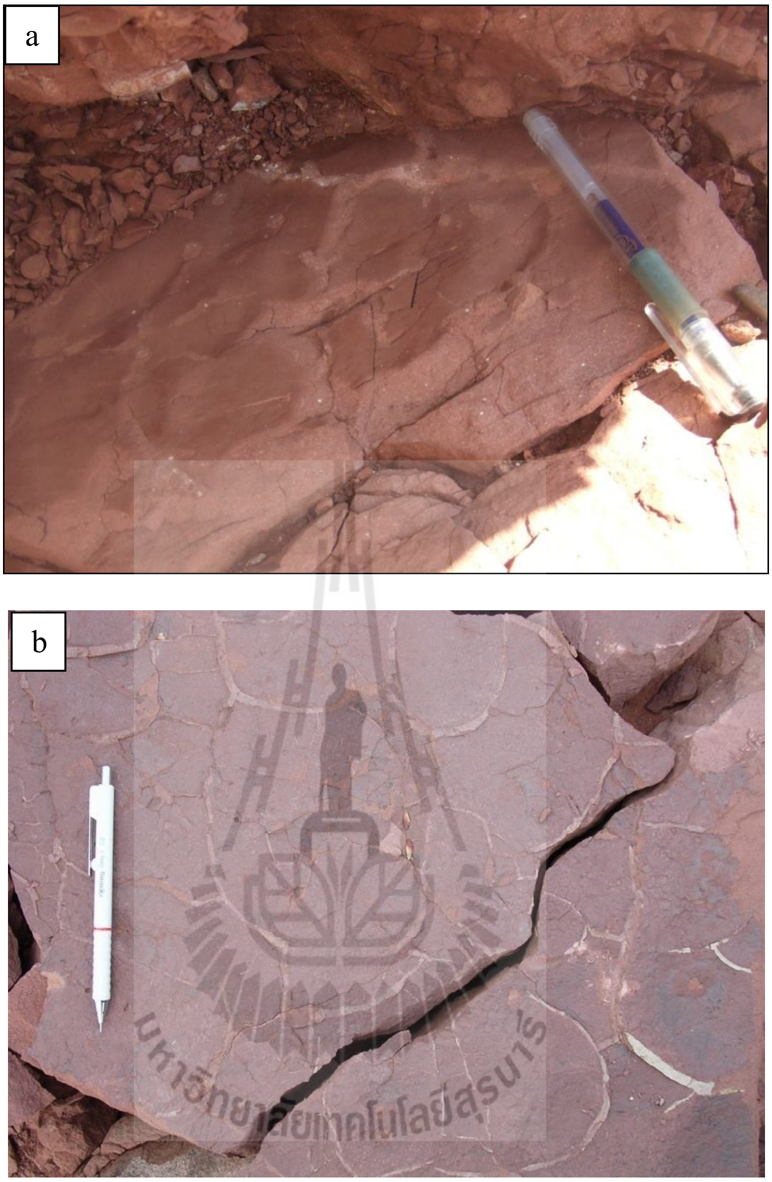


Figure 4.25 Dessication cracks found in facies Fm a) Dessication cracks of mud drap of facies Fm on top of facies Ss in the locallity 1. b) Dessication cracks of over bank deposite of facies Fm associated with facies Fl in the locality 3.

Table 4.1 Lithofacies of the Phu Khat Formation in various localities. Interpretation process after Miall (1985; 1996), Collinson (1996) and Selley (2000)

Reference locality / Facies Code	1	2	3	4	5	Description	Interpretation Process
Gms	**000**					Massive, matrix to clast - supported conglomerate	Debris flow
Gm	**000**	**0**				Massive or crudely bedded gravel	Channel lag deposit
Ss	**00**	**000**				Poorly sorted, coarse grained sandstone with some pebbly	Scour fills, rapid deposition of poorly sorted sand
Sh	**00**	**00**	**000**	**00**	**000**	Fine- to coarse-grained sandstone with planar lamination	Planar bed flow (lower or upper flow regime)
Sp			**00**	**0**	**000**	Medium- to coarse-grained sandstone with planar cross bedding	Straight-crested dune (lower flow regime)
Sr			**00**		**0**	Fine- to medium-grained sandstone with cross laminated	Ripple (lower flow regime)
Fl	**0**	**0**	**00**	**00**		Sand, silt, mud with fine lamination	Overbank or waning flood deposit
Fsc		**0**				Silt and mud with lamination to massive	Backswamp or abandon channel deposit
Fm		**0**	**0**	**0**		Mud and silt with desiccation cracks	Overbank or drape deposit

Occurrence: 0 = rare; 00 = common; 000 = abundant

4.1.3.2 Facies associations

The terms of facies associations are defined as a group of facies that occur together and are considered to be genetically or environmentally related. The principal reason behind the used of facies association is that the individual facies may not specific environmental deposition but facies associations are environmental specific (Pirrie, 1998). So in this study the facies associations were used to interpret the depositional environment of the Phu Khat Formation. Following to the lithostratigraphy, three facies association can be delineated as shown in Table 4.2 and the details of each facies association are as following.

Facies association A

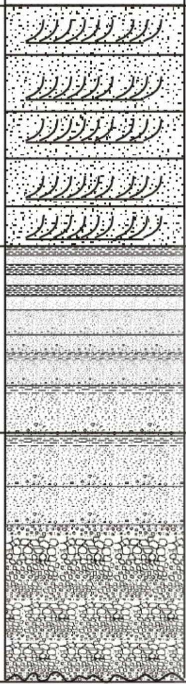
This association occupies the lower part of the formation. It is abundant in the western part of the Nakhon Thai region (the localities 1 and 2) extending in NNE–SSW direction. The rocks contain the coarsest sediments in the succession which their grained sizes decrease remarkably from west to east. It is sub-divided into two facies association A1 and A2 which is composed of facies Gms, Gs, Ss, Sh, Fl, Fsc and Fm.

Description The facies association A1 is gravel-dominated and well exposed in the western part of the Nakhon Thai region (the locality 1). It consists mainly of the association of facies Gms, Gm, Ss, Sh and Fl. The facies Gms and Gm are matrix to clast-supported, poorly sorted conglomerate. The clasts range in size from granule to cobble with a maximum clast size of 14cm (Figure 4.26a). The clasts of conglomerates are sub-rounded to rounded, elongate to spherical. The bedrock provenances are composed of quartz, chert, sandstone, volcanic clastic, mudstone, siltstone and little small pebble of limestone. The amount of resistant pebble (quartz+chert+sandstone) is 70% while 22% is volcanic clastic and 8% remainder is mudstone and siltstone. The geometry of conglomerates displays massive-channel structure with some coarsening upward sequence and grade upward into structureless, poorly sorted, coarse-grained sandstones of facies Ss and Sh. Some sandstone beds contain scattered pebbles and planar cross-stratification (Figures 4.26b and c). The sandstones are generally capped by very fine-grained sandstone, siltstone and mudstone of facies Fl that contain rare vertical burrows (Figures 4.26d and e). The tabular cross-bedding and clast-imbrications are locally observed which indicate paleocurrent unidirectional mostly eastward direction.

The facies association A2 is well exposed in the central part of the Nakhon Thai region (the locality 2). It consists mainly of the association of facies Gm, Ss, Sh, Fl, Fm and Fsc (Figure 4.27). It is dominated by poorly-sorted texture, medium- to coarse-grained sandstones of facies Ss and Sh (Figures 4.27a and b). These sandstones beds are massive and structureless. But some horizontal stratification is observed locally. In general, the successions display thinning and fining upward sequence which sandstone beds are capped by fine-grained siltstone and mudstone of facies Fl, Fm and Fsc with abundant trace fossils in facies Fsc (Figure 4.27c) and some calcareous nodules in facies Fl. The sandstone to fine-grained siltstone and mudstone ratio is likely to be more than 3 with rarely conglomerate (Gm).

Interpretation The facies association A is interpreted to represent alluvial fan deposit. The occurrence of facies characteristics, i.e., matrix to clast-supported, poorly sorted conglomerate, local clast imbrication, the absence of marine influence, unidirectional paleoflow direction and the downdip decrease in grain size from facies association A1 to A2 indicate bedload fluvial stream under unsteady flow and discharge conditions (Collinson, 1996; Miall, 1996).

Table 4.2 Facies associations of the Phu Khat Formation (see text for more description and interpretation)

Formation			Facies Association	Lithofacies	Description	Environmental Interpretation
Phu Khat Fm.	Upper		C	Sp Sh Sr	Pale red to yellow brown color, fine- to coarse-grained, poorly sorted, sub- angular to- rounded, thick bedded sandstone with planar and tabular cross bedding intercalated with carbonaceous silt and claystone.	Fluvial (Braided Stream)
	Middle		B	Sh Sr Sp Fl Fm	Reddish brown, medium-grained, moderately sorted, sub-round to- rounded, thick bedded sandstone, with plane cross bedding. Some beds are carbonaceous and gradually graded up in to the silt and clay. Trace fossil and dessication crack can be observed. The upper part is thin bedded sandstone interbedded with siltstone and claystone.	Distal Braided Alluvial Fan
	Lower		A	Gms Gm Ss Sh Fl Fsc Fm	Polymictic conglomerate, the pebbles are composed of quartz, chert, lithic volcanic, sandstone, silts and claystone and small limestone. Channel and scour structure are common and associated with some coarsening upward sequence. The upper part are composed of purple conglomeratic sandstone and purple, fine- to coarse- grained, poorly sorted sandstone with high lithic volcanic fragments.	Proximal

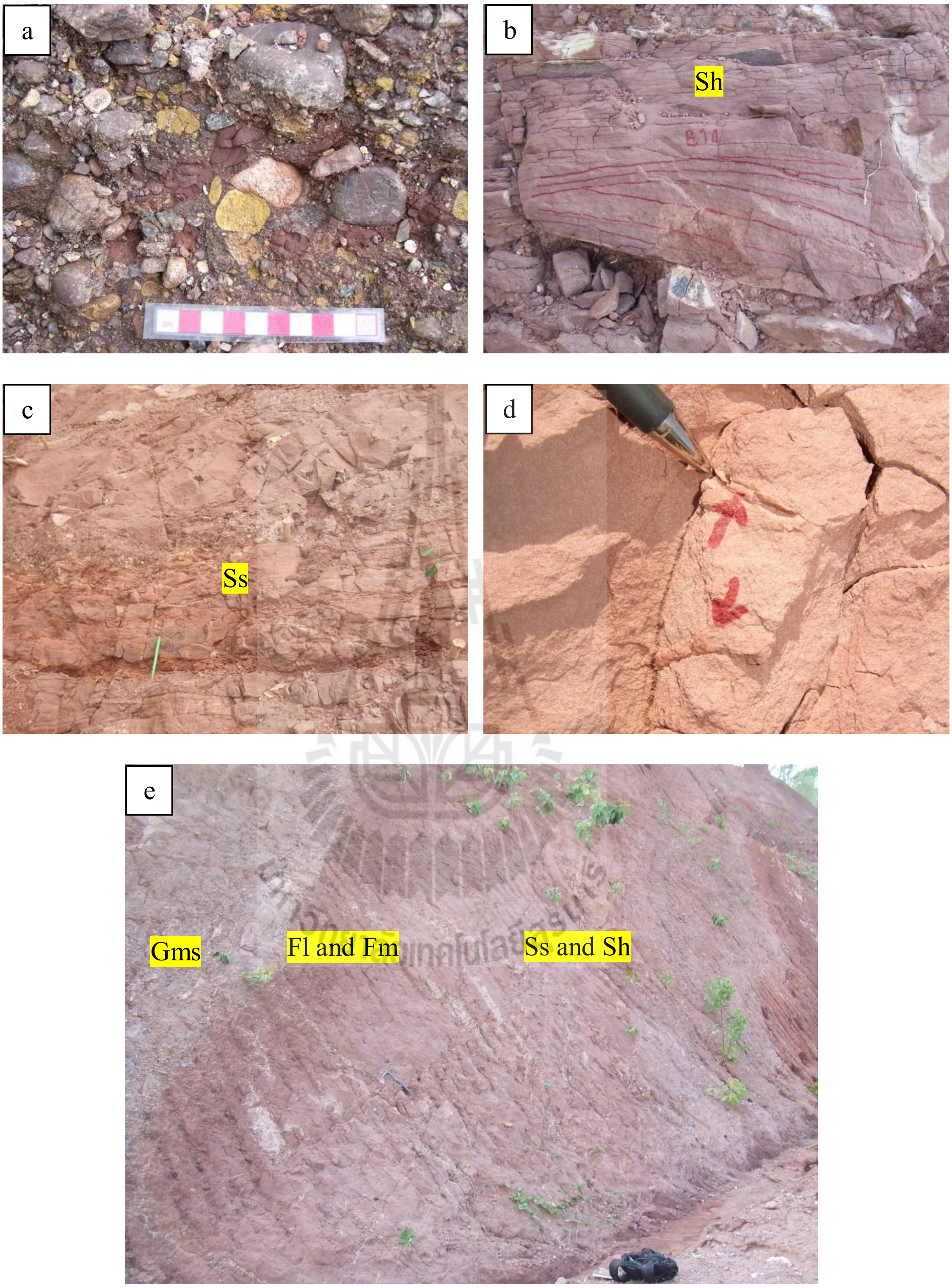


Figure 4.26 Photographs of facies association A1 in the locality 1. a) Facies Gms. b) Cross-stratification in facies Sh and Ss. c) Massive sandstone of facies Ss. d) Trace fossils in facies Ss. e) Facies Fl associated with facie Ss, Sh and Gms.

The conglomerates beds of facies Gms in the facies associations A1 are characterized by matrix to clast-support with coarsening upward sequence. It is similar to facies 'Gms' of Nichols and Uttamo (2005) which was interpreted as debris flow deposit in alluvial fan environment (Miall, 1996). The facies Gms is associated with the facies Gm, Ss and Sh. Their sedimentary structures are composed of the channel-like structures and cross-stratification in the sandstone of facies Ss and Sh. The occurrence of facies Gm with channel-like structure suggests the channel lag deposit. The facies Ss is interpret to deposit by rapid deposition of poorly sorted, coarse bed load as scour fills (Miall, 1996) since they are associated with the facies Gms and Gm. The facies Sh are normally interpreted either as plane bed in shallow water of lower flow regime or during flood stage when plane bed develops under upper flow regime condition (Miall, 1996). In this study the facies Sh in the facies association A1 and A2 are interpreted as a result of flood stage deposit under upper flow regime of the sheet flood deposit of debris flow environment because it is close relation to the facies Ss and Gms facies. The Fl facies represent the deposition from suspension and weak traction current (Miall, 1985). It can be interpreted either as the flood plain deposit, overbank deposit or waning flood deposit based on their association facies (Miall, 1996). In this study the facies Fl in the facie association A1 is associated with the alluvial fan facie, i.e., Gms, Gm, Ss and Sh facies (Figure 4.26e). Therefore, it is reasonable to interpret the Fl facies in facies association A1 as a result of waning flood deposit. While in the facies association A2, the facies Fl, Fm and Fsc is interpreted to be deposited mainly by overbank deposit because they are collaborated with thin, sheet-like sandstone (Figure 4.27d) and associated with facies Ss of scout fill**.** The occurrence of calcareous nodules in facies Fl of facies association A2 may due to the result of the evaporation of soil moisture within capillary rise of groundwater in semi-arid climate which leave the calcium carbonate precipitate as the nodules in poorly drained soil (Thomas, 1994).

In summary, based on all features above, it might imply that the depositional environment of the facies associations A is under alluvial fan deposit (Miall, 1996; Stanistreet and McCarthy, 1993; Blair, 1987; Heaward, 1977). The presence of channel-like structure and cross-stratification in facies association A1 may reflect the confined stream flow which palaeocurrent indicate SEE ward flowed direction. These features may suggest that the alluvial fan condition is non-arid climatic condition and that it is possibly semi-arid condition (Blair and McPherson, 1992). It is similar with the proximal facies of braided alluvial fan of Stanistreet and McCarthy (1993), Kelly and Olsen (1993) and Nichols and Fisher (2007) that are characterized by amalgamated coarse, pebbly and sandy channel deposit with little preservation of overbank facies. Meanwhile the facies association A2 which is similar to facies association A1 in terms of facies characteristic but they are different in terms of composition of lithofacies type. There is significantly deceasing of conglomeratic succession and grained size distribution of sandstone as well as channel-like structure when compare with the facies association A1. However, the preservation of fine grained sediments is increased. These facies characteristic indicate deposition of facies association A2 on topographically low areas, probably on the downstream far more away from proximal fan area as stated by Stanistreet and McCarthy (1993), Kelly and Olsen (1993) and Nichols and Fisher (2007).

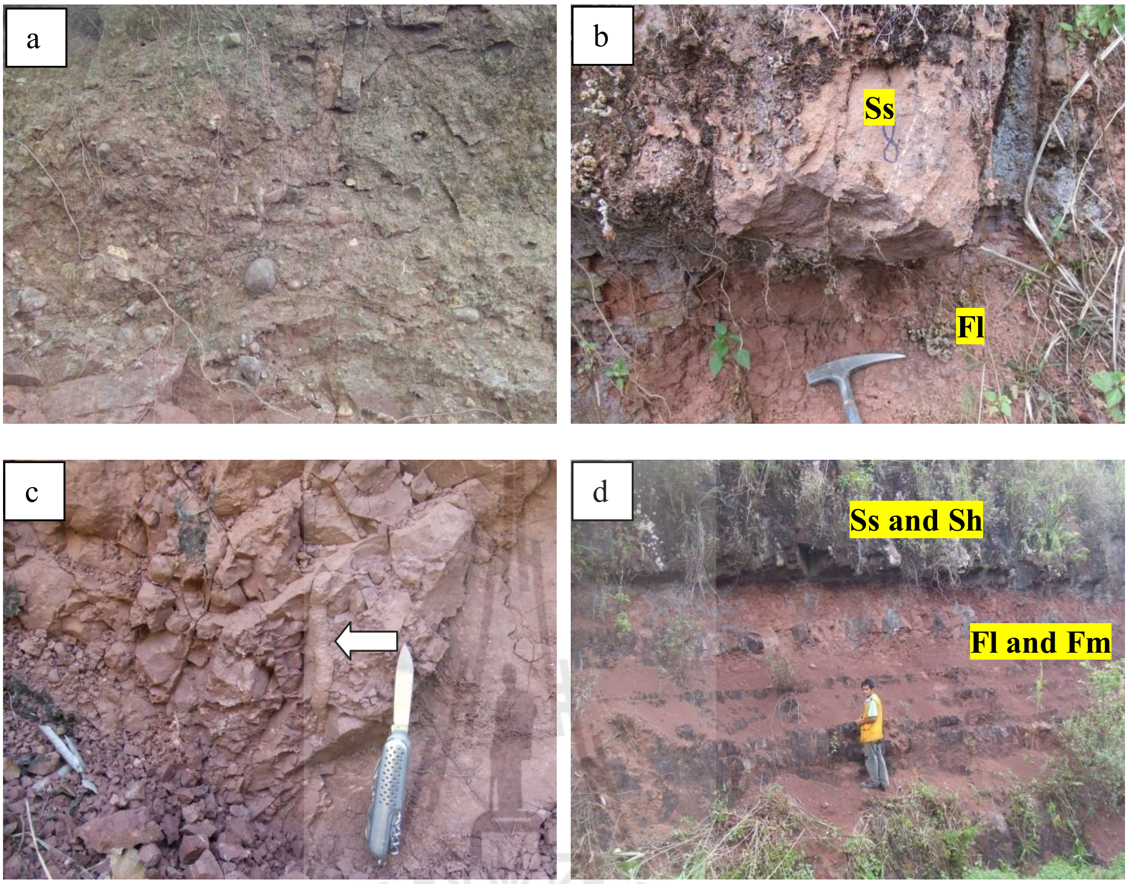


Figure 4.27 Photographs of facies association A2 in the locality 2. a) Conglomeratic sandstone of facies Gm and Ss. b) Associations of facies Ss (resistant beds) with facies Fl (non-resistant beds). c) Trace fossils in facies Fsc (arrow head). Knife is scale 10 cm. d) Association of facies Gm, Ss (resistant beds) with facies Fl (non-resistant beds). The man is scale 163 cm height.

Facies Association B

This association occupies the middle part of the formation. It is abundant in the eastern part of the Nakhon Thai region (the localities 3 and 4). It consists mainly of fine-grained sandstone with a remarkable increasing textural maturity than the facies associations A (also see section 4.1.2.3). It is composed of facies Sh, Sr, Fl and Fm with subordinated facies Sp.

Description Tabular sandstone bodies of facies Sh occur throughout most measured sections and are composed of fine- to medium-grained sandstone (Figure 4.28a). Ripple cross-stratified sandstone of facies Sr are also common throughout the sandstone beds (Figures 4.28b and c). The facie Sh and Sr is dominated in the lower succession and decrease gradually in the upper succession of the facies association B. Trough cross-stratification with low-angle cross-stratification and epsilon cross-bedding are absent. Individual beds range from 0.4 to 3m thick and extend laterally for 150 to 200m showing sheet-like geometry. There is no evidence to suggest the sand sheet are channel fills or were laterally accreted since tabular sandstone bodies have sharp contacts with underlying deposit with laterally extensive (>150 m) sheets. Tabular sandstone bodies are sometime capped by thin-bedded, very fine-grained sandstone, but in many cases they are capped by siltstone and mudstone of facies Fl and Fm. The sand dyke that probably induced by earthquake activity in the region are observed locally (Figures 4.28e and f). Width-to-thickness ratios are consistently greater than 100:1 for individual tabular sandstone beds. More commonly, the tops of succession of the facies association B are characterized by laminated siltstone and mudstone interbedded with thin sheet-like sandstone of facies Fl (Figure 4.28d).

Figure 4.28 Photographs of facies association B in the locality 3. a) Tabular sandstone bodies of facies Sh. b and c) Cross-laminated sandstone of facies Sr. d) Laminated siltstone and mudstone interbedded with thin sheet-like sandstone of facies Fl. e and f) Sand dyke structures cut through siltstone of facies Fl.

Interpretation Tabular sandstone bodies of facies Sh are generally interpreted as a result of rapid flood deposition in laterally extensive, unconfined sheets and poorly confined fluvial channels. In this study, sheets-like geometries are interpreted as down slope terminal splays (Nichols and Fisher, 2007). The abundance of laterally extensive sandstone units consisting of horizontal stratification and ripple cross-stratified sandstone combined with rare occurrences of trough cross-stratification, low-angle and epsilon cross stratification suggests that flow events were short-lived and of high intensity (Tunbridge, 1984). The close association of facies Sh horizontally stratifications and Sr ripple cross-stratified sandstone may suggest fluctuation of flow conditions. The occurrence of facies Fl and Fm capped on both tabular and ripple cross-stratified sandstone is a common product of waning flow velocity associated with flow termination or channel abandonment (Smith et al., 1989; Miall, 1996). The majority of unconfined deposits may represent single flood event which flow was characterized by initial upper plane-bed conditions under traction transport during peak flood conditions, afterward by current-ripple migration during waning flood flow. The rare occurrence of trough cross-stratification and bar elements, together with the obvious lack of planar cross-stratification suggests less lateral migration of channel elements of meandering stream system (Todd, 1996; Bridge, 2003). The facies Fl and the thin sheet-like sandstone in the upper succession are interpreted to be overbank down-slope floodplain. This facie may be similar with the crevasse splay deposits adjacent to channel. However, crevasse splay deposits adjacent to channel sandstone units are typically <0.75 m thick, whereas unconfined sheet deposits are typically <2 m thick (0.75 to 2.0 m thick). Therefore, distinguishing between overbank crevasse splay deposits and down slope terminal splays can be difficult. In this study, the majority of fine-grained deposits and sheet sandstone units are <0.75m thick in the upper succession and lack of the close association with channel sandstone or levee deposit, so they are interpreted to represent terminal floodplain deposits associated with the most distal portion of the system.

In summary, based on the tabular, sheet-like geometry of these deposits, and the vertical distribution of horizontally stratified and ripple cross-stratified sandstone with thin drapes of mudstone and flood plain deposit, the facies associations B is interpreted to have been deposited by unconfined to poorly confined sheetflow conditions of down slope distal area of alluvial fan environment (Hompton and Horton, 2007; Nichols and Fisher, 2007).

Facies association C

This association occupies the upper part of the formation. It is abundant in the western part of the Nakhon Thai region and formed as the high mountain ranges extending in NNE–SSW direction with altitudes normally over 1000m. It is dominated by facies Sh and Sp.

Description The facies association C is dominated by sandstone which well exposed in the western part of the Nakhon Thai region. It consists mainly of the association of facies Sh and Sp. Sandstone bodies of facies Sh and Sp occur throughout the measured sections and are characterized by fine- to coarse-grained, poorly- to moderately-sorted sandstone. The beds are ranging from thick to very thick with 1- 4m thick on the average (Figure 4.15). The sharp erosional contact and pebble lag are also evident. It is calcareous in some beds but the most are siliceous. The carbonaceous beds of siltstone and mudstone are observed as intercalated beds. Cross-stratified beds are generally found in sandstone beds especially tabular and plane cross-bedding (Figures 4.13e and f). Cross-bedding with overturn foreset structures are observed in some beds (Figure 4.22). All cross-stratification indicate SSW ward palaeocurrent direction with foreset angle ranging between 18^0 and 26^0.

Interpretation Tabular cross-bedded sandstone of facies Sp are interpreted as a product of straight crest dune under lower flow regime while the plane cross-bedding of facies Sh are interpreted as a result of upper flow regime (Collinson, 1996). The association of both facies which represent lower flow interbedded with upper flow regimes may caused by the discharge fluctuation. In this study, both facies are interpreted as the sandstone channel because of the occurrence of pebble lag at the base. This channel may be under the braided fluvial because the facies association is dominated by the Sp and Sh sandstone facies associated with lacking of fine-grained facies of flood plain, e.g., siltstone and mudstone (Collinson, 1996; Selley, 2000). Moreover, the occurrence of overturn foreset cross-bedding which is commonly observed in braided alluvial also substantiates the interpretation (Selley, 2000). In summary, the facies association C is interpreted to have been deposited by fluvial braided stream environment. The presence of fluvial braided stream in the facies association C may imply a gradual change from semi-arid in the facies association A and B to semi-humid environments in the upper Phu Khat and/or represent the last stage of basin filled.

4.1.4 Summary

The Phu Khat Formation is composed of a sequence of conglomerate, purple sandstone, reddish brown sandstone and fine-grained clastic sedimentary rocks. The lower contact of the Phu Khat Formation is in general placed at the presence of successions of polymictic conglomerate with inverse graded bedding but in some other places it is place below the reddish brown sandstone which overlie unconformably on the large-scale cross-bedding aeolian sandstone of the Khao Ya Puk Formation. As the Phu Khat Formation is the upper most of the red bed, therefore the upper contact has not been recognized. However, in general the upper part of the formation is defined by the presence of thick-bedded, reddish brown, medium- to coarse-grained sandstone of fluvial braided stream. The thickness throughout the formation following the detailed section measurement in the Nakhon Thai region is approximately 490 m. The formation can be subdivided into two large units, i.e., the lower sequence (the lower and the middle Phu Khat Formation) and the upper sequence (the upper Phu Khat Formation) which is composed of nine lithofacies including Gms, Gm, Ss, Sh, Sp, Sr, Fl, Fm and Fsc within three facies associations i.e., facies association A, B and C. Based on the facies association, the Phu Khat Formation is largely interpreted to have been deposited by alluvial fan in the lower sequence and fluvial braided stream in the upper sequence. The lower sequences are mainly characterized by the succession of alluvial fan facies consisting of facies association A and B. The facies association A is composed of the conglomerate, coarse-grained sandstone of stream flow deposits in proximal alluvial fan (the lower Phu Khat Formation). The facies association B is characterized by continuous even parallel bedded, medium- to fine-grained sandstone grading up in to siltstone and mudstone in more distal alluvial fan (the middle Phu Khat Formation). The upper sequence comprises a succession of facies association C (the upper Phu Khat Formation). It is chiefly of thick-bedded, coarse-grained sandstone of the fluvial braided stream that overlies conformably on the lower sequence.

4.2 Petrography, geochemistry and U-Pb detrital zircon dating of the Phu Khat Formation : implications for provenance and geotectonic setting

4.2.1 Introduction

The purpose of this section is to determine the provenance and geotectonic setting type of the Phu Khat Formation in the Nakhon Thai region by using petrography and the whole-rock geochemistry integrated with the U-Pb detrital zircon dating.

The modal petrography has long been utilized in clastic sandstone to determine their provenance and sediment recycling (e.g., Dickinson and Suczek , 1979; Dickinson, 1985). The use of this method has been proved to be a powerful tool to evaluate tectonic setting conducted together with the geochemistry of the whole-rock (Hara et al., 2012; Yang et al., 2012; Khanehbad et al., 2012; Etermad-Saeed et al., 2011; Gabo et al., 2009). These methods are based on the basis of framework of grains and geochemical composition contained in classtic sandstone which is regarded as representative of their parent rocks. It means that different source areas of the parent rock will provides different framework and geochemical composition (Weltje, 1994; McLennan et al., 1993; Taylor and McLennan, 1995). Additionally, since many provenance regions have been destroyed by different kind of tectonics settings and the only evidence that is still be found, lies in the geochemical composition contained in sediment derived from them. Therefore, the geochemical composition of sandstone can make important contribution in an interpretation of plate tectonic setting (Bhatia, 1983:1985; Bhatia and Crook, 1986; Roser and Korsch, 1986; 1988; Ryan and Williams, 2007). However, if the source terrane areas of the classtic sandstone are broadly in an uniform geology, method such as petrography and geochemistry may lack precise signature of specific location or terrane (Carter and Bristow, 2003). To overcome this problem detrital zircon age dating of representative samples are required in order to constrain on the location of the source areas by identifying the main crust-forming events. Additionally, the validity of the mineralogical discrimination can also be tested by the zircon age data (Morton et al, 2005; Carter and Bristow, 2003).

The clastic rocks of the Phu Khat Formation in this study are situated in the Nakhon Thai region north-central Thailand (Figure 4.1b). The rocks are composed entirely of non-marine clastic rocks which are interpreted to have been deposited in an alluvial fan and braided stream. They overlie unconformably on the top of the aeolian sandstone of the Khao Ya Puk Formation. The studies of these two formations were carried out in this section in order to explain their genesis. The study profile of the upper Khao Ya Puk Formation and the whole sequence of the Phu Khat Formation are shown in Figure 4.17. In this study seventy one samples were collected for analyses; 51 sample from the Phu Khat Formation which is collected from all three parts of the formation and 20 samples from the Khao Ya Puk Formation that are mainly from the sandstone of the middle and the upper parts. The methods of study are given in more detail in Chapter III.

4.2.2 Petrography and modal sandstone of the Phu Khat and Khao Ya Puk Formations

The summarized results of framework grained counting are shown in Table B.1. The clastic composition plotted QFR diagram (Folk, 1974) indicates that most of the sandstones in the Phu Khat Formation are classified as litharenite which reflects less maturity. The sandstones of the Khao Ya Puk Formation are fallen within the sublitharenite which implies that they are more maturity than the Phu Khat Formation. The Khao Ya Puk Formation shows higher textural and mineral maturity than the Phu Khat Formation. The rocks of the Khao Ya Puk Formation are medium- to coarse-grained, sub-rounded to rounded sandstones with moderately to well-sorted texture (Figure 4.29a). The stable quartz detrital grains are significantly high with more than 80% on average while unstable lithic fragments are normally less than 20% and the feldspar is rare as same as represented in the Phu Khat Formation.

The sandstones in the lower part of the Phu Khat Formation are fine- to very coarse-grained which show poorly sorted textures with angular to sub-rounded grains. The quartz clasts represent 58% of the rocks on average. They are predominantly monocrystalline with minor about 3% polycrystalline quartz. The lithic fragments comprise dominantly volcanic fragments and some sedimentary rocks and represent 35 to 40% of the rock samples. The volcanic grains are mainly of intermediate type containing phenocrysts of plagioclase (Figure 4.29b). Feldspar is quite rare representing 3 to 5%. The middle part of the Phu Khat Formation is characterized by fine- to medium-grained sandstones. They are moderately-sorted texture with sub-angular to rounded grains (Figure. 4.29c). The quartz clasts contain 65% on average which are slightly higher than the lower part. Monocrystalline quartz is still the main constituent with some polycrystalline quartzs. The volcanic fragment is about 32% of the total lithic grains. Feldspar is still quite rare about 3 to 5% the same as the lower part. Sandstones in the upper part of the Phu Khat Formation are petrographically identical to the lower part. They are fine- to coarse-grained sandstone and show poorly to moderately sorted texture with angular to sub-rounded grains (Figure 4.29d). Detrital quartz grains comprise about 56% and are mainly monocrystalline quartz. Unstable volcanic fragments are about 38% of the rock.

In summary, variations of the compositional attributes of those two formations are shown in Figure 4.30. It should be noted that the quartz clearly presents negative linear correlation with the lithic fragments (Figures 4.30a and b), while the feldspar shows a various correlation (Figures 4.30c and d). The negative linear correlation between stable quartz and unstable lithic fragments may reflect the sorting process, while the variation of feldspar may or may not as it is un-uniform with relative to quartz. Comparing the two formations regarding their components, the Phu Khat Formation shows less maturity than the Khao Ya

Puk Formation. This may be explained by un-sorted sediments in the Phu Khat Formation as they were deposited not far from the source area by alluvial fan process relatively. This explanation is further supported by the presence of the very large pebbles of soft siltstone and mudstone in the conglomerate beds. The occurrence of well rounded pebbles of resistant quartz and sandstone associated with non-resistant siltstone and mudstone was considered by reworking process of those quartz and sandstone. The binary plot between ln(Q/F) and ln(Q/L) of Weltje (1994) also suggests that the source area of the Phu Khat Formation had been subjected to less chemical weathering and sorting (Figure 4.30e). Based on this plot, it may imply that the provenances of the Phu Khat Formation probably were under high mechanical breakdown for supplying sediments to the depositional areas. Comparing the three parts of the Phu Khat Formation, the middle part shows higher degree of sorting than the other two (Figures 4.30a and b). However, these three parts are similar in petrographic composition and are probably derived from the same source. They show different sorting due to the different transporting energy.

4.2.3 The whole-rock geochemistry

4.2.3.1 Major elements

The results of geochemical analysis of major elements are shown in Table C.1. The geochemical classification of sandstones indicates that most of the Phu Khat Formation are litharenite whereas the Khao Ya Puk Formation is fallen entirely in sub-litharenite (Figure 4.31). The general trend variation of various sandstones of those the Phu Khat Formation and the Khao Ya Puk Formation are demonstrated on Harker diagram (Figure 4.32a) with the correlation coefficient among them listed in Table. C.2. Generally, all samples of the Phu Khat Formation contain a higher concentration of elements than the Khao Ya Puk Formation except the SiO_2 concentration. The SiO_2 in the Khao Ya Puk Formation is higher than 90 wt.% whereas the Phu Khat Formation contains 70 to 80 wt.% on average. TiO_2 (0.36 wt.%), Al_2O_3 (6 wt.%), Fe_2O_3 (2.3 wt.%), MgO (0.8 wt.%), Na_2O (0.6 wt.%) and K_2O (1.4 wt.%) are relatively high in the Phu Khat Formation comparing with the Khao Ya Puk Formation. This is caused by an increase in unstable detrital grains particularly the volcanic rock fragments and a decrease in mineralogical maturity as shown in the less quartz content of the Phu Khat Formation in the petrographic study. Figure 4.32b illustrates the model of possible path of sediment in relation to weathering and sorting. It agrees well with the petrographic study in Figure 4.30e which suggests that the Phu Khat Formation shows a low degree of chemical weathering and sorting. It contrasts with the Khao Ya Puk Formation that was experienced a high degree of sorting.

The mean values of the major elements of the Khao Ya Puk sandstone and the Phu Khat sandstone normalized to Post-Archean Australian Shale (PAAS) are illustrated in Figure 4.33a. The CaO content is depleted in the Khao Ya Puk Formation whereas it is enriched in the Phu Khat Formation. The enrichment of the CaO in the Phu Khat Formation is probably due to the diagenetic secondary calcite cement as shown in the microscopic petrography (Figures.4.29e and f). In addition, the CaO contents confirm the low correlation coefficient to the immobile elements (e.g. TiO_2) which does not represent the concentration derived from the nature primary source area .The depletion of CaO in the Khao Ya Puk Formation may reflect either lacking of CaO from their provenance or a reduction during the sorting process or both (Bhatia, 1983). This assumption is amplified by bivariate plot of TiO_2 vs. Al_2O_3 of Young and Nesbitt (1998) (Figure 4.32b). It clearly indicates the low chemical weathering and short transportation of the Phu Khat Formation whereas the Khao Ya Puk Formation has shown the long history of transportation and/or high degree of weathering in the source area.

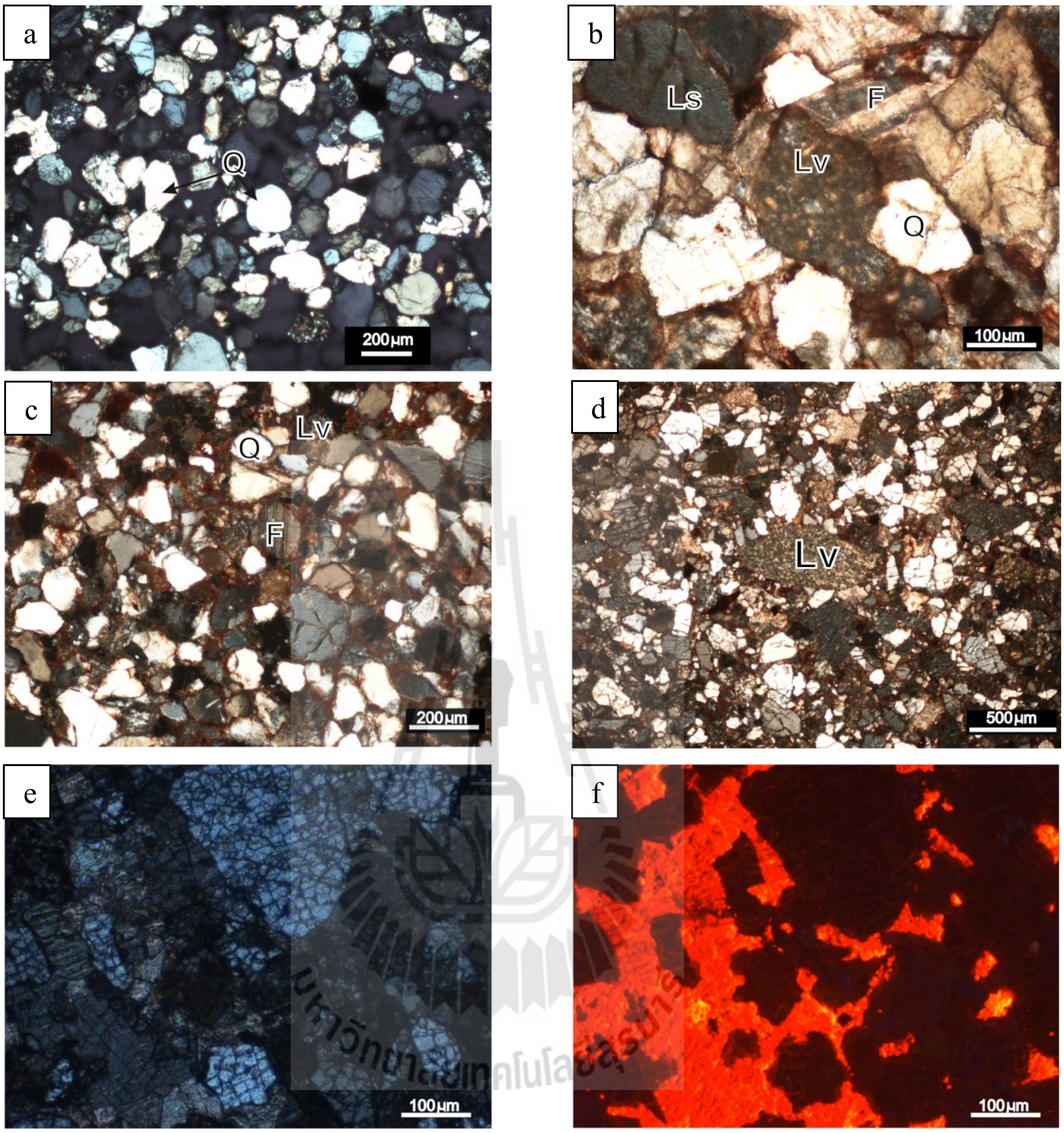


Figure 4.29 Photomicrographs of sandstones of the Khao Ya Puk and the Phu Khat Formations. a) Well sorted sublitharenite of the upper Khao Ya Puk. b and d) Poorly sorted litharenite of the lower and the upper Phu Khat. c) Moderately sorted litharenite of the middle Phu Khat. e) Calcareous sandstone of the lower Phu Khat Formation f) Cathodoluminescence image of calcareous sandstone of e. The pale red patch to the left indicates calcite cement around clastic grains. a, b, c, d and e were taken under cross polarized. Q: Quartz, F: Feldspar, Lv: Volcanic lithic fragment, Ls: sedimentary lithic fragment.

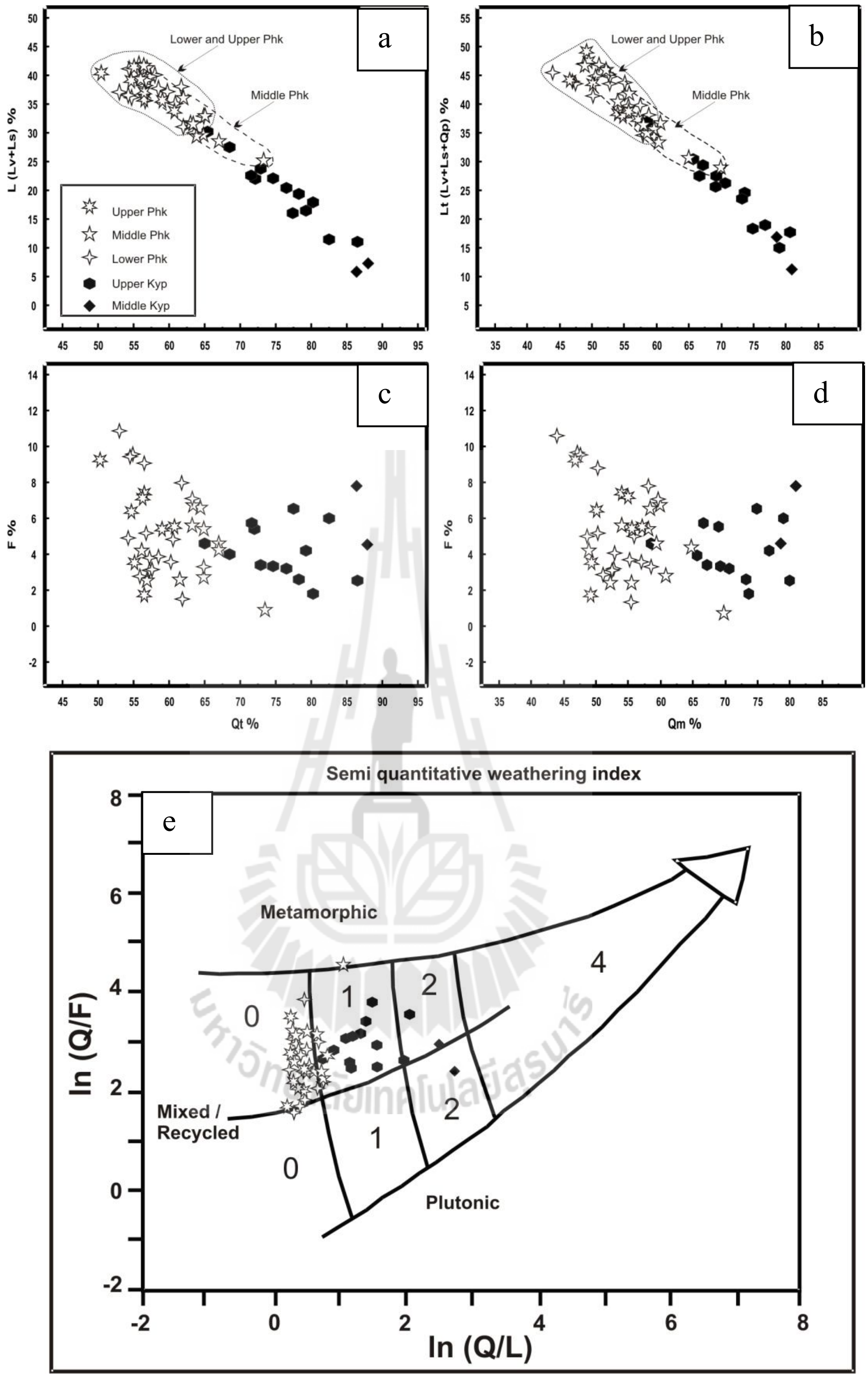


Figure 4.30 Harker diagrams plot of framework grain composition. a, b, c and d) Harker diagram plot of QFL e) The semi quantitative weathering index plot after Weltje (1994). Upper Phk: Upper Phu Khat Fm. Middle Phk: Middle Phu Khat Fm. Lower Phk: Lower Phu Khat Fm. Upper Kyp: Upper Khao Ya Puk Fm.

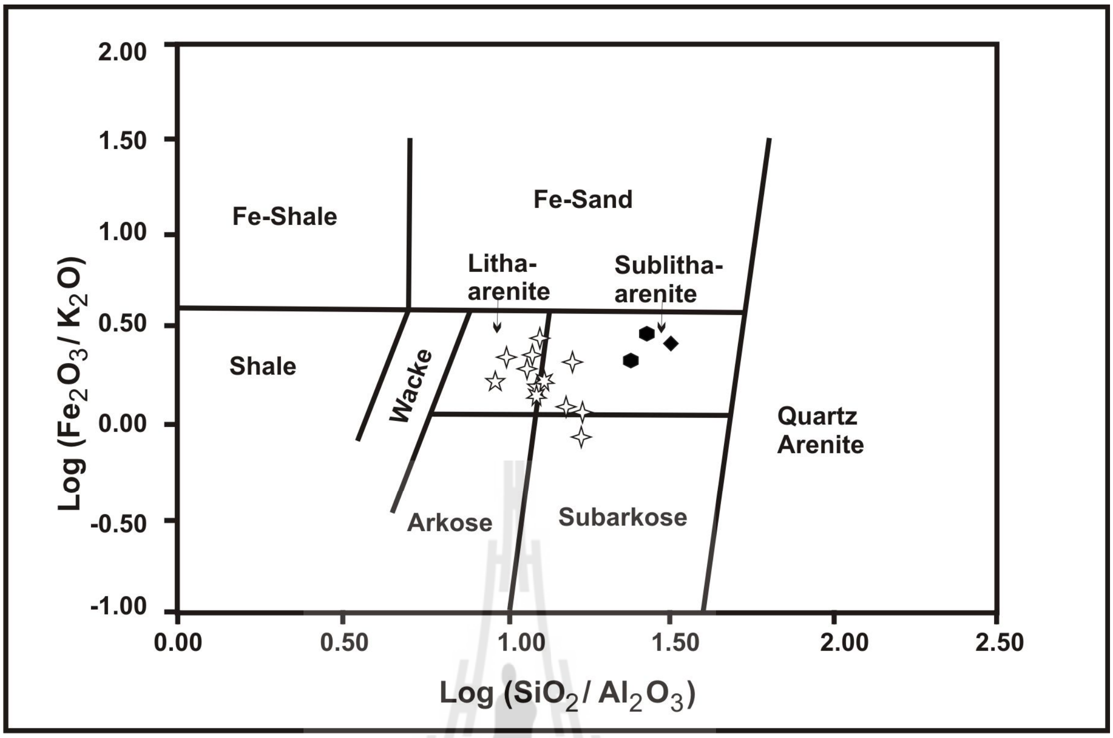


Figure 4.31 Sandstone classifications of the Phu Khat and the Khao Ya Puk Formations based on chemical composition (after Herron, 1988). For symbols see Figure 4.30.

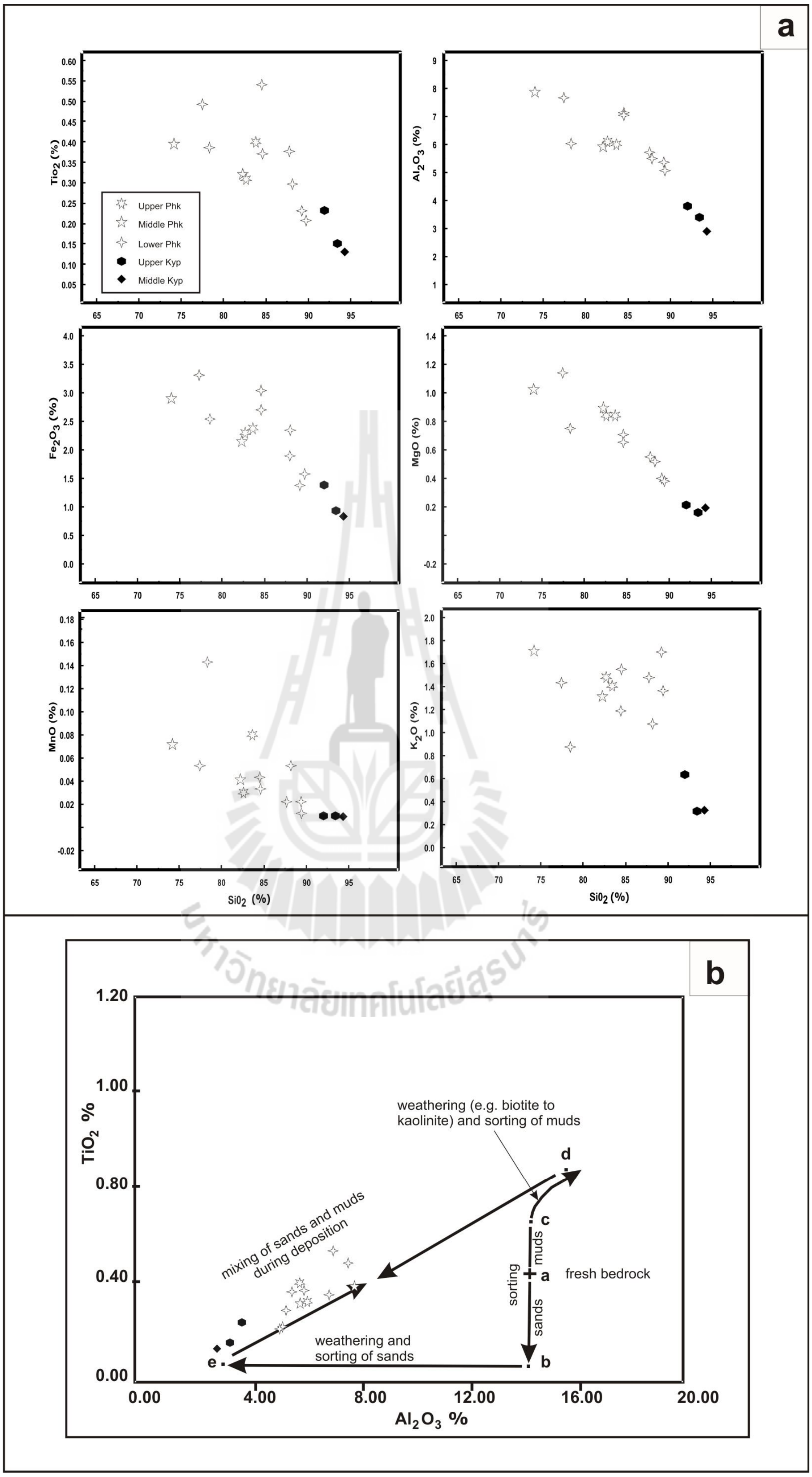


Figure 4.32 Harker diagrams plot of major elements.

a) Harker variations diagram of major elements for clastic sandstone of the Khao Ya Puk and the Phu Khat Formations.

b) Bivariate plot of Al_2O_3 against TiO_2 diagram showing possible weathering and sorting paths for sandstone of the Khao Ya Puk and the Phu Khat Formations. (after Young and Nesbitt, 1998).

For symbol see Figure 4.30.

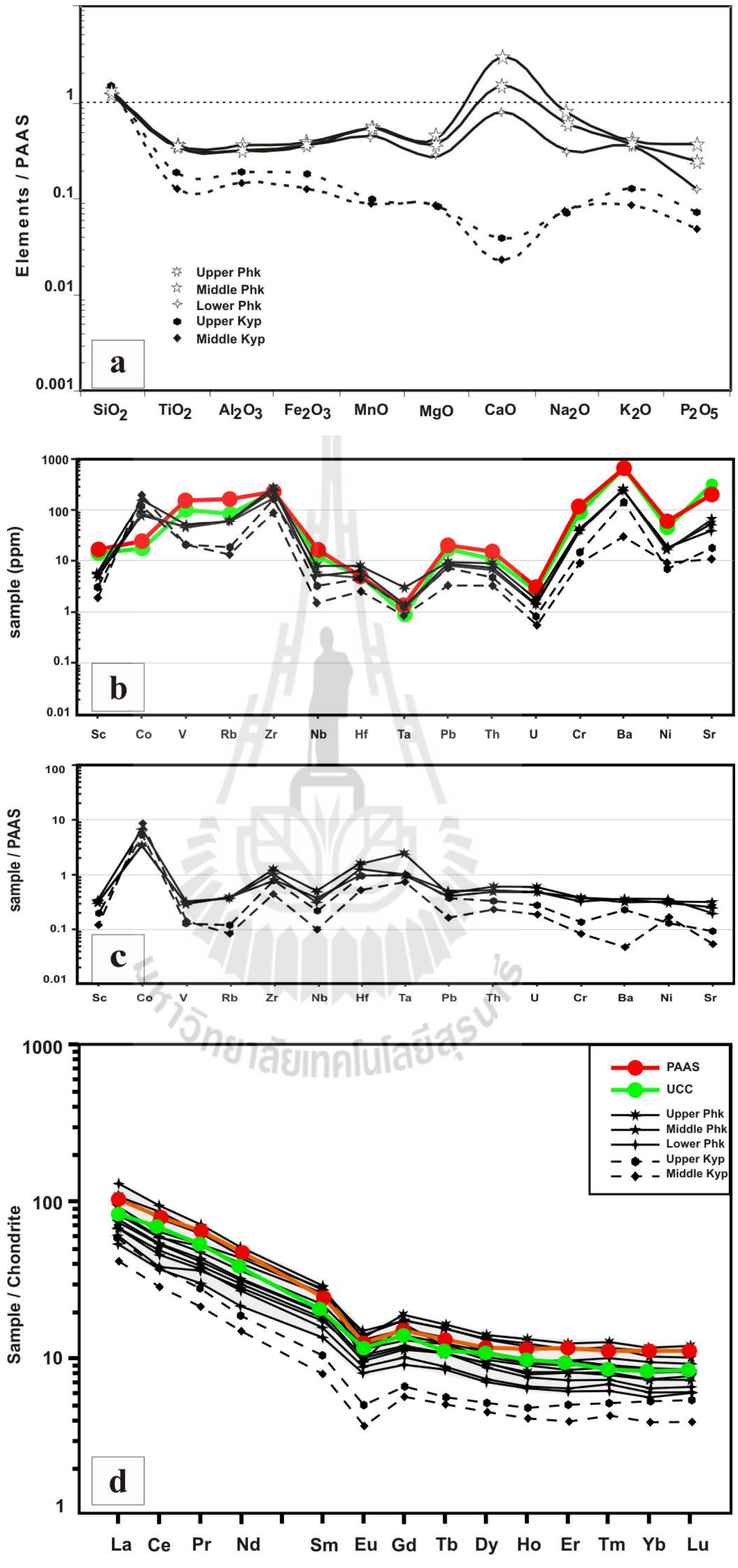


Figure 4.33 Major and REEs patterns of the clastic Phu Khat and the Khao Ya Puk Formations.

a) Major elements normalized against Post-Archean Australian Shale (PAAS) (Taylor and McLennan, 1985).

b) Concentrations of Trace elements relative with PAAS and Upper Continental Crust (UCC) (Rudnick and Gao, 2003).

c) Trace elements normalized against PAAS.

d) Rear earth elements normalized against Chondrite (Sun and McDonough, 1989).

For symbol see Figure 4.30.

4.2.3.2 Trace and rare earth elements (REEs)

The concentrations of trace elements are shown in Table C.1 and plotted in Figure. 4.33b. The trace elements normalized against PAAS are shown in Figure 4.33c. Both the Khao Ya Puk and the Phu Khat Formations display similar trace element trends which are comparable to the PAAS and Upper Continental Crust (UCC) values. However, the Phu Khat Formation shows relatively high concentration of trace elements comparing to the Khao Ya Puk Formation. The significant higher values are Sc, V, Rb, Cr, Ni and Sr elements as shown in Table C.1. The average of Sc = 5, V = 50, Rb = 60, Cr = 40, Ni = 20 and Sr = 45 ppm are found in the Phu Khat Formation, while the Khao Ya Puk Formation shows Sc = 2, V = 20, Rb = 20, Cr = 13, Ni = 8 and Sr = 16 ppm. These higher values were caused by the presence of volcanic material in the form of lithic grain and less textural and chemical maturity of the Phu Khat Formation (Bhatia, 1985). The Khao Ya Puk Formaion shows the uniform Th/U and Th/Sc ratios which are higher than 5 and 1 respectively representing upper continental and/or recycled provenance (McLennan et al., 1993). While the Phu Khat Formation yields a wide range of Th/U and Th/Sc ratios between 3.77 to 6.81 and 0.93 to 2.3 respectively reflecting variable provenance (McLennan et al., 1993).

Both the Khao Ya Puk and the Phu Khat Formations have a similar chondrite-normalized REEs trend as shown in Figure. 4.33d. They show parallel trend to both the PAAS and the UCC. The LREE enrichment and HREE depletion values as reflected by La_N/Yb_N and Gd_N/Yb_N are 10 to 15 and 1.26 to 1.80, respectively. They are also display significantly negative Eu anomalies (average Eu/Eu* = 0.61 in the Khao Ya Puk and 0.42 to 0.74 in the Phu Khat Formation). The total abundant of REEs (La to Lu) is low (on average 100 ppm and 50 ppm in the Phu Khat and the Khao Ya Puk Formations respectively) comparing to the PAAS (184.77 ppm) and UCC (148.14ppm). These lower values are caused by abundant detrital quartzs which dilute the total REEs values (Taylor and Mclennan, 1995; Barth et al., 2000) especially in the sub-litharenite of the upper Khao Ya Puk Formation. A slight difference between the Phu Khat and the upper Khao Ya Puk Formations in the chondrite-normalized REEs patterns is that the Phu Khat Formation pattern is close PAAS and UCC but the upper Khao Ya Puk Formation is significantly lower as shown in Figure. 4.33d.

4.2.4 U-Pb detrital zircon dating

The U-Pb detrital zircon dating was employed in this study in order to overcome the limitation of petrography and geochemistry for constraining the specific source terrane. Three representative samples, one from the upper Khao Ya Puk Formation (Up-Kyp) and the other two from the lower (Low-Phk) and the middle Phu Khat Formation (Mid-Phk) were selected for analysis. The age distribution of the three samples is presented on the Kernel density plots.

4.2.4.1 Upper Khao Ya Puk Formation (well sorted large-scale cross-bedded sandstone)

The analysed sample was taken from the upper Khao Ya Puk Formation immediately below the contact with the overlying Phu Khat Formation. It is composed of medium- to coarse-grained, very well-sorted sandstone with high angle foresets of large-scale cross-bedding. The analysis of 133 detrital zircon grains shows that the upper Khao Ya Puk Formation contains six pervasive zircon cluster ages, i.e., 2800 to 2280 Ma (peak 2462 Ma), 2050 to 1530 Ma (peak1831 Ma), 1302 to 1050 Ma (peak 1184 Ma), 930 to 720 Ma (peak 821 Ma), 630 to 420 Ma (peak 546 Ma) and 300 to 160 Ma (peak 215 Ma). The dominant ages are the Meso-Proterozoic, the Neo-Proterozoic and the Phanerozoic. All zircons grains have Th/U ratios higher than 0.2 suggesting that they are probably from igneous origin (Rubatto, 2002).

4.2.4.2 Lower Phu Khat Formation (poorly sorted sandstone intercalated in conglomerate beds)

The analysed sample was taken from sandstone of the lower Phu Khat Formation which is intercalated with polymictic conglomerate**.** The analysis of 107 detrital zircon grains shows different distribution of U-Pb age cluster from the underlying formation (Up-Kyp) (Figure 4.34). Four major cluster ages are recognized, i.e., 2800 to 2280 Ma (peak 2453 Ma), 2050 to 1530 Ma (peak 1850 Ma), 1200 to 900 Ma (peak 934 Ma) and 300 to 160 Ma (peak 230 Ma) with dominant age in the Phanerozoic. The Th/U ratios of all zircons are higher than 0.2 suggesting that most of them are probably from igneous origin.

4.2.4.3 Middle Phu Khat Formation (moderately sorted sandstone)

The analyzed sample is from fine- to medium- grained sandstone of the middle Phu Khat Formation. The analysis of 66 zircon grains yielded an age ranging from 2667 to 112 Ma and can be classified into five cluster age groups of 2667 to 2350 Ma (peak 2450 Ma), 2050 to 1530 Ma (peak 1880 Ma), 1200 to 900 Ma (peak 996 Ma), 640 to 370 Ma (peak 510 Ma) and 300 to 112 Ma (peak 240 Ma). The cluster age of the Mid-Phk is similar to the Low-Phk particularly the Pre-cambrian, the Th/U > 0.2 and the dominant age in the Phanerozoic. In general, most of the Phanerozoic or younger zircon ages are characterized by euhedral prismatic shape with oscillatory zoning internal structure. Based on these features and the Th/U > 0.2, the zircons are probably derived from the igneous rock and the first sediments process (Wu and Zheng, 2004).

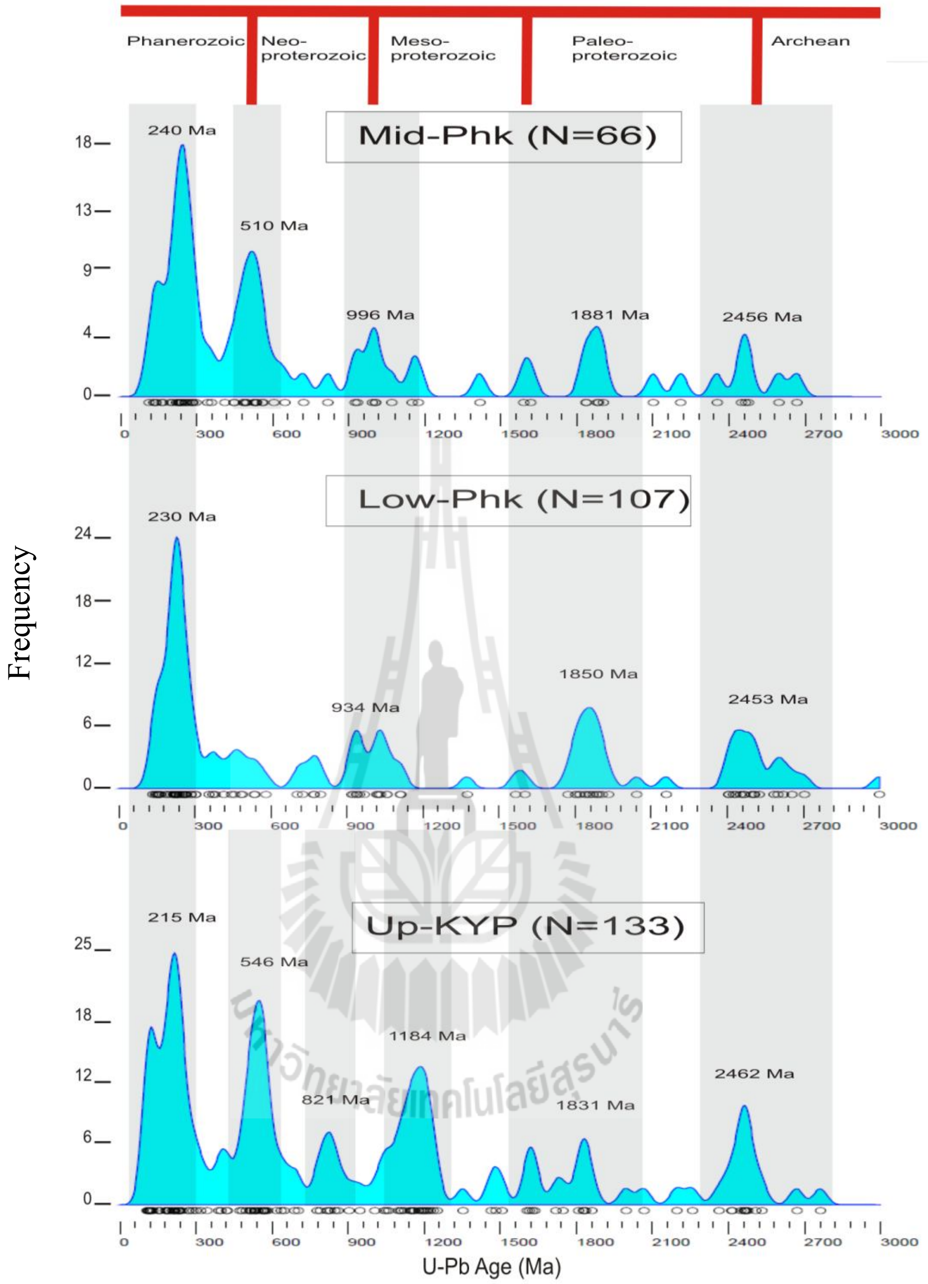


Figure 4.34 Kernel density plots and age distribution showing ages of detrital zircons from the sandstone of the upper Khao Ya Puk Formation (Up-KYP) and the lower (Low-Phk) and middle (Mid-Phk) Phu Khat Formation. N is total number of analyzed grains. $^{206}Pb/^{238}U$ ratio are used to determine age younger than 1000 Ma, and $^{207}Pb/^{206}Pb$ ratio are for those at 1000 Ma or older.

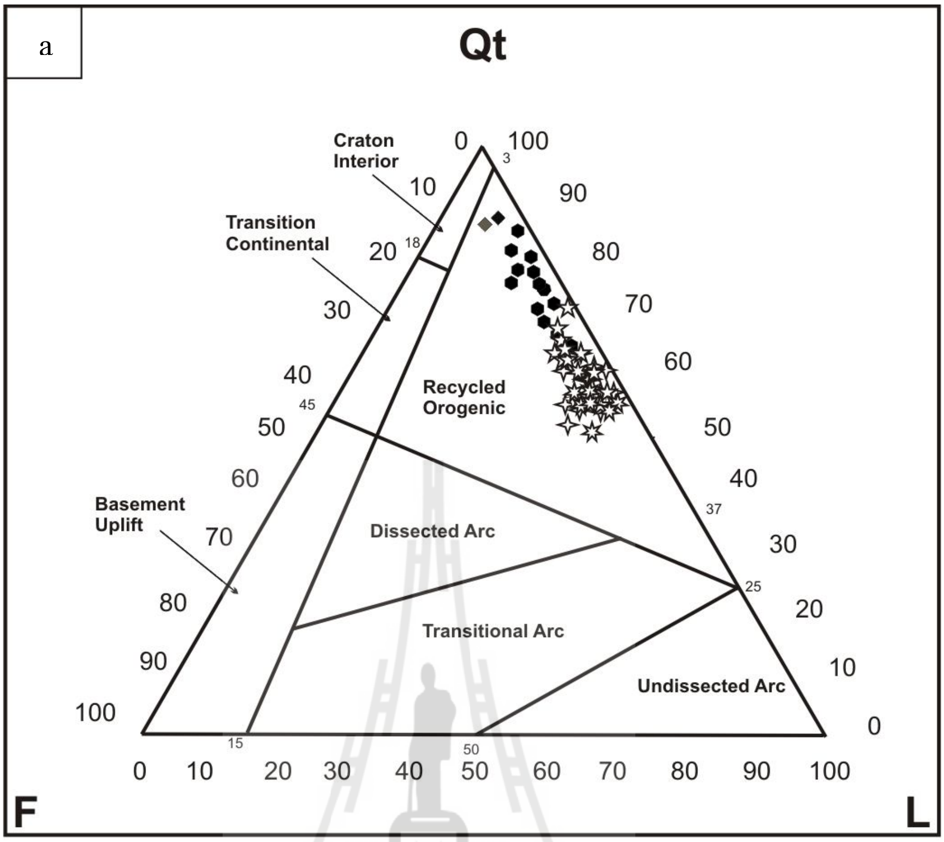
4.2.5 Implications for provenances and geotectonic setting

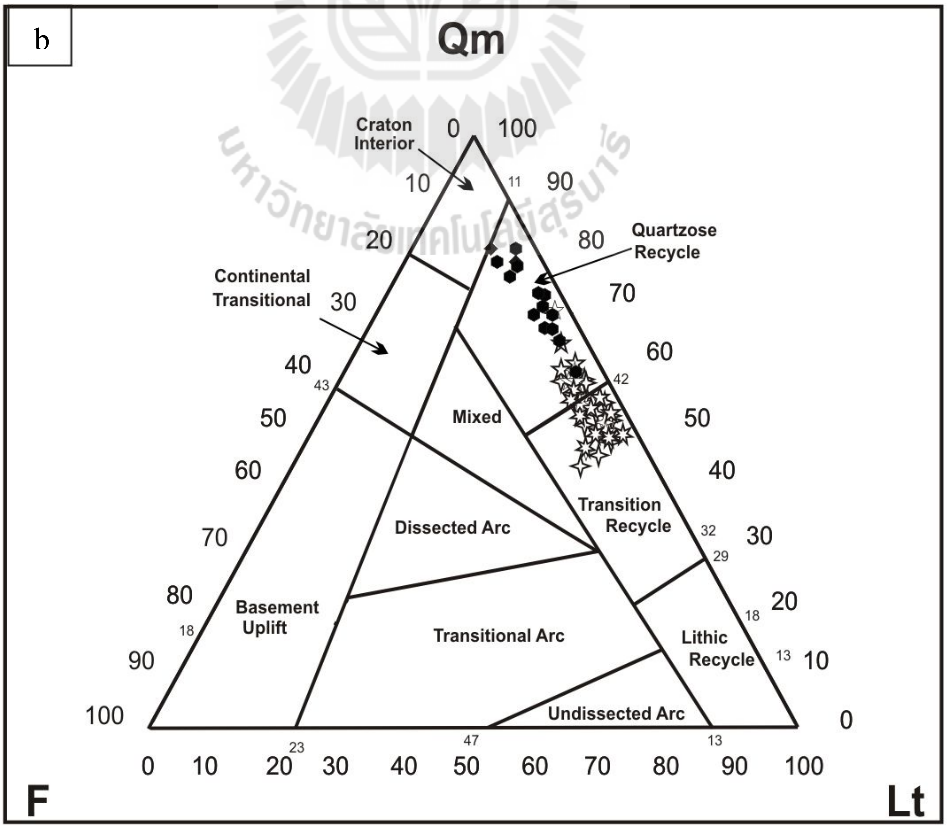
The present study was designed to determine the provenance and tectonic setting using the petrography and the bulk geochemistry of sandstone in the Phu Khat Formation. The study of this type has never been carried out in the study area. The petrography utilized in provenance study as proposed by Dikinson and Suczek (1979); Dikinson (1985) are followed in this study. However, as suggested by Bhatia (1986), Mclennan et al. (1993) and Ryun and Williams (2007) using of one discrimination scheme may lead to less accurate interpretation. So in order to minimize these limitations, various discriminations based upon bulk geochemical scheme were also used including major and trace elements. In this study the geochemical discrimination proposed by Roser and Korsch (1988) and the bivariate plot of Mclennan et al. (1993) and Floyd and Leveridge (1987) were used to determine the provenance, while the tectonic setting were clarified by the discrimination proposed by the Bhatia (1983), Bhatia and Crook (1986) and Roser and Korsch (1986).

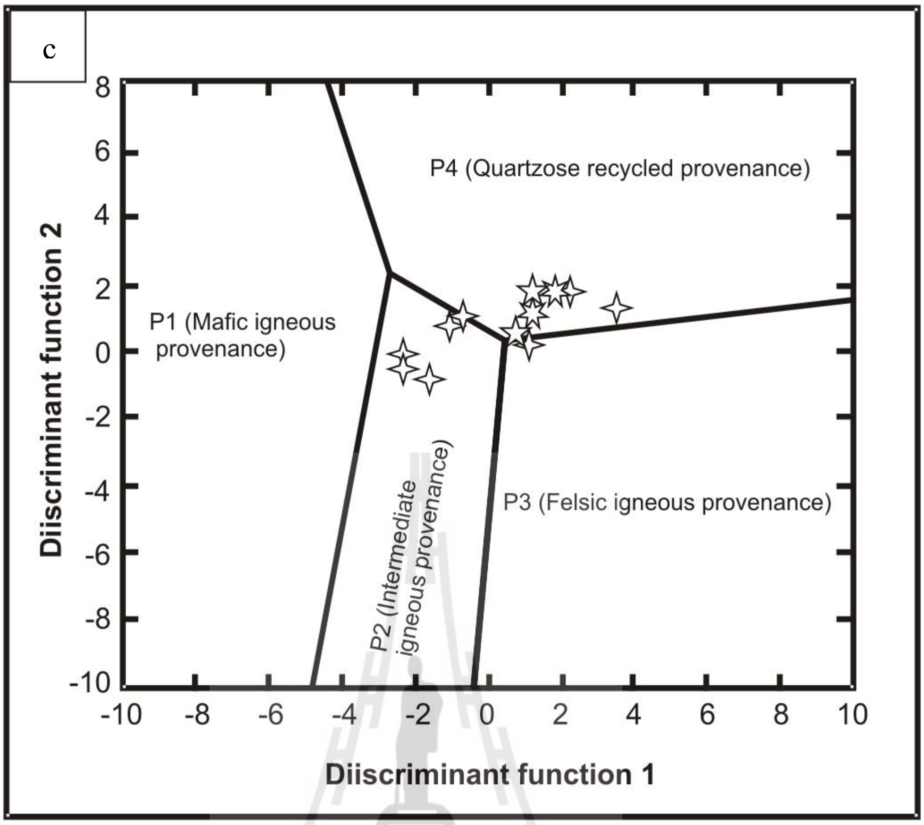
4.2.5.1 Provenances of sandstones

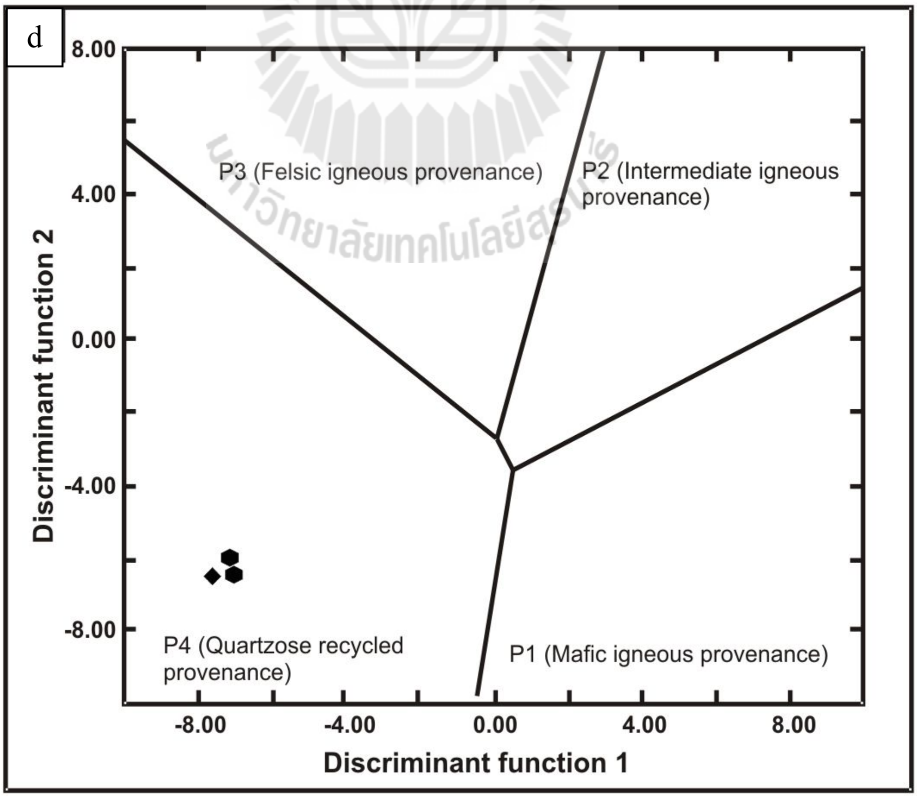
The widely used method for provenance discrimination in the petrographic study is the Qt-F-L and Qm-F-Lt triangular plots of Dikinson and Suczek (1979) and Dikinson (1985). The plots of the Phu Khat and the Khao Ya Puk Formations indicate that both were derived mostly from the recycled orogenic terrane (Figure 4.35a). Dikinson and Suczek (1979) demonstrates that it could be formed either from the deformed and uplifted sequences of the collision orogens or the foreland fold and thrust belts. On the Qm-F-Lt plot, most of the Phu Khat Formation samples are in transitional between the quartzose recycled and the lithic recycled fields. Whereas the Khao Ya Puk samples are entirely fallen in the quartzose recycle (Figure 4.35b). The result may suggest that sandstones of the two formations were fed by different sources. The Khao Ya Puk Formation which shows high quartzose recycle was derived mainly from polycyclic sedimentary sources since it shows both high textural and mineral maturity. Whereas the Phu Khat Formation was derived from mixed sedimentary and volcanic sources as evident in a high content of volcanic and lithic fragments. The well-rounded and high resistant pebbles associated with non-resistant siltstone and mudstone clasts in the conglomerate also suggest a low maturity.

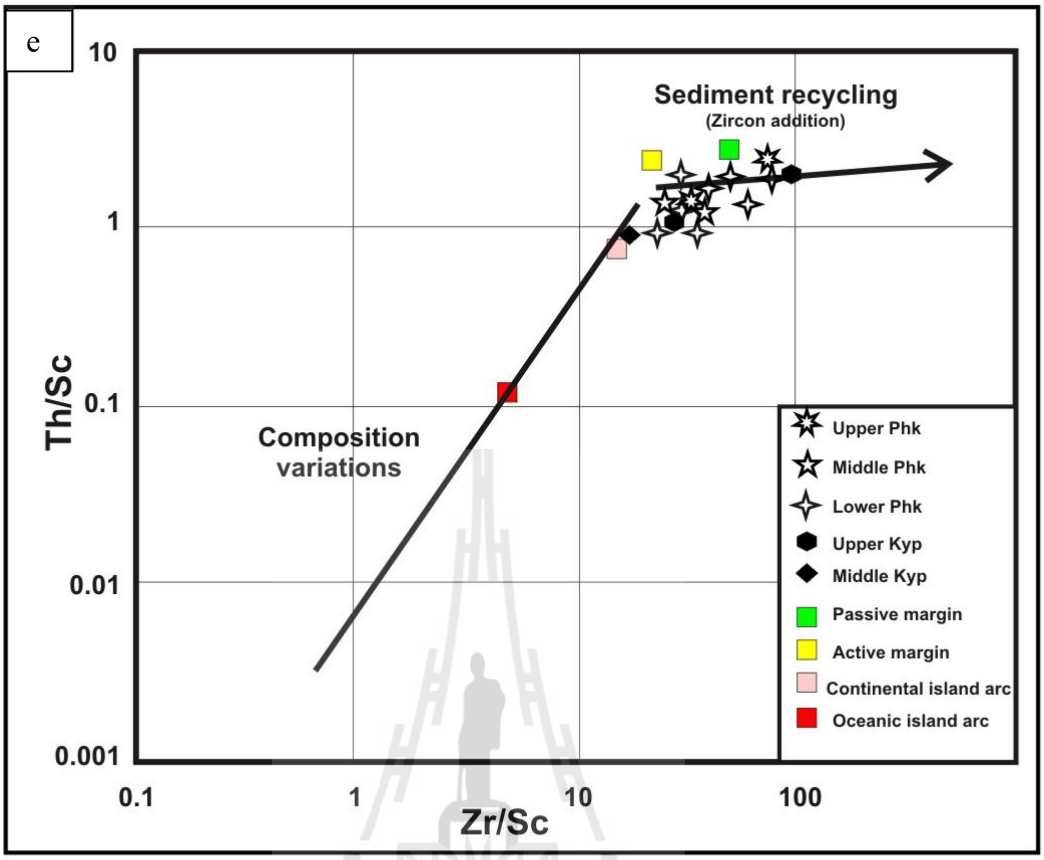
Roser and Korsch (1988) presented the provenance discriminant function plot based on the major element component to distinguish four different lithologic types of the source area, i.e., mafic igneous, intermediate igneous, felsic igneous and recycled rocks. Roser and Korsch (1988) categorized the plot into two schemes. One is based on seven major elements (TiO_2, Al_2O_3, Fe_2O_3 (t), MgO, CaO, Na_2O and K_2O) and the other on Oxide/Al_2O_3 ratios (e.g. TiO_2/Al_2O_3, $Fe_2O_3(t)/Al_2O_3$, MgO/Al_2O_3, Na_2O/Al_2O_3 and K_2O/Al_2O_3). As suggested by Roser and Korsch (1988) the later scheme should be applied for the high CaO samples due to rich carbonate cement and/or bio-calcareous clasts in sandstone. In this study the Oxide/Al_2O_3 ratio scheme is used to distinguish provenance of sandstones in the Phu Khat Formation due to their high content of secondary calcite cement, but in the Khao Ya Puk Formation the other discriminant function is applied. Half of the samples of the Phu Khat Formation are fallen in the quartzose sedimentary recycle and the rest is in the intermediate igneous field as shown in Figure 4.35c. While all samples of the Khao Ya Puk Formation fall in the quartzose recycled field (Figure 4.35d). The result is comparable to those of the petrographic study which indicates that the bulk composition of the Phu Khat sandstone was derived from volcanic and quartzose sedimentary sources.


a
Qt
Craton Interior
Transition Continental
Recycled Orogenic
Basement Uplift
Dissected Arc
Transitional Arc
Undissected Arc
F
L


b
Qm
Craton Interior
Quartzose Recycle
Continental Transitional
Mixed
Dissected Arc
Transition Recycle
Basement Uplift
Transitional Arc
Lithic Recycle
Undissected Arc
F
Lt


c
P4 (Quartzose recycled provenance)
P1 (Mafic igneous provenance)
P2 (Intermediate igneous provenance)
P3 (Felsic igneous provenance)
Diiscriminant function 2
Diiscriminant function 1
8
6
4
2
0
-2
-4
-6
-8
-10
-10
-8
-6
-4
-2
0
2
4
6
8
10


d
P3 (Felsic igneous provenance)
P2 (Intermediate igneous provenance)
P4 (Quartzose recycled provenance)
P1 (Mafic igneous provenance)
Discriminant function 2
Discriminant function 1
8.00
4.00
0.00
-4.00
-8.00
-8.00
-4.00
0.00
4.00
8.00



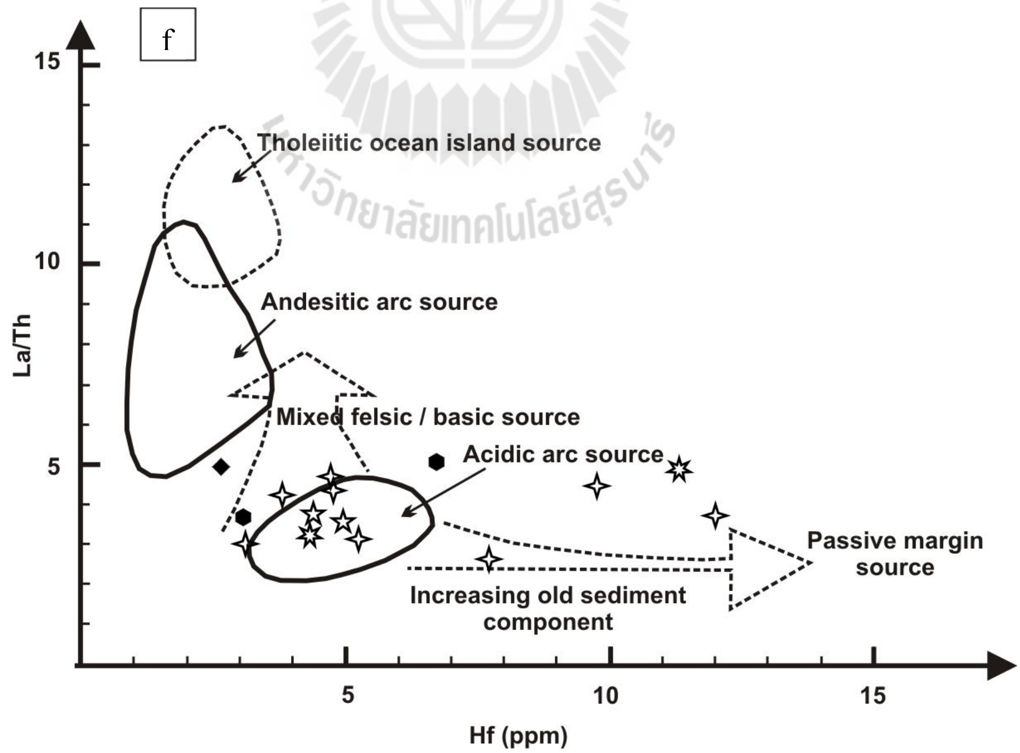


Figure 4.35 Petrographic and geochemical discriminant plot for provenance types.

a and b) QtFL and QmFLt diagrams for distinguishing provenance of the sandstones from the Phu Khat and the Khao Ya Puk Fms. based on Dickinson (1985). Qt: total quartz grains (mono- and polycrystalline quartz), Qm: monocrystalline quartz, F: felspar grains (plagioclase and K-felspar), L: lithic fragments, Lt: lithic fragments and polycrystalline quartz.

c and d) Major elements discriminant diagrams for provenance types.

c) The Phu Khat Fm. containing high secondary CaO contents

<u>Function 1</u>= $[(TiO_2/Al_2O_3)*30.638] + [(Fe_2O_{3T}/Al_2O_3)*-12.541] + [(MgO/Al_2O_3)*7.329] + [(Na_2O/Al2O3)* 12.031] + [(K_2O/Al_2O_3)* 35.402] - 6.382$

<u>Function 2</u>= $[(TiO_2/Al_2O_3)*56.500] + [(Fe_2O_{3T}/Al_2O_3)*-10.879] + [(MgO/Al_2O_3)*30.875] + [(Na_2O/Al_2O_3)*-5.404] + [(K_2O/Al_2O_3)* 11.112] - 3.890$

d) The Khao Ya Puk Fm. with normal CaO contents (Roser and Korsch, 1988)

<u>Function 1</u>= $[TiO_2*-1.773] + [Al_2O_3*0.607] + [Fe_2O_{3T} *0.760] + [MgO* 1.500] + [CaO* 0.616] + [Na_2O*0.509] + [K_2O*-1.224] - 9.090$

<u>Function 2</u>= $[TiO_2*0.455] + [Al_2O_3*0.070] + [Fe_2O_{3T} *-0.250] + [MgO*-1.142] + [CaO* 0.438] + [Na_2O*1.475] + [K_2O*1.426] - 6.861$

e) Plot of Th/Sc versus Zr/Sc for variation of provenance from McLennan et al.(1993). The variation values of passive margin, active margin, continental island arc and oceanic island arc from Bhatia (1985)

f) Source and composition discrimination of sandstones using La/Th ratio and Hf abundance (Floyd and Leveridge, 1987).

For symbol see Figure 4.30.

The plot of trace elements Th/Sc against Zr/Sc was proposed by McLennan et al. (1993) to outline the potential source of sediment. The Th/Sc is a good indicator of chemical differentiation process in igneous rock whereas Zr/Sc is an useful index of zircon enrichment in the sedimentary recycling process (Figure 4.35e) (McLennan et al., 1993). The Phu Khat Formation is characterized by a wide range of Zr/Sc ratios whereas Th/Sc is more uniform. Some samples of the Phu Khat Formation are close to the felsic volcanic rock and some are close to the sedimentary recycling process. This may suggest that the provenance of the Phu Khat Formation was from the felsic volcanic rocks associated with sedimentary recycled source. It is also supported by the variation of the Eu/Eu* anomalies (0.42 to 0.74) of the Phu Khat Formation. Some samples show negative Eu/Eu* value in the range of the PAAS (0.64) which suggests the major contribution from sedimentary source. But the others are higher than the PAAS indicating that they were derived from the volcanic source (Bhatia, 1985). The La/Th against Hf plot introduced by Floyd and Leveridge (1987) also supports this interpretation. The Phu Khat Formation sample is fallen in the field of acidic arc with some mixed felsic and basic sources. However, the recycling passive margin could also be the source as shown in Figure 4.35f.

In order to indicate a specific age of source terrane of the Phu Khat sandstone, the U-Pb zircon dating was conducted in three samples, one from the upper Khao Ya Puk Formation and the other two from the lower and middle Phu Khat Formation. The result shows that all three samples provide a wide range of zircon age from Pre-Cambrian to Mesozoic age but most are concentrated in the Mesozoic. The presence of the Pre-Cambrian zircon age in the Phu Khat Formation may relate directly to the Pre-Cambrian formation within the source area, or to recycling of the younger rocks. In this study the recycling process is preferable as no exposed Pre-Cambrian rocks in the adjacent area are known according to the U-Pb zircon dating data (Clift et al., 2006; Carter and Bristow, 2003; Dunning et al., 1995; Lepvrier et al., 2004; Hansen and Wemmer, 2011). One notable difference between the Phu Khat Formation and the upper Khao Ya Puk Formation is the difference in the Pre-Cambrian zircon age distribution (Figure 4.34). The difference of the provenance ages of the two formations may imply the presence of a tectonic event or a major erosional event subsequent to the deposition of the Khao Ya Puk Formation. Moreover, the difference between the lower Phu Khat Formation and the upper Khao Ya Puk Formation is evident in the youngest zircon age which shows the gap (youngest age peak 114 Ma and 155 Ma in the upper Khao Ya Puk and the lower Phu Khat Formations respectively) between two formations. This difference may reflect the different provenance between two formations (Figure 4.36). This interpretation is supported by the lithostratigraphic study which indicates the abrupt facies change from the aeolian sandstone of the Khao Ya Puk Formation to the polymictic conglomerate of the alluvial fan environment of the Phu Khat Formation. It is consistent with the previous study which indicated the presence of a tectonic event and a subsequently formed unconformity between the two formations (Heggemann et al., 1994; Meesook et al., 2002; Assavapatchara and Raksasakulwong, 2010).

The result of geochemical and petrographical studies of the Phu Khat Formation indicates that it was derived from the volcanic source. The cluster of zircon age in the Phanerozoic of the Phu Khat Formation (Figure 4.36) may relate directly to the exposed rocks of the source terrane. Additionally, the presence of euhedral prismatic shape and oscillatory zoning internal structure of zircon grains in this cluster may reflect the first cycle sediments of an igneous origin. So this zircon age cluster will relate directly to the provenance. The age distributions on the Kernel density plots of the Phu Khat samples since the Cambrian are shown in Figure 4.36. They can specify the precise source location of the Phu Khat Formation.

The zircon age distribution of the Phu Khat Formation is characterized by the presence of age cluster in the Late Ordovician and the peak of dominant zircon age in the Late Triassic which are closely related with the igneous activity of the western terrane as shown in Figures 4.36 and 4.37. The Late Ordovician volcanic activity which was present in the western terrane was not detected in the eastern terrane. The volcanic activity of the western terrane was dominant in the Middle to the Late Triassic (Qian et al., 2013; Shichan, 2008: 2009; Khositanont, 2008; Barr et al., 2000:2006) but in the Late Permian to Middle Triassic in the eastern terrane (Khin Zaw et al., 2014; Salam et al, 2014; Kamvong et al., 2014; Feng et al., 2009; Khositanont, 2008; Intasopa, 1993). The presence of widespread Late Triassic to Jurassic volcanic rock (ms_2 of Drumm et al., 1993) in northern Thailand is also consistent with the interpretation. Moreover, the paleocurrent direction in sandstone beds of the Phu Khat Formation indicates the western source. However, Heggemann (1994) concluded that the provenance of the Phu Khat Formation was from both the western and the eastern terranes based on the imbrication of pebbles in outcrops. Nevertheless, the pebble imbrications in the complex Nakhon Thai region may be formed by tectonic rotation post the deposition of the Phu Khat Formation. The outcrop (Km 35 Road No1268) mentioned by Heggemann (1994) was revisited by the authors but the possible source from the eastern terrane could not be confirmed since there is no exposure of the outcrop. In summary based on the available evidence so far, it can be suggested that the main provenance of the Phu Khat Formation was the volcanic associated with the polycyclic sedimentary rocks from the terrane west of the Nakhon Thai region.

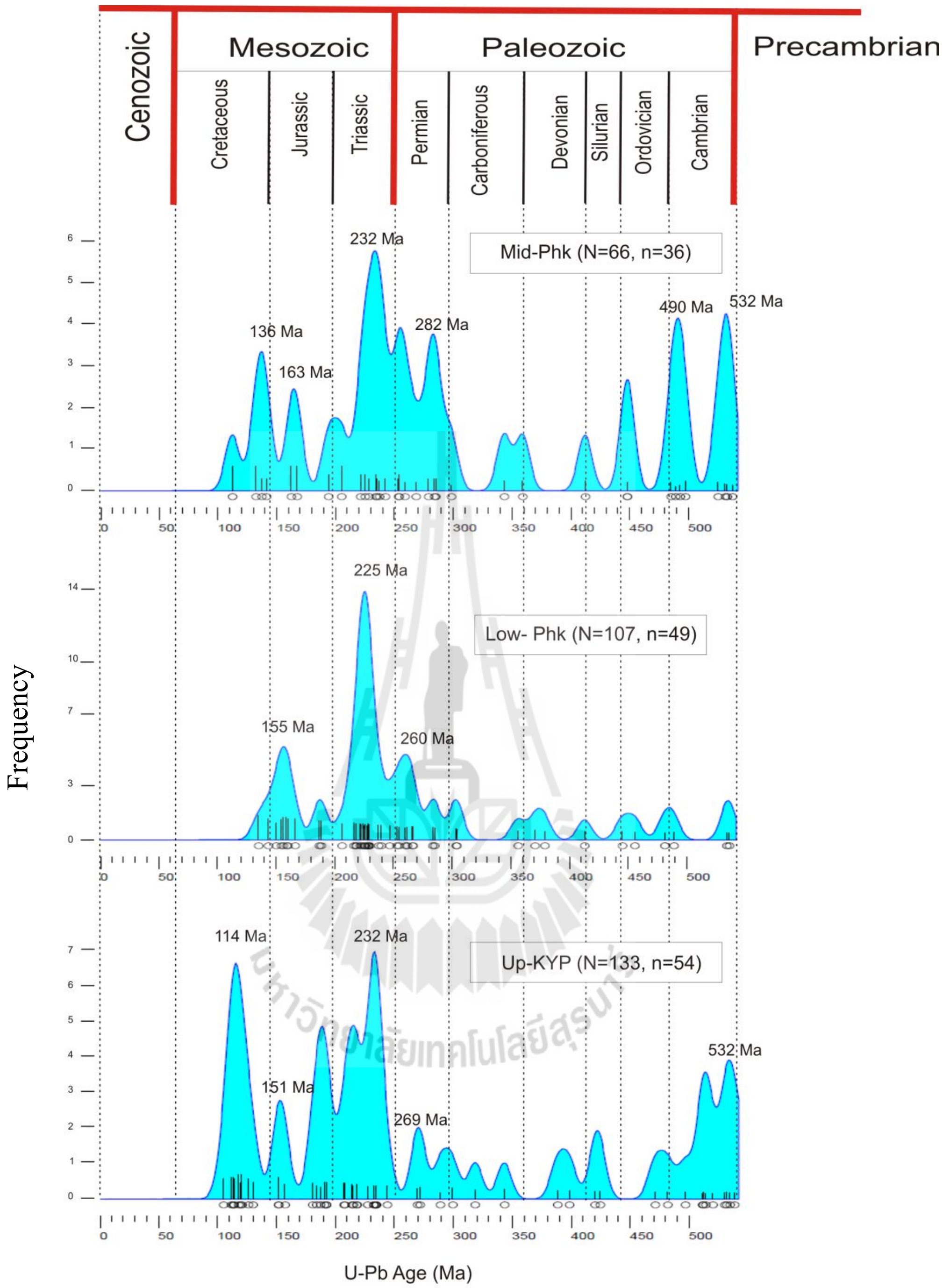
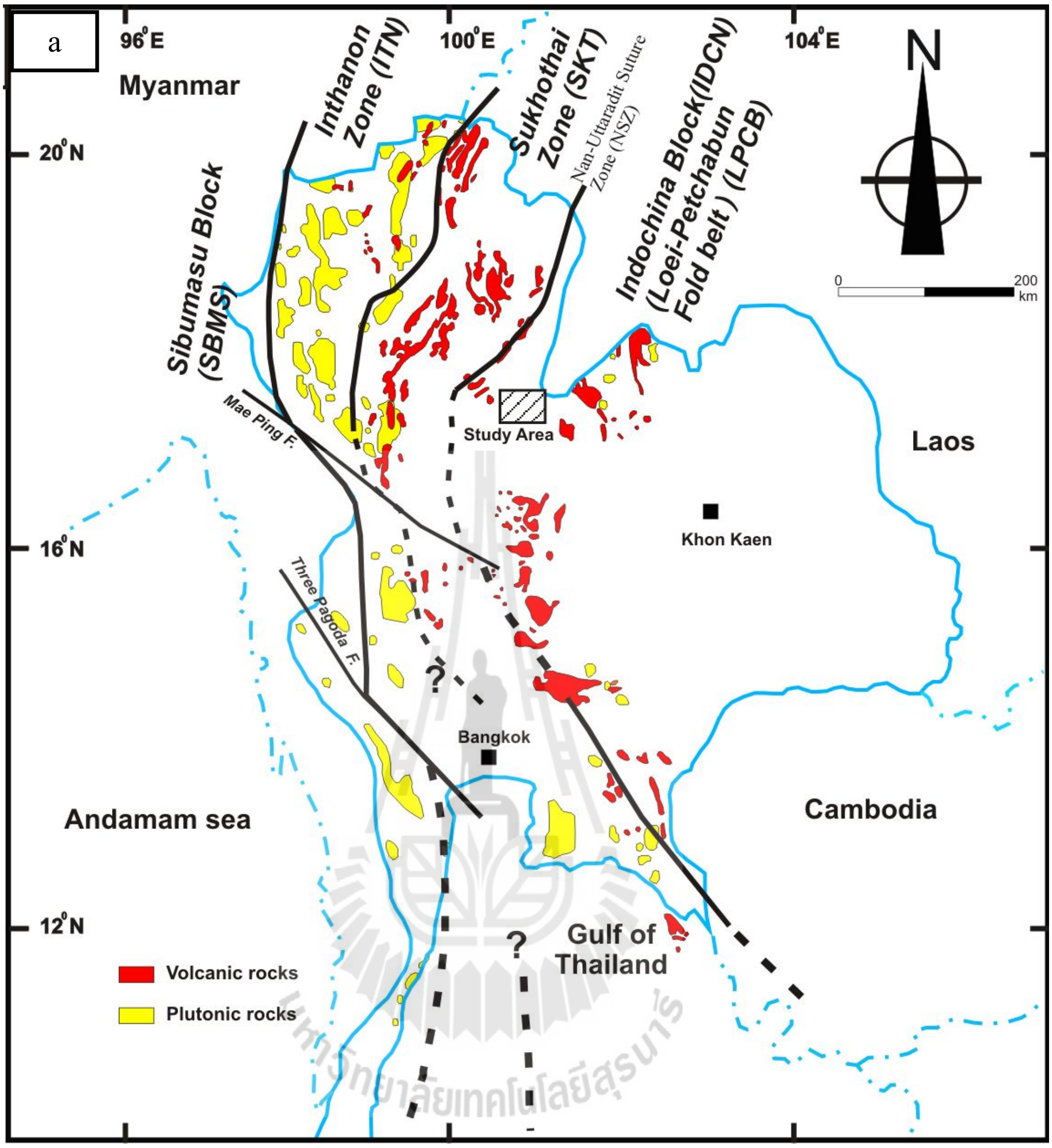


Figure 4.36 Kernel Density plots of Post-Cambrian age distributions of detrital zircons from the sandstone of the upper Khao Ya Puk Formation (Up-KYP) and the lower (Low-Phk) and the middle (Mid-Phk) Phu Khat Formation. N is total number of analyzed grains and n is number of post-Cambrian age grains.



a
96°E
100°E
104°E
20°N
16°N
12°N
N
0
200
km
Myanmar
Inthanon Zone (ITN)
Sukhothai Zone (SKT)
Nan-Uttaradit Suture Zone (NSZ)
Indochina Block(IDCN) (Loei-Petchabun Fold belt) (LPCB)
Sibumasu Block (SBMS)
Mae Ping F.
Three Pagoda F.
Study Area
Laos
Khon Kaen
Bangkok
Andamam sea
Cambodia
Gulf of Thailand
Volcanic rocks
Plutonic rocks

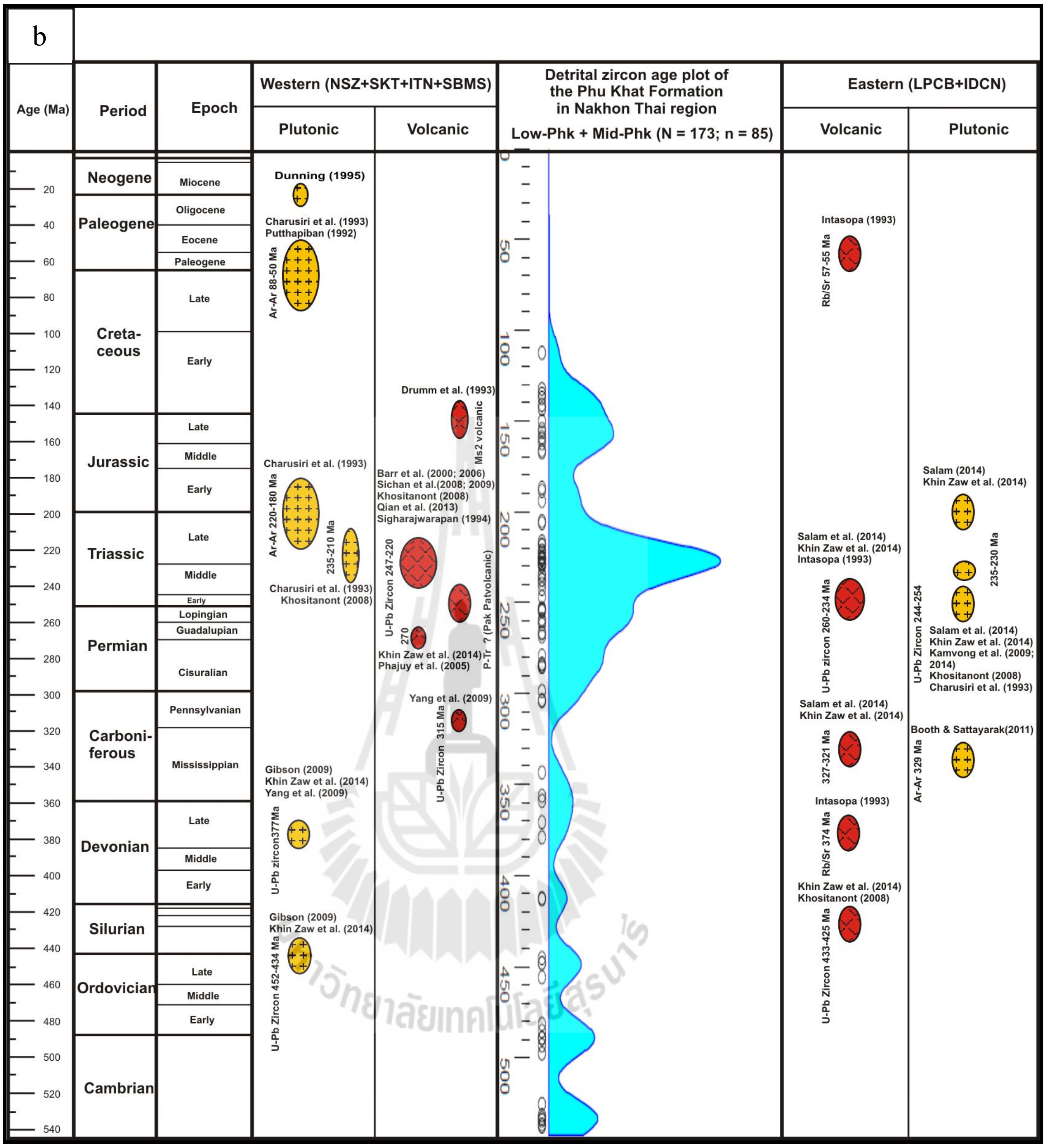


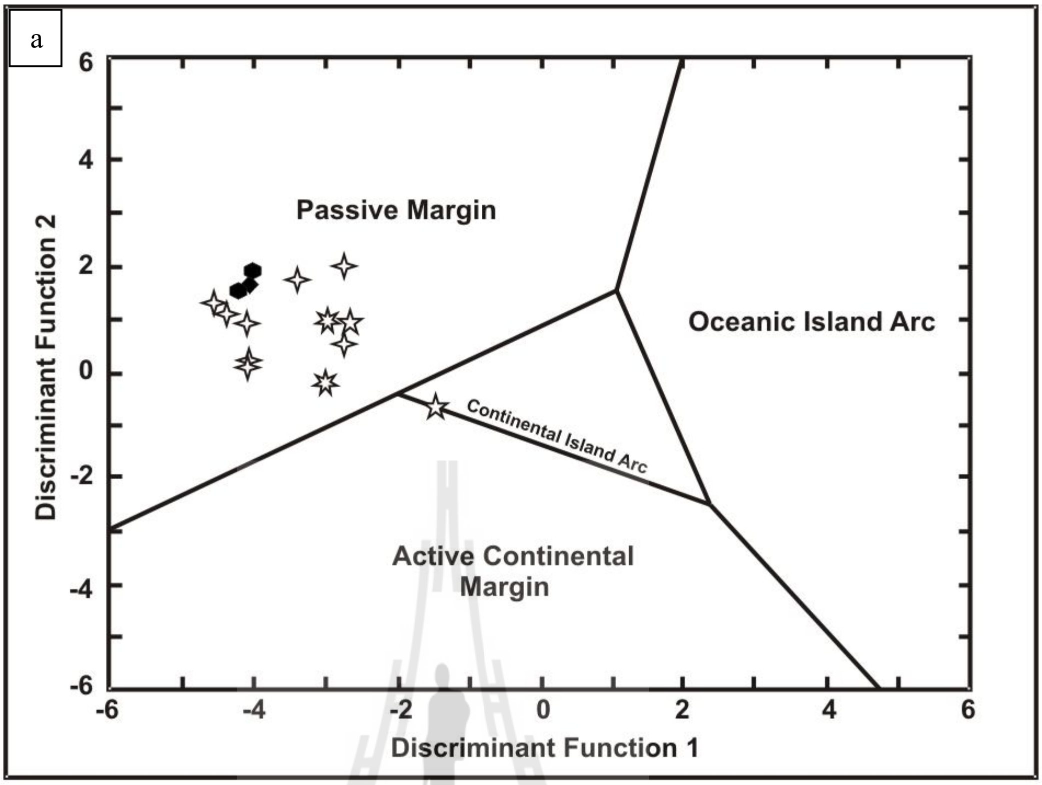
Figure 4.37 Potential sources of detrital zircon for the Phu Khat Formation. a) Distribution of igneous rocks which are the possible sources for the Phu Khat Formation (after Barr and Charusiri, 2011). b) The zircon ages distribution of the Phu Khat Formation compared with those of the western and the eastern terranes of the Nakhon Thai region with references there in.

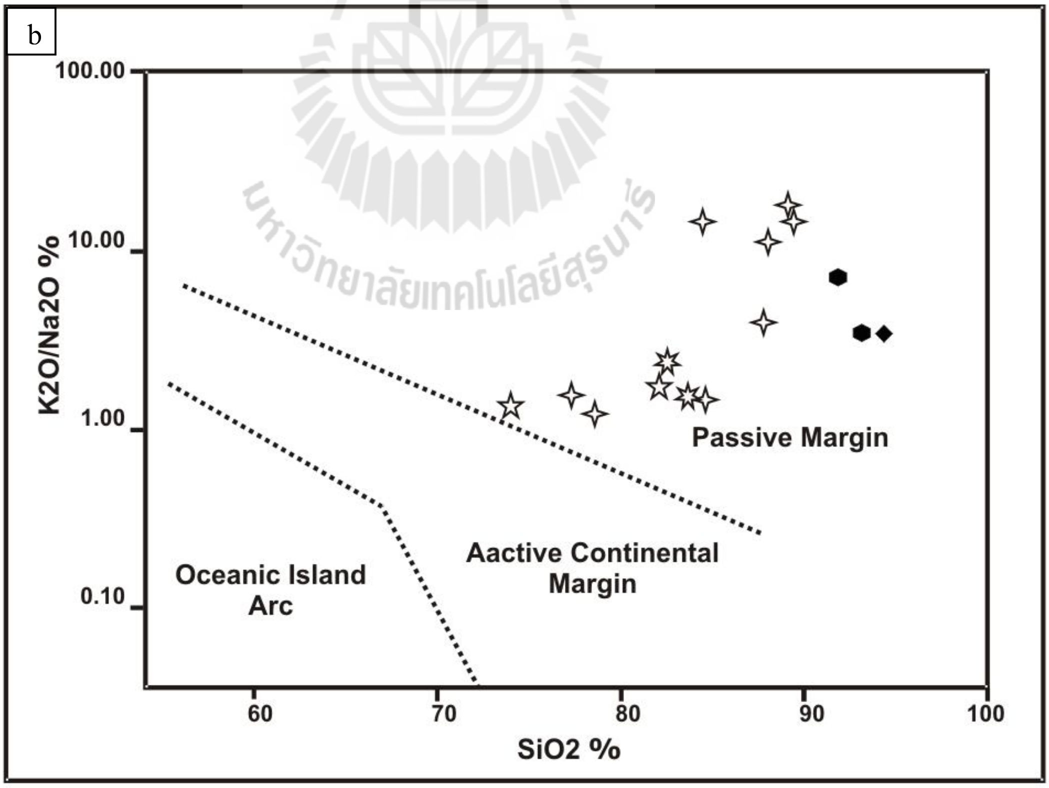
4.2.5.2 Geotectonic setting

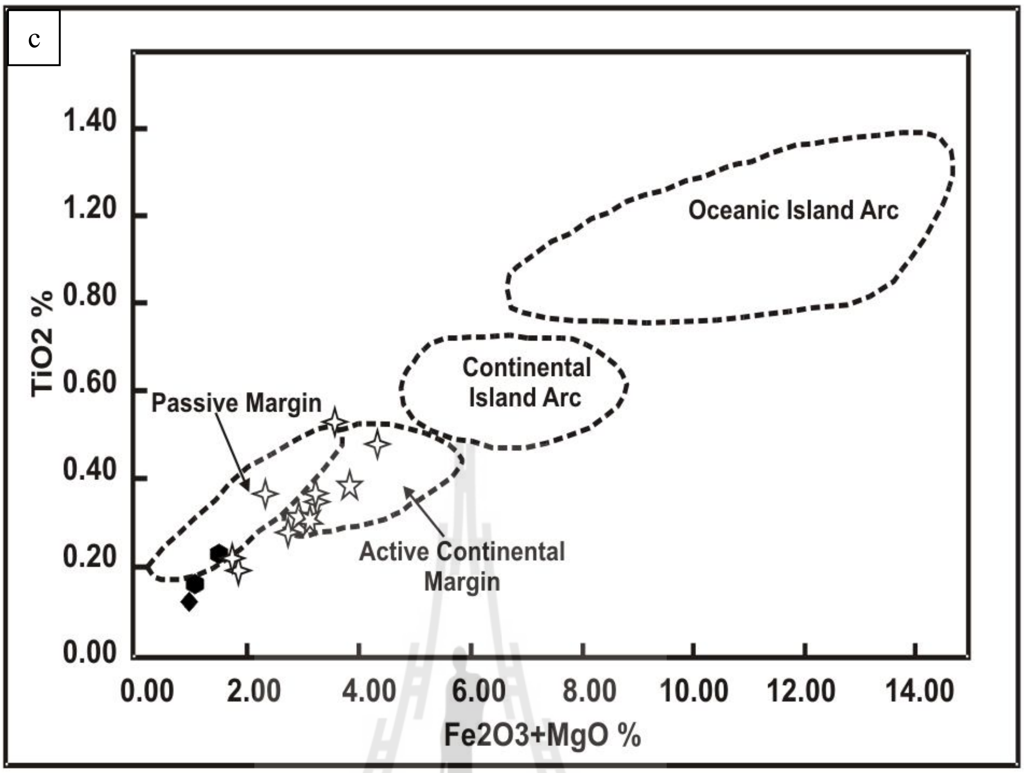
In order to gain more understanding of tectonic setting of the sedimentary deposits, the major elements together with the trace elements are used by various studies (e.g., Bhatia and Crook, 1986; Hara et al., 2012; Yang et al., 2012). The tectonic discrimination diagram of Roser and Korsch (1986) using K_2O/Na_2O ratio against SiO_2 content was applied in this study. Moreover, the discriminant function plot of 11 major elements and bivariate plot of immobile elements of Bhatia (1983) are also used. In this study the TiO_2 and Al_2O_3/SiO_2 ratios are used to plot bivariation against (Fe_2O_3 + MgO) because they show high correlation coefficient (0.9 and 0.84), whereas (K_2O/Na_2O) and Al_2O_3/(CaO+Na_2O) were omitted owing to their low correlation coefficient with Fe_2O_3 + MgO (-0.29 and - 0.53). Figure 4.38b shows the result of K_2O/Na_2O ratio against SiO_2 plot. It indicates that most samples are fallen in the passive margin field. The result shows a similarity with the discriminant function plot of Bhatia (1983) and Al_2O_3/SiO_2 bivariate plot (Figures. 4.38a and d). However, a slight difference is shown in the bivariate plot of TiO_2 against (Fe_2O_3 + MgO) which indicates that the Phu Khat Formation is in the overlapping field between the passive margin and the active continental margin (Figure 4.38c).

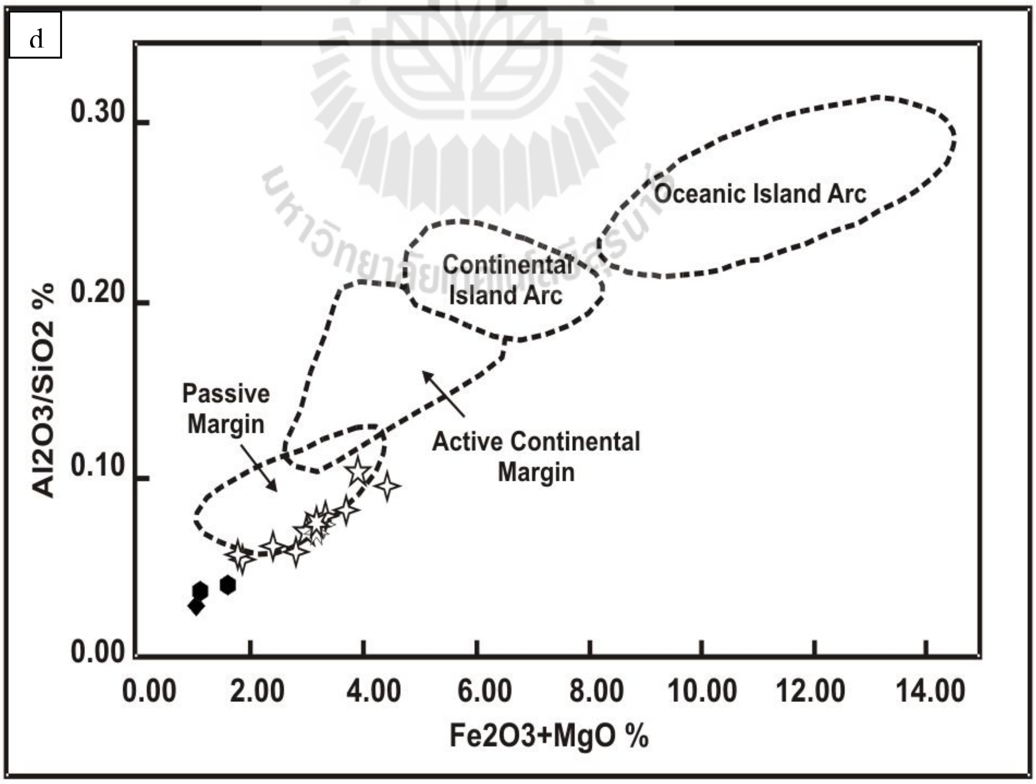
The La-Th-Sc and Th-Sc-Zr/10 diagrams were presented by Bhatia and Crook (1986) as a useful tool to distinguish the sandstones derived from different tectonic settings and provenance fields. According to the the La-Th-Sc plot, half of the Phu Khat Formation samples were in the field of continental island arc and the other half in the field of active continental and passive margins (Figure 4.38e). In order to distinguish between active continental and passive margins, the Th-Sc-Zr/10 was employed. Figure 4.38f clearly indicates that the Phu Khat Formation samples were in the continental island arc and the passive margins. While the Khao Ya Puk Formation is entirely fallen in the passive margin field.

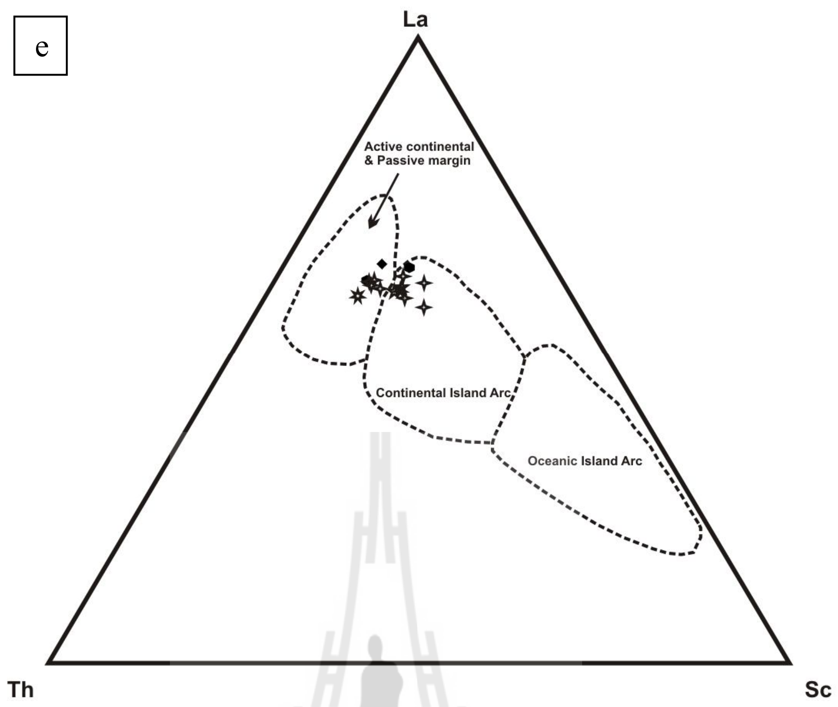
Based on the plots of major and trace elements of the Phu Khat Formation samples, the tectonic setting during deposition of the Phu Khat Formation was associated with the passive margin and the continental island arc fields. However, the result of the U-Pb detrital zircon dating is dominated in the Triassic which is older than the depositional age of the Phu Khat Formation (Late Cretaceous - Early Paleogene). So it may indicate that the tectonic settings derived from the geochemical element analyses do not reflect the tectonic setting of the deposition but it represents the tectonic setting of the rock in the provenance in the Triassic time. It agrees with the study of Barr et al. (2000: 2006) and Qian et al. (2013) who claimed that the Triassic volcanic belt west of the Nakhon Thai region is dominated by the continental island arc. The Phu Khat Formation is, therefore, considered to have been accumulated in the passive continental margin.


a
Passive Margin
Oceanic Island Arc
Continental Island Arc
Active Continental Margin
Discriminant Function 2
Discriminant Function 1
6
4
2
0
-2
-4
-6
-6
-4
-2
0
2
4
6


b
100.00
10.00
1.00
0.10
K2O/Na2O %
Passive Margin
Aactive Continental Margin
Oceanic Island Arc
60
70
80
90
100
SiO2 %


c
1.40
1.20
0.80
0.60
0.40
0.20
0.00
TiO2 %
Oceanic Island Arc
Continental
Island Arc
Passive Margin
Active Continental
Margin
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
Fe2O3+MgO %


d
0.30
0.20
0.10
0.00
Al2O3/SiO2 %
Oceanic Island Arc
Continental
Island Arc
Passive
Margin
Active Continental
Margin
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
Fe2O3+MgO %



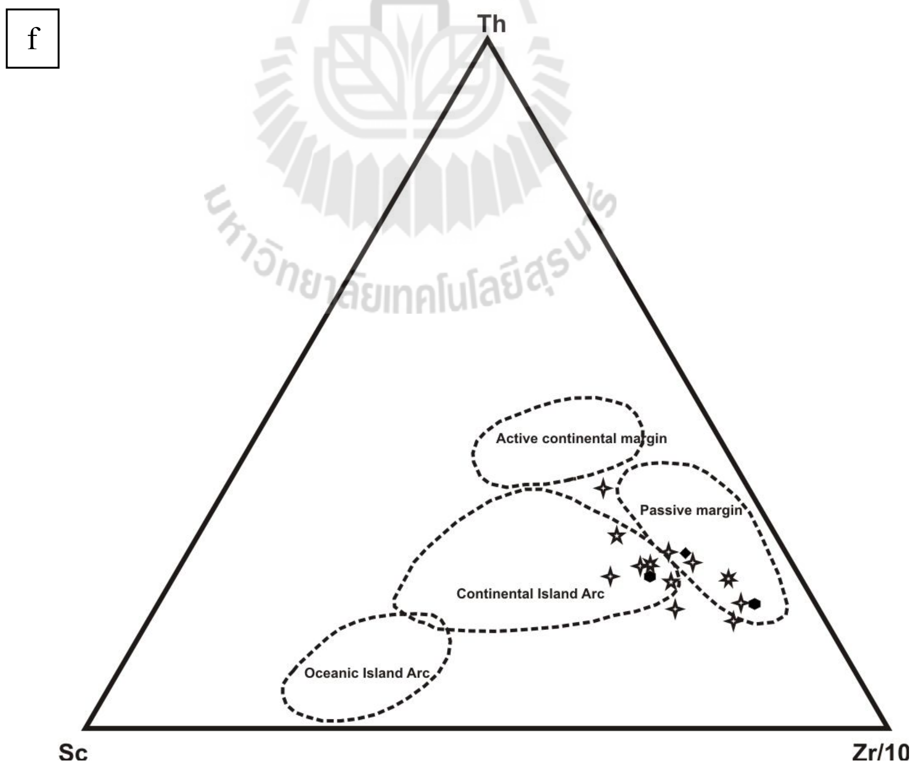


Figure 4.38 Geochemical discriminant plot for tectonic setting types.

a) Discriminant function plot after Bhatia (1983)

Function 1= [SiO_2 *-0.0447] + [TiO_2*-0.972] + [Al_2O_3*0.008] + [Fe_2O_{3T} *-0.267] + [FeO*0.208] + [MnO*-3.082] + [MgO*0.140] + [CaO*0.195] + [Na_2O*0.719] + [K_2O*-0.032] + [P_2O_5*7.510] + 0.303

Function 2= [SiO_2 *-0.421] + [TiO_2*1.988] + [Al_2O_3*-0.526] + [Fe_2O_{3T} *-0.551] + [FeO*-1.610] + [MnO*2.720] + [MgO*0.881] + [CaO*-0.907] + [Na_2O*0.177] + [K_2O*-1.840] + [P_2O_5*7.244] + 43.57

b) SiO_2 versus K_2O/Na_2O discrimination plot after Roser and Korsch (1986).

c and d) Plots of TiO_2, Al_2O_3/SiO_2 versus Fe_2O_3 + MgO after Bhatia (1983) (Fe_2O_3 represents total iron). e and f) Trace element plots La-Th-Sc and Th-Sc-Zr/10 of sandstone for tectonic setting discrimination after Bathai and Crook (1986). For symbol see Figure 4.30.

4.2.6 Summary

The sandstone of the Phu Khat Formation is chiefly characterized by unsorted texture and high unstable volcanic lithic fragments. Geochemically, the tectonic setting discrimination including plot of: 1) K_2O/Na_2O ratio against SiO_2, 2) Al_2O_3/SiO_2 versus (Fe_2O_3 + MgO), 3) discriminant function plot of major elements and 4) Th-Sc-Zr/10 triangular plot indicate that the Phu Khat Formation was accumulated in the passive margin tectonic setting. Based on this result integrated with the petrographic study which indicates the source from recycled orogen, the Phu Khat Formation could be derived either from the deformed and uplifted sequence of the collision orogens or the foreland fold and thrust belts. The provenance discrimination comprising discriminant function plot of major elements and plot of La/Th ratio against Hf collaborated with plot of Th/Sc against Zr/Sc ratios and the variation of Eu anomaly value (Eu/Eu* 0.42 to 0.74) reveal that the provenance of the Phu Khat Formation consists primarily of sedimentary rocks associated with continental volcanic arc rocks in the uplifted either the western or the eastern continental terranes or both. However, the U-Pb detrital zircon dating provides clear evidence that the provenance of the Phu Khat Formation was uniquely from the western terrane with igneous activity predominantly occurred in the Middle to the Late Triassic time.

CHAPTER V

DISCUSSIONS AND CONCLUSIONS

In this chapter the results of previous chapters were discussed with the data from published literatures on the topic of tectonic evolution and depositional age of the Phu Khat Formation. In addition, discussion on further study and conclusion are also included.

5.1 Discussions on tectonic evolution and age constraint

Since the Triassic, the Indochina Block and the Sukhothai Zone have been joined together as a single continent by the closure of the Nan-Uttaradit back arc basin (Chonglakmani, 2002). After the collision, the Indochina Block was pulled apart obliquely due to the extensional collapse of the overthickened crust of the orogen (Cooper et al., 1989). Consequently, continental haft-garben basins were formed with deposition of the fluvio-lacustrine Huai Hin Lat Formation (Chonglakmani and Sattayarak, 1987). While in the Sukhothai Zone the Triassic Lampang Group was deposited in a marine environment (Chonglakmani, 2011). After the deposition of the Triassic sequence the continental red bed has blanketed the Indochina Block and the Sukhothai Zone while western Thailand was still covered by the marine sediments in the Jurassic (Meesook and Seangseechan, 2011). The widespread deposition of the continental red bed is dominated in the Cretaceous (Racey, 2009) and is known as the Khorat Group and younger formations in the Khorat Plateau or the Indochina Block by a thermal cooling phase and/or under the foreland basin associated with flexural subsidence (Carter and Bristow, 2003). The Khorat Group and younger formations are exposed over large areas and extend beyond the Indochina Block to the Sukhothai Zone through the Nakhon Thai region (part of Loei-Phetchabun Fold Belt) and go further to the central plain (Morley, 2012). The deposition of Khorat Group had continued since the Late Jurassic to the Early Cretaceous with the total thickness of more than 3500m (Racey et al., 1996). In the Mid-Cretaceous the inversion took place after the end of the Khorat Group accumulation as marked by unconformity contact between the Khorat Group and the younger rocks (Racey, 2009; Lovatt Smith et al., 1996). The inversion in the Mid-Cretaceous was probably due to the arc collision around the western subduction margin of continental West Burma (Barber and Crow, 2009; Hall et al., 2009). The inversion in the Mid-Cretaceous led to the deposition of rock salt layers of the Maha Sarakham Formation under the hyper saline land-lock lake basin of an arid condition (Racey et al., 1996; Meesook, 2000). The basin was subsequently covered by the Phu Tok Formation in the Late Cretaceous under the desert environment (Meesook, 2011; Hasegawa et al, 2010). The coming of the India in the Latest Cretaceous and subsequent collision with the Eurasia in the Early Paleogene have led the Southeast Asian region including Thailand subjected to a strong deformation (Morley, 2012). The result of the apatite fission track study of the Khorat Group shows that the Khorat Group was subjected to two stages of cooling history (Racey et al., 1997; Upton, 1999). The first stage was during 65 and 45 Ma and the second between 35 and 25 Ma. Racey et al. (1997) concluded that the cooling stages were related to the folding and thrusting of the fold belt and the uplift of the Phu Phan range in the Khorat Plateau. To the west of the Nakhon Thai region, Singharajwarapan and Berry (2000) recognised the Phu Khon Kaen thrust fault that brought the sequences of the pre-Khorat Group in the Nan-Uttaradit Suture Zone to overlie the Khorat Group. Ahrendt et al. (1993) studied the K-Ar dating of mica in metamorphic rocks along this fault zone and concluded that the last deformational event was dated back to the Late Cretaceous (63 Ma). It is consistent with the apatite fission track data of Upton (1999) which indicates that the central age of the apatite fission track sample nearby the fault zone is the Late Cretaceous (≈73 Ma).

The Phu Khat Formation was accumulated in the Late Cretaceous to Early Paleogene in the Nakhon Thai region which is located between the Nan-Uttaradit Suture Zone and the Loei-Phetchabun Fold Belt. As stated by Heggemann (1994) the main source of sediments were derived from both terranes. However, the results of this study comprising paleocurrent pattern, petrographic and whole-rock geochemical data and the U-Pb detrital zircon age dating have revealed that the main provenance of the Phu Khat Formation is mainly from the western terrane without eastern terrane source (see more detailed discussion in section 4.2.5.1). Therefore, it may imply that the Phu Khat Formation have accumulated before the uplift and erosion of the eastern terrane. The terrane west of the Nakhon Thai region was uplifted by folding and thrusting while the terrane on the east was still quiescent. This event may relate to the reactivation of pre-existing structure resulting from the renewed subduction of oceanic crust along the Eurasian margin during the Late Cretaceous - the Early Paleogene (Searle and Morley, 2011). The Nakhon Thai region, located at the front of thrust zone, is therefore the site of sediment accumulation that eroded from the uplifted zone. It is represented by the alluvial fan facies of the lower Phu Khat Formation. This event might occur during 70 Ma to 63 Ma as indicated by K-Ar dating and the apatite fission track central age in the western terrane (Ahrendt et al., 1993; Upton, 1999). The accumulation of the Phu Khat Formation would extend to the Early Paleogene. This interpretation is supported by the absence of source materials from the eastern terrane in the Phu Khat Formation. Morley (2012) and Racey et al. (1997) used the apatite fission track data to constrain the age of the up-lifting event in the Loei-Pethcabun Fold Belt and concluded that it was uplifted by reactivation of the pre-existing structure at the Early Paleogene (~50 Ma based on apatite central age) (Morley et al., 2011; Chantong, 2005) when the Greater India amalgamated with the Eurasia (Zhu et al., 2005; Rowley, 1998). The author believed that during this time the Nakhon Thai region would also be uplifted with the Loei-Pethcabun Fold Belt since the present elevation of these two regions are comparable. Consequently, the depositional age of the Phu Khat Formation can be considered as the Late Cretaceous (Maastrichtian) to not younger than the Early Paleogene (Ypresian).

5.2 Conclusions

The result of facies study integrated with the petrography, the whole-rock geochemistry and the U-Pb detrital zircon age dating of the Phu Khat Formation in the Nakhon Thai region have revealed the environmental deposition, provenance and tectonic setting. It also leads to the discussion on the geotectonic evolution and age constraint. The major results can be summarized as following.

1. The Phu Khat Formation is composed of nine lithofacies representing three facies association, i.e., the facies association A (the lower Phu Khat), facies association B (the middle Phu Khat) and facies association C (the upper Phu Khat). The facies association A is chiefly characterized by the polymictic conglomerate, coarse-grained, poorly sorted sandstone and subordinated siltstone and shale. It was interpreted to have been deposited under stream flow in proximal fan environment. The facies association B is dominated by continuous even parallel beds, reddish

brown, fine- to medium-grained sandstone grading up into siltstone and claystone. It was interpreted to have been deposited under more distal fan environment. The facies association C comprises chiefly a succession of thick-bedded, coarse-grained sandstone with tabular cross-bedding. It was interpreted to have been deposited under braided stream environment. The Phu Khat Formation overlies unconformably on the Khao Ya Puk Formation with the total thickness of approximately 500 m.

2. Based on geochemical and petrographical tectonic discriminations including 1) plot of K_2O/Na_2O ratio against SiO_2, 2) Al_2O_3/SiO_2 versus (Fe_2O_3 + MgO), 3) discriminant function plot of major elements and 4) Th-Sc-Zr/10 triangular plot as well as QFL and QmFLt indicate that the Phu Khat Formation was accumulated in the passive margin tectonic setting and was derived either from the deformed and uplifted sequences of the collision orogens or the foreland fold and thrust belt.

3. The provenance discriminations comprising discriminant function plot of major elements and plot of La/Th ratio against Hf collaborated with plot of Th/Sc against Zr/Sc ratios and the variation of Eu anomaly value (Eu/Eu* 0.42 to 0.74) reveal that the provenance of the Phu Khat Formation consists primarily of sedimentary rocks associated with continental volcanic arc rocks in the uplifted either the western or the eastern continental terranes or both. However, the U-Pb detrital zircon dating provides clear evidence that the provenance of the Phu Khat Formation was uniquely from the western terrane with igneous activity predominantly occurred in the Middle to the Late Triassic time.

4. Tectonically, while the Phu Khat Formation was accumulated in the Nakhon Thai region, the western terrane was uplifted by reactivation of the pre-existing structure probably since the Maastrichtian time to be the source area of sediments. Meanwhile, the

eastern terrane (mainly the Loei-Phetchabun Fold Belt) had not been uplifted probably until the accumulation of the Phu Khat Formation was terminated since there are no source materials from the eastern terrane in the Phu Khat Formation. Subsequently, the whole region began to uplift forming a high mountainous area since the Ypresian time when the Greater India collided with the Eurasia. Consequently, the depositional age of the Phu Khat Formation can be constrained at the Maastrichtian to Ypresian.

5.3 Recommendations for further research

1. The occurrence of the Phu Khat Formation is located at the front of the thrust fault zone. The source of the Phu Khat Formation was from the uplifted zone of the reactivated pre-existing structure. So the extent and continuation of the Phu Khat Formation should be discovered beyond the study area, particularly nearby the major pre-existing structure, e.g., the Nan-Uttaradit Suture Zone across Thai-Laos border into the Ken Thao area in Laos or in the north of the Nakhon Thai region in the Uttaradit and Nan Provinces. So the next researcher should extend the study area into the above recommended areas.

2. The more details of structural analysis should be carried out in order to recognize deformation phase after the deposition of Phu Khat Formation. If possible apatite fission track study of the Phu Khat Formation should be carried out to supplement the structural analysis.

3. The U-Pb zircon dating has shown to be a powerful tool to identify the provenance of sediment. It should be performed continually for the future discovery of the Phu Khat Formation extension in order to delineate specific provenance.

4. Micro-paleontological study in fine-grained sediments and paleomagnetic study should be considered for future study in order to confirm the depositional age.

REFERENCES

Ahrendt, H., Chonglakmani, C., Hansen, B. T., and Helmcke, D. (1993). Geochronological cross section through northern Thailand. **Journal of Southeast Asian Earth Sciences.** 8(1-4): 207-217. doi: http://dx.doi.org/10.1016/0743-9547(93)90022-H

Assavapatchara, S., and Raksasakulwong, L. (2010). Geologic investigation at Paklay - Kenthao area, Lao PDR. In **The Thai-Lao technical conference on geology and mineral resources**. Bankok, Thailand.

Barber, A. J., and Crow, M. J. (2009). Structure of Sumatra and its implications for the tectonic assembly of Southeast Asia and the destruction of Paleotethys. **Island Arc.** 8(1): 3-20. doi: 10.1111/j.1440-1738.2008.00631.x

Barr, S. M., and Charusiri, P. (2011). Volcanic rocks. In M. F. Ridd, A. J. Barber and M. J. Crow (Eds.), **The Geology of Thailand**. United Kingdom: The Geological Society of London.

Barr, S. M., and Cooper, M. A. (2013). Late Cenozoic basalt and gabbro in the subsurface in the Phetchabun Basin, Thailand: Implications for the Southeast Asian Volcanic Province. **Journal of Asian Earth Sciences**. 76(25): 169-184.

Barr, S. M., and Macdonald, A. S. (1987). Nan River suture zone, northern Thailand. **Geology.** 15: 907-910.

Barr, S. M., and Macdonald, A. S. (1991). Toward a late Paleozoic–early Mesozoic tectonic model for Thailand. **Journal of Thai Geosciences**. 1: 11–22.

Barr, S. M., Macdonald, A. S., Dunning, G. R., Ounchanum, P., and Yaowanoiyothin, W. (2000). Petrochemistry, U–Pb (zircon) age, and palaeotectonic setting of the Lampang volcanic belt, northern Thailand. **Journal of the Geological Society**.157(3): 553-563. doi: 10.1144 /jgs.157.3.553

Barr, S. M., Macdonald, A. S., Ounchanum, P., and Hamilton, M. A. (2006). Age, tectonic setting and regional implications of the Chiang Khong volcanic suite, northern Thailand. **Journal of the Geological Society.** 163(6): 1037-1046. doi: 10.1144/0016-76492005-118.

Barr, S. M., Tantisukrit, C., Yaowanoiyothin, W., and Macdonald, A. S. (1990). Petrology and tectonic implications of Upper Paleozoic volcanic rocks of Chiang Mai belt, northern Thailand. **Journal of Southeast Asian Earth Sciences**. 4: 37-47.

Barth, M. G., McDonough, W. F., and Rudnick, R. L. (2000). Tracking the budget of Nb and Ta in the continental crust. **Chemical Geology**. 165(3–4): 197-213. doi: http:// dx.doi.org/10.1016 /S0009-2541(99)00173-4

Bhatia, M. R. (1983). Plate tectonics and geochemical composition of sandstones. **Journal of Geology**. 91(6): 611-627.

Bhatia, M. R. (1985). Rare earth element geochemistry of Australian Paleozoic graywackes and mudrocks: provenance and tectonic control. **Sedimentary Geology**. 45: 97–113.

Bhatia, M., and Crook, K. W. (1986). Trace element characteristics of graywackes and tectonic setting discrimination of sedimentary basins. **Contributions to Mineralogy and Petrology**. 92(2): 181-193. doi: 10.1007/bf00375292

Blair, T. C. (1987). Tectonic and hydrologic controls on cyclic alluvial fan, fluvial, and lacustrine rift-basin sedimentation, Jurassic-Lowermost Cretaceous Todos Santos Formation, Chiapas, Mexico. **Journal of Sedimentary Research**. 57(5): 845-862. doi: 10.1306/212f8c83-2b24-11d7-8648000102c1865d

Blair, T. C., and Mcpherson, J. G. (1992). The Trollheim alluvial fan and facies model revisited. **Geological Society of America Bulletin**. 104(6): 762-769. doi: 10.1130/0016-7606(1992)104<0762:TTAFAF>2.3.CO;2

Botev, Z. I., Grotowski, J. F. and Kroese D. P., 2010: Kernel density estimation via diffusion. **Annals of Statistics**. 38, 5: 2916-2957.

Booth, J., and Sattayarak, N. (2011). Subsurface Carborniferouse-Cretaceous geology of Northeast Thailand. In M. F. Ridd, A. J. Barber and M. J. Crow (Eds.), **The Geology of Thailand**. United Kingdom: The Geological Society of London.

Boucot, A. (2007). What happens at the northern end of the Shan-Thai Terrane: what does it go frome there. In **The international conference on the geology of Thailand : Toward sustainable developement and sufficiency economy**. Bangkok, Thailand.

Bridge, J. S. (2003). **Rivers and Floodplains: Forms, Processes and Sedimentary Records**. Oxford: Blackwell.

Brown, G. F., Buravas, S., Charaljavanaphet, J., Jalichan, N., Johnson, W., Sresthapura, V and Taylor, G. C. (1951). **Geologic Reconnaissance of the Mineral Deposits of Thailand** (Vol. Memoir Geological No.1). Washington D.C.: Department of Mines, USGS.

Buffetaut, E., and Suteethorn, V. (1998). The biogeographical significance of the Mesozoic vertebrates from Thailand. **Biogeography and geological evolution of SE Asia**. 83-90.

Bunopas, S. (1981). Paleogeographic History of Western Thailand and Adjacent Parts of South-East Asia. A Plate Tectonics Interpretation **Geological Survey Paper** 5. Bangkok, Thailand: Department of Mineral Resources.

Bunopas, S. (1992). Regional stratigraphic correlation in Thailand. In: Jaroen, P., ed. In **The National conference on geologic resources of Thailand: Potential for future development**. Bangkok, Thailand.

Bunopas, S. (1994). Regional stratigraphy, paleogeographic and tectonic event of Thailand and continental Southeast Asia. In **The international symposium on stratigraphic correlation of Southeast Asia**. Bangkok, Thailand.

Caridroit, M., Bohlke, D., Lamchuan, A., Helmcke, D., and De Wever, P. (1993). A mixed Radiolarian fauna (Permian/Triassic) from clastics of the Mae Sariang area, northwestern Thailand. In: THANASUTHIPITAK, T. (ed.) In **The International Symposium on Biostratigraphy of Mainland Southeast Asia: Facies and Paleontology**. Chiang Mai University, Chiang Mai.

Carter, A., and Bristow, C. (2003). Linking hinterland evolution and continental basin sedimentation by using detrital zircon thermochronology: a study of the Khorat Plateau Basin, eastern Thailand. **Basin Research**. 15(2): 271–285.

Chairangsee C, Hinze C, Machareonsap S, Nakhonsri N, Silpalit M, and Sinpoolanunt., S. (1990). Geological map of Thailand 1:50,000-Explanation for Amphoe Pak Chom, Ban Huai Khop, Ban Na Kho and Amphoe Nam Som. **Geologisches Jahrbuch Reihe**. Hannover.

Chantong, W. (2005). **Structural evolution of the Khorat Plateau, Thailand**. Unpublished PhD thesis, University of Leeds, United Kingdom.

Charoenpravat, A., Wongwanich, T., Tantiwanit, W, and Theetiparivatra, U. (1976). **Geologic Map of Thailand, sheet NE47-12 Changwat Loei, scale 1: 250,000**. Geological Survay Division, Department of Mineral Resources. Bangkok, Thailand.

Charusiri, P., Clark, A. H., Farrar, E., Archibald, D., and Charusiri, B. (1993). Granite belts in Thailand: evidence from the 40Ar/39Ar geochronological and geological syntheses. **Journal of Southeast Asian Earth Sciences**. 8(1–4): 127-136. doi: http://dx.doi.org/10.1016/0743-9547(93)90014-G

Chonglakmani, C. (2002). Current status of Trisasic stratigraphy of Thailand and its implication for geotectonic evolution. In **The symposium on Geology of Thailand**. Bangkok, Thailand.

Chonglakmani, C. (2011). Triassic. In M. F. Ridd, A. J. Barber and M. J. Crow (Eds.). **The Geology of Thailand**. United Kingdom: The Geological Society of London.

Chonglakmani, C., Chaodumrong, P., Munjai, D., Malila, K., Udchachon, M., Udchachon, H., .Wang, W. (2010). **Comparative research on tectonic framework and geological evolution of Loei-Phetchabun Foldbelt and Jiangcheng-Mojiang Mountain Belt (Yunnan)**. Nakhon Ratchasima, Thailand: Suranaree University of Technology.

Chonglakmani, C., and Sattayarak, N. (1978). Stratigraphy of the Huai Hin Lat Formation (Upper Triassic) in northeastern Thailand. In **The Proceedings of the third regional conference on geology and minerals resources of Southeast Asia**. Bangkok.

Clift, P. D., Carter, A., Campbell, I. H., Pringle, M. S., Van Lap, N., Allen, C. M., Tan, M. T. (2006). Thermochronology of mineral grains in the Red and Mekong Rivers, Vietnam: Provenance and exhumation implications for Southeast Asia. **Geochemistry, Geophysics, Geosystems**. 7(10): Q10005.

Cobbing, E. J. (2011). Granitic Rocks. In M. F. Ridd, A. J. Barber and M. J. Crow (Eds.). In **The Geology of Thailand**. United Kingdom: The Geological Society of London.

Cocks, L. R. M., Fortey, R. A., and Lee, C. P. (2005). A review of Lower and Middle Palaeozoic biostratigraphy in west peninsular Malaysia and southern Thailand in its context within the Sibumasu Terrane. **Journal of Asian Earth Sciences.** 24: 703–717.

Collinson, J. D. (1996). Alluvial Sediments. In H. G. Reading (Ed.). **Sedimentary Environments: Process, Facies and Stratigraphy**. Oxford: Blackwell Publishing.

Dickinson, W. (1985). Interpreting Provenance Relations from Detrital Modes of Sandstones. In G. G. Zuffa (Ed.). **Provenance of Arenites** (Vol. 148, pp. 333-361): Springer Netherlands.

Dickinson, W. R., and Suczek, C. A. (1979). Plate tectonics and sandstone compositions. **AAPG Bulletin**. 63(12): 2164-2182.

DMR (Cartographer). (1999). **Geological Map of Thailand** ; scale 1: 2500000.

Drumm, A., Heggemann, H., and Helmcke, D. (1993). Contribution of sedimentology and sediment petrology of the non marine Mesozoic sediments in northern Thailand (Phrae and Nan provinces). **The Biostratigraphy of mainland southeast asia: facies and paleontology.** Chiang Mai, Thailand.

Dunning, G. R., Macdonald, A. S., and Barr, S. M. (1995). Zircon and monazite U-Pb dating of the Doi Inthanon core complex, northern Thailand: implications for extension within the Indosinian Orogen. **Tectonophysics.** 251(1–4): 197-213. doi: http://dx.doi.org/10.1016/0040-1951(95)00037-2

Etemad-Saeed, N., Hosseini-Barzi, M., and Armstrong-Altrin, J. S. (2011). Petrography and geochemistry of clastic sedimentary rocks as evidences for provenance of the Lower Cambrian Lalun Formation, Posht-e-badam block, Central Iran. **Journal of African Earth Sciences**. 61(2): 142-159. doi: http://dx.doi.org/10.1016/j.jafrearsci.2011.06.003

Feng, Q., Helmcke, D., Chonglakmani, C., Ingavat-Helmcke, R., and Liu, B. (2004). Early Carboniferous radiolarians from north-west Thailand: palaeogeographical implications. **Palaeontology.** 47(2): 377-393.

Feng, Q., Malila, K., Wonganan, N., Chonglakmani, C., Helmcke, D., Ingavat-Helmcke, R., and Caridroit, M. (2005). Permian and Triassic Radiolaria from Northwest Thailand:

paleogeo graphical implications. **Revue de Micropaléontologie**. 48(4): 237-255. doi: http://dx.doi. org/ 10.1016/j.revmic.2005.09.004

Feng, Q., Chonglakmani, C., and Ingavat-Helmcke, R. (2009). Evolution of the Loei Belt in northeas -tern Thailand and northwestern Laos. **Acta Geoscientica Sinica**. 30: 9-9.

Floyd, P. A., and Leveridge, B. E. (1987). Tectonic environment of the Devonian Gramscatho basin, south Cornwall: framework mode and geochemical evidence from turbiditic sandstones. **Journal of the Geological Society**. 144(4): 531-542. doi: 10.1144/gsjgs.144.4.0531

Folk, R. L. (1974). **Petrology of sedimentary rocks**. Austin,Texas: Hemphil Publishing Company.

Fontaine, H., Salyapongse, S., and Suteethorn, V. (2003). Glimpses into Fossil Assemblages of Thailand: Coral Perspectives. **Natural History Bulletin of the Siam Society**. 51(1): 37-67.

Gabo, J. A. S., Dimalanta, C. B., Asio, M. G. S., Queano, K. L., Yumul, G. P., and Imaie, A. (2009). Geology and geochemistry of the clastic sequences from Northwestern Panay (Philippines): Implications for provenance and geotectonic setting. **Tectonophysics.** 479(1–2): 111–119.

Gibson, L. (2009). **Geology and geochronology of the northern Nan Suture, Thailand**. Unpublished BSc (Hons) thesis, University of Tasmania, Hobart, Australia.

Hall, R., Clements, B., and Smyth, H. R. (2009). Sundaland: basement character, structure and plate tectonic development. In **The Proceedings of the Indonesian Petroleum Association**. 33rd annual convention and exhibition. Indonesia.

Hampton, B. A., and Horton, B. K. (2007). Sheetflow fluvial processes in a rapidly subsiding basin, Altiplano plateau, Bolivia. **Sedimentology**. 54(5): 1121-1148. doi: 10.1111/j.1365-3091.2007.00875.x

Hahn, L. (1976). The Stratigraphy and palaeogeography of the non-marine Mesozoic deposit in northern Thailand. **Geo.Jb**. B21: 155-169.

Hansen, B. T., Wemmer, K., Pawlig, S., Klaus, J., Assavapatchara, S., Nontaso, M., and Putthapiban, P. (2002). Isotopic evidence for a Late Cretaceous age of the potash and rock salt deposit at Bamnet Narong, NE Thailand. In **The Symposium on Geology of Thailand** (pp. 26-31).

Hansen, B. T., and Wemmer, K. (2011). Age and evolution of the basement rocks in Thailand. In M. F. Ridd, A. J. Barber and M. J. Crow (Eds.). **The Geology of Thailand**. United Kingdom: The Geological Society of London.

Hara, H., Kunii, M., Hisada, K., Ueno, K., Kamata, Y., Srichan, W., Charusiri, P.,Charoentitirat, T., Watarai, M., Adachi, Y., and Kurihara, T. (2012). Petrography and geochemistry of clastic rocks within the Inthanon zone, northern Thailand: Implications for Paleo-Tethys subduction and convergence. **Journal of Asian Earth Sciences**. 61(0): 2-15. doi: http://dx.doi.org/10.1016/j.jseaes.2012.06.012

Hara, H., Kurihara, T., Kuroda, J., Adachi, Y., Kurita, H., Wakita, K., Ken, H., Charusiri, P., Charoentitirat, T., and Chaodumrong, P. (2010). Geological and geochemical aspects of a Devonian siliceous succession in northern Thailand: Implications for the opening of the Paleo-Tethys. **Palaeogeography, Palaeoclimatology, Palaeoecology**. 297: 452–464.

Hara, H., Wakita, K., Ueno, K., Kamata, Y., Hisada, K., Charusiri, P., Charoentitirat, T., and Chaodumrong, P. (2009). Nature of accretion related to Paleo-Tethys subduction recorded in northern Thailand: Constraints from mélange kinematics and illite crystallinity. **Gondwana Research**. 16(2): 310-320. doi: http://dx.doi.org/10.1016/j.gr.2009.01.006

Hasegawa, H., Imsamut, S., Charusiri, P., Tada, R., Horiuchi, Y., and Hisada, K. (2010). 'Thailand was a desert' during the mid-Cretaceous: Equatorward shift of the subtropical high-pressure belt indicated by eolian deposits (Phu Thok Formation) in the Khorat Basin, northeastern Thailand. **Island Arc**. 19(4): 605-621. doi: 10.1111/j.1440-1738.2010.00728.x

Hasegawa, H., Tada, R., Jiang, X., Suganuma, Y., Imsamut, S., Charusiri, P., Ichinnorov, N., and Khand, Y. (2012). Drastic shrinking of the Hadley circulation during the mid-Cretaceous supergreenhouse. **Clim. Past Discuss**. 8(1): 1323-1337.

Heggemann, H. (1994). **Sedimentare Entwicklung der Khorat-Gruppe (ober-Trias bis Paleogen) in NE- und N-Thailand**. Gottingen: Geologische Institute, Universitat Gottingen.

Heggemann, H., Helmcke, D., and Tietze, K. W. (1994). Sedimentary evolution of the Mesozoic Khorat basin in Thailand. **Geol.Palaont Teil l**. 1992(11/12): 1267-1285.

Helmcke, D. and Kraikhong, C. (1982). On the geocynclinal and orogenic evolution of central and northeastern Thailand. **Jour. Geol. Soc. Thailand**. 5: 52-47.

Herron, M. M. (1988). Geochemical classification of terrigeneous sand and shale from core or log data. **Journal of Sedimentary Petrology**. 58(5): 820-829.

Heward, A. P. (1977). Alluvial Fan Sequence and Megasequence Models: With Examples From Westphalian D - Stephanian B Coalfields, Northern Spain. **Fluvial Sedimentology - Memoir.** 5: 669-702.

Hinthong, C., Chuaviroj, S., Kaewyana, W., Srisukh, S., Pholprasit, C., and Pholachan, S. (1985). **Geological map of Thailand scale 1:250,000, sheet Changwat Phra Nakhon Si Ayutthaya (ND 47-8)**. Geological Survey Division, Department of Mineral Resources, Bangkok, Thailand.

Intasopa, S. B. (1993). **Petrology and geochonology of the volcanic rock of the central Thailand volcanic belt**. Unpublished PhD Thesis, University of New Brunswick, Canada.

Intasopa, S., and Dunn, T. (1993). Petrology and Sr-Nd isotopic systems of the basalts and rhyolites, Loei, Thailand. **Journal of Southeast Asian Earth Sciences**. 9: 167-180.

Intasopa, S. B., Dunn, T., and Lambert, R. S. J. (1995). Geochemistry of Cenozoic basaltic and silicic magmas in the central portion of the Loei–Phetchabun volcanic belt, Lop Buri, Thailand. **Canadian Journal of Earth Sciences**. 32: 393–409.

Japakasetr, T., and Suwanich, P. (1982). Potash and rock salt in Thailand. **Nonmetallic Mineral Bulletin (Vol. 2)**. Bangkok, Thailand: Department of Mineral Resources.

Kamata, Y., Sashida, K., Ueno, K., Hisada, K. I., Nakornsri, N., and Charusiri, P. (2002). Triassic radiolarian faunas from the Mae Sariang area, northern Thailand and their paleogeographic significance. **Journal of Asian Earth Sciences**. 20: 491–506.

Kamvong, T., and Zaw, K. (2009). The origin and evolution of skarn-forming fluids from the Phu Lon deposit, northern Loei Fold Belt, Thailand: Evidence from fluid inclusion and sulfur isotope studies. **Journal of Asian Earth Sciences**. 34(5): 624-633. doi: http://dx.doi.org/ 10.1016 /j. jseaes.2008.09.004

Kamvong, T., Zaw, K., Meffre, S., Maas, R., Stein, H., and Lai, C. K. (2014). Adakites in the Truong Son and Loei fold belts, Thailand and Laos: genesis and implications for geodynamics and metallogeny. **Gondwana Research.** 26(1): 165–184. doi: http://dx.doi.org/10.1016/j.gr.2013.06.011.

Kelly, S. B., and Olsen, H. (1993). Terminal fans – a review with references to Devonian examples. **Sedimentary Geology.** 85: 339–374.

Khanehbad, M., Moussavi-Harami, R., Mahboubi, A., Nadjafi, M., and Mahmudy Gharaie, M. H. (2012). Geochemistry of Carboniferous Sandstones (Sardar Formation), East-Central Iran: Implication for Provenance and Tectonic Setting. **Acta Geologica Sinica - English Edition**. 86(5): 1200-1210. doi: 10.1111/j.1755-6724.2012.00741.x

Khin Zaw., Meffre, S., Lai, C.K., Burrett, C., Santosh, M., Graham, I., Manaka, T., Salam, A., Kamvong, T., and Cromie, P. (2014) Tectonics and metallogeny of mainland Southeast Asia - A review and contribution. **Gondwana Research.** 26 (1): 5–30.doi: http://dx.doi.org/10.1016/j.gr.2013.10.010

Khositanont, S. (2008). **Gold and iron-gold mineralization in the Sukhothai and Loei-Phetchabun Fold belt**. Unpublished PhD thesis, Chiang Mai University, Chiang Mai, Thailand.

Kosuwan, S. (1990). **Geology of Nakhon Thai District and Ban Nam Kum; in scale 1:50000**. Bangkok, Thailand (in Thai): Department of Mineral Resources.

Kromkhun, K., Baines, G., Satarugsa, P., and Foden, J. (2013). Petrochemistry of Volcanic and Plutonic Rocks in Loei Province, Loei-Petchabun Fold Belt, Thailand. In **The International Conference on Geological and Environmental Sciences**, Singapore.

Lee, C. P. (1983). Stratigraphy of the Tarutao and Machinchang Formations. **The Stratigraphic correlation of Thailand and Malaysia**. Bangkok.

Lee, C. P. (2006). The Cambrian of Malaysia. **Palaeoworld**. 15: 242–255.

Lepvrier, C., Maluski, H., Van Tich, V., Leyreloup, A., Truong Thi, P., and Van Vuong, N. (2004). The Early Triassic Indosinian orogeny in Vietnam (Truong Son Belt and Kontum Massif); implications for the geodynamic evolution of Indochina. **Tectonophysics**. 393(1–4): 87-118. doi: http://dx.doi.org/10.1016/j.tecto.2004.07.030

Li, P., Rui, G., Junwen, C., and Ye, G. (2004). Paleomagnetic analysis of eastern Tibet: implications for the collisional and amalgamation history of the Three Rivers Region, SW China. **Journal of Asian Earth Sciences**. 24(3): 291-310. doi: http://dx.doi.org/10.1016/j.jseaes.2003.12.003

Lovatt Smith, P. F., Stokes, R. B., Bristow, C., and Carter, A. (1996). Mid-Cretaceous inversion in the Northern Khorat Plateau of Lao PDR and Thailand. **Geological Society, London, Special Publications**. 106(1): 233-247. doi: 10.1144/gsl.sp.1996.106.01.15

Luddecke, S., Chonglakmani, C., and Helmcke, D. (1991). Analysis of pebble association from the marine Triassic of northern Thailand. **Journal of Thai Geosciences**. 2: 91-101.

Mahawat, C. (1984). The geological characteristics of the Pilok Sn-W-Mo deposits, west Thailand. In **The International symposium on the geology of tin deposits**. Naning, China.

Malila, K. (2005). **Provenance of the Nam Duk Formation and implications fro the geodynamic evolution of the Phetchabun Fold Belt**. Unpublished PhD thesis, Suranaree University of Technology, Thailand.

Mantajit, N. (1997). Stratigraphy and tectonic evolution of Thailand. In **The international conference on stratigraphy and tectonic evolution of Southeast Asia and South Pacific**. Bangkok, Thailand.

Macdonald, A. S., Barra, S. M., Dunning, G. R., and Yaowanoiyothin, W. (1993). The Doi Inthanon metamorphic core complex in NW Thailand: age and tectonic significance. **Journal of Southeast Asian Earth Sciences.** 8(1-4): 117-125.

McLennan, S. M., Hemming, S., McDaniel, D. K., and Hanson, G. N. (1993). Geochemical approaches to sedimentation, provenance, and tectonics. **Geological Society of America Special Papers**. 284: 21-40. doi: 10.1130/SPE284-p21

Meesook, A. (2000). Cretaceous environments of northeastern Thailand. In O. Hakuyu and J. M. Nlall (Eds.). **Developments in Palaeontology and Stratigraphy** (Volume 17, pp. 207-223): Elsevier.

Meesook, A. (2011). Cretaceous. In M. F. Ridd, A. J. Barber and M. J. Crow (Eds.). **The Geology of Thailand**. United Kingdom: The Geological Society of London.

Meesook, A., and Saengsrichan, W. (2011). Jurassic. In M. F. Ridd, A. J. Barber and M. J. Crow (Eds.). **The Geology of Thailand**. United Kingdom: The Geological Society of London.

Meesook, A., Suteethorn, V., Chaodumrong, P., Teerarungsigul, N., Sardsud, A., and Wongprayoon, T. (2002). Mesozoic rocks of Thailand: A summary. In **The symposium on Geology of Thailand**. Bangkok, Thailand.

Metcalfe, I. (2011). Palaeozoic–Mesozoic history of SE Asia. **Geological Society, London, Special Publications.** 355(1): 7-35. doi: 10.1144/sp355.2

Metcalfe, I. (2013). Gondwana dispersion and Asian accretion: Tectonic and palaeogeographic evolution of eastern Tethys. **Journal of Asian Earth Sciences**. 66(0): 1-33. doi: http:// dx. doi. Org/10.1016/j.jseaes.2012.12.020

Miall, A. D. (1985). Architectural-element analysis: A new method of facies analysis applied to fluvial deposits. **Earth-Science Reviews.** *22*(4): 261-308. doi: 10.1016/0012-8252(85)90001-7

Miall, A. D. (1996). **The Geology of Fluvial Deposits: Sedimentary Facies, Basin Analysis, and Petroleum Geology**. Germany: Springer.

Monjai, D. (2006). **Facies genesis analysis of tha Phu Thok Formation and the Upper clastic cap rock of the Mahasarakham Formation (in Thai with English Abstract)**. Unpublished MSc Thesis, Khon Kaen University, Khon Kaen, Thailand.

Morley, C. K. (2012). Late Cretaceous - Early Palaeogene tectonic development of SE Asia. **Earth-Science Reviews**. 115(1–2): 37-75. doi: 10.1016/j.earscirev.2012.08.002.

Morley, C. K., Charusiri, P., and Watkinson, I. M. (2011). Structural Geology of Thailand during the Cenozoic. In M. F. Ridd, A. J. Barber and M. J. Crow (Eds.). **The Geology of Thailand**. United Kingdom: The Geological Society of London.

Morley, C. K., and Racey, A. (2011). Tertiary Stratigraphy. In M. F. Ridd, A. J. Barber and M. J. Crow (Eds.). **The Geology of Thailand**. United Kingdom: The Geological Society of London.

Morley, C. K., Woganan, N., Sankumarn, N., Hoon, T. B., Alief, A., and Simmons, M. (2001). Late Oligocene–Recent stress evolution in rift basins of northern and central Thailand: implications for escape tectonics. **Tectonophysics.** 334 (2): 115–150.

Morton, A. C., Whitham, A. G., and Fanning, C. M. (2005). Provenance of Late Cretaceous to Paleocene submarine fan sandstones in the Norwegian Sea: Integration of heavy mineral, mineral chemical and zircon age data. **Sedimentary Geology**. 182(1-4): 3–28.

Nichols, G. J., and Fisher, J. A. (2007). Processes, facies and architecture of fluvial distributary system deposits. **Sedimentary Geology**. 195(2007): 75–90.

Nichols, G., and Uttamo, W. (2005). Sedimentation in a humid, interior, extensional basin: the Cenozoic Li Basin, northern Thailand. **Geological Society of London**. 162: 333–347.

Panjasawatwong, Y. (1991). **Petrology, geochemistry and tectonic implications of igneous rocks in Nan Suture, Thailand and an empirical study of the effects of Ca/Na, Al/Si and H2O on Plagioclase-melt equilibria at 5-10 k pressure**. Unpublished PhD Thesis, University of Tasmania, Australia.

Panjasawatwong, Y., Chantaranee, S., Limtrakun, P., and Pirarai, K. (1997). Geochemistry and tectonic setting of eruption of central Loei volcanics in the Pak Chom area, Loei, Northeast Thailand. In **The international conference on stratigraphy and tectonic evolution of Southeast Asia and South Pacific**. Bangkok, Thailand.

Panjasawatwong, Y., Phajuy, B., and Hada, S. (2003). Tectonic Setting of the Permo-Triassic Chiang Khong Volcanic Rocks, Northern Thailand Based on Petrochemical Characteristics. **Gondwana Research.** 6(4): 743-755.

Phajuy, B., Panjasawatwong, Y., and Osataporn, P. (2005). Preliminary geochemical study of volcanic rocks in the Pang Mayao area, Phrao, Chiang Mai, northern Thailand: tectonic setting of formation. **Journal of Asian Earth Sciences**. 24(6): 765-776. doi: http://dx.doi. org/10. 101 6/j.jseaes.2004.06.001

Pirrie, D. (1998). Interpreting the record: facies analysis. In P. Doyle, and M.R.Bennett (eds.). **Unlocking the Stratigraphical Record: Advances in Modern Stratigraphy** (pp 395-420). England: John Willey and Sons.

Piyasin, S. (1972). Geology of Lampang Sheet NE 47-4 Scale 1: 250,000. **Technical Report** (Vol. 14). Bangkok, Thailand:Geological Survey Division, Department of Mineral Resources.(In Thai)

Putthapiban, P. (1992). The Cretaceous-Tertiary granite magmatism in the west coast of peninsular Thailand and the Mercui archipelago of Myanmar/Burmar. In **The geologic resources of Thailand : Potential for future development**. Bangkok, Thailand.

Putthapiban, P. (2002). Geology and geochonology of igneous rocks of Thailand. In **The symposium on geology of Thailand**. Bangkok, Thailand.

Pye, K. (1995). The nature, origin and accumulation of loess. **Quaternary Science Reviews**. 14(7–8): 653-667. doi: 10.1016/0277-3791(95)00047-x

Pye, K., and Tsoar, H. (2009). **Aeolian Sand and Sand Dunes**. Berlin, Germany: Springer.

Qian, X., Feng, Q., Chonglakmani, C., and Monjai, D. (2013). Geochemical and geochronological constrains on the Chiang Khong volcanic rocks (northwestern Thailand) and its tectonic implications. **Frontiers of Earth Science**. 7(4): 508-521. doi: 10.1007/s11707-013-0399-2

Racey, A. (2009). Mesozoic red bed sequences from SE Asia and the significance of the Khorat Group of NE Thailand. **Geological Society of London, Special Publications**. 315(1): 41-67.

Racey, A. (2011). Petroleum geology. In M. F. Ridd, A. J. Barber and M. J. Crow (Eds.). **The Geology of Thailand**. United Kingdom: The Geological Society of London.

Racey, A., and Goodall, J. G. S. (2009). Palynology and stratigraphy of the Mesozoic Khorat Group red bed sequences from Thailand. **Geological Society of London, Special Publications**. 315(1): 69-83.

Racey, A., Duddy, I., and Love, M. (1997). Apatite fission track analysis of Mesozoic red beds from northeastern Thailand and western Laos. In **The International Conference on Stratigraphy and tectonic evolution of Southeast Asia and the South Pacific.** Bangkok, Thailand.

Racey, A., Love, M., Canham, A., Goodall, J., Polachan, S., and Jones, P. (1996). Stratigraphy and reservoir potential of the Mesozoic Khorat Group, NE Thailand: Part 1: Stratigraphy and Sedimentary Evolution. **Journal of Petroleum Geology**. 19(1): 5-39.

Raksasakulwong, L. (2002a). Thung Yai Group: Jurassic-Cretaceous transitional and continental deposits in southern Thailand. **Technical report of Geological Survey Division** (Vol. 260/2545, pp 49): Department of Mineral Resources. (in Thai with English abstract).

Raksasakulwong, L. (2002b). Mopping up the stratigraphic mess of the Phu Thok Formation in the vicinity of Phu Thok Noi area, Sriwilai District, Nong Khai Province. **Technical report of Geological Survey Division** (Vol. 261/2545, pp. 57): Department of Mineral Resources. (in Thai with English abstract).

Ridd, M. F. (2011). Lower Palaeozoic. In M. F. Ridd, A. J. Barber and M. J. Crow (Eds.). **The Geology of Thailand**. United Kingdom: The Geological Society of London.

Roser, B. P., and Korsch, R. J. (1986). Determination of tectonic setting of sandstone-mudstone suites using SiO2 content and K2O/Na2O ratio. **The Journal of Geology.** 94: 635–650.

Roser, B. P., and Korsch, R. J. (1988). Provenance signatures of sandstone-mudstone suites determined using discriminant function analysis of major-element data. **Chemical Geology**. 67 (1–2): 119–139.

Rowley, D. B. (1998). Minimum Age of Initiation of Collision between India and Asia North of Everest Based on the Subsidence History of the Zhepure Mountain Section. **The Journal of Geology**. 106: 229–235.

Rubatto, D. (2002). Zircon trace element geochemistry: partitioning with garnet and the link between U–Pb ages and metamorphism. **Chemical Geology**. 184: 123–138.

Rudnick, R. L., and Gao, S. (2003). Composition of the Continental Crust. In R. L. Rudnick (Ed.). **Treatise on Geochemistry** (Vol. 3, pp. 1-64): Elsevier.

Ryan, K. M., and Williams, D. M. (2007). Testing the reliability of discrimination diagrams for determining the tectonic depositional environment of ancient sedimentary basins. **Chemical Geology**. 242(1–2): 103-125. doi: http://dx.doi.org/10.1016/j.chemgeo.2007.03.013

Saesaengseerung, D., Sashida, K., and Sardsud, A. (2008). Late Devonian to Early Carboniferous radiolarian fauna from the Pak Chom area, Loei Province, northeastern Thailand. **Paleontological research.** 11(2): 109-121.

Salam, A., Zaw, K., Meffre, S., McPhie, J., and Lai, C.K. (2014). Geochemistry and geochronology of the Chatree epithermal gold-silver deposit: Implications for the tectonic setting of the Loei Fold Belt, central Thailand. **Gondwana Research**. 26(1): 198–217. doi: http://dx.doi.org/10.1016/j. gr.201 3.10.008

Sashida, K., Igo, H., Hisafa, K., Nakornsri, N., and Ampornmaha, A. (1993). Occurrence of Paleozoic and Early Mesozoic radiolarian in Thailand (preliminary report). **Journal of Southeast Asian Earth Sciences**. 8(1–4): 97–108.

Sattayarak, N., and Polachan, S. (1990). Rocksalt underneath the Khorat plateau. In **The Proceedings of the Department of Mineral Resources Technical conference**. Bangkok, Thailand (in Thai).

Sattayarak, N., Polachan, S. and Charusirisawad, R. (1991). Cretaceous rock salt in the northeastern part of Thailand. In **Geology, Mineralogy and Hydrocarbon Resources in Southeast Asia (GEOSEA) VII** (Bangkok, 5–8 November 1991), Abstract, p. 36.

Searle, M. P., and Morley, C. K. (2011). Tectonic and themal evolution of Thailand in the regional context of SE Asia. In M. F. Ridd, A. J. Barber and M. J. Crow (Eds.). **The Geology of Thailand**. United Kingdom: The Geological Society of London.

Selley, R. C. (2000). **Applied Sedimentology** (2 ed.): Elsevier Inc.

Sha, J.G., Meesook, A., and Nguyen, X. K. (2012). Non marine Cretaceous bivalve biostratigraphy of Thailand , Southern Lao PDR and central Vietnam. **Journal of Stratigraphy.** 36(2): 382-399.

Singharajwarapan, S. (1994). **Deformation and metamorphism of the Sukhothai Fold Belt, northern Thailand**. Unpublished PhD Thesis, University of Tasmania, Australia.

Singharajwarapan, S., and Berry, R. (2000). Tectonic implications of the Nan Suture Zone and its relationship to the Sukhothai Fold Belt, Northern Thailand. **Journal of Asian Earth Sciences**. 18(6): 663-673. doi: http://dx.doi.org/10.1016/S1367-9120(00)00017-1.

Singharajwarapan, S., Berry, R., and Panjasawatwong, Y. (2000). Geochemical characteristics and tectonic significance of the Permo-Triassic Pak Pat Volcanics, Uttaradit, Northern Thailand. **Journal of Geological Society of Thailand.** 1: 1-7.

Smith, N. D., Cross, T. A., Dufficy, J. P., and Clough, S. R. (1989). Anatomy of an avulsion. **Sedimentology**. 36: 1–23.

Sone, M., and Metcalfe, I. (2008). Parallel Tethyan sutures in mainland Southeast Asia: New insights for Palaeo-Tethys closure and implications for the

Indosinian orogeny. **Comptes Rendus Geoscience**. 340(2–3): 166-179. doi: http://dx.doi.org/10.1016/j.crte.2007.09.008

Srichan, W., Crawford, A. J., and Berry, R. F. (2008). Geochemistry and Geochronology of the Lampang Area Igneous Rocks,Northern Thailand. In **The International Symposia on Geoscience Resources and Environments of Asian Terranes (GREAT 2008), 4th IGCP 516,and 5th APSEG**. Bangkok, Thailand.

Srichan, W., Crawford, A. J., and Berry, R. F. (2009). Geochemistry and geochronology of Late Triassic volcanic rocks in the Chiang Khong region, northern Thailand. **Island Arc**. 18(1): 32-51. doi: 10.1111/j.1440-1738.2008.00660.x

Stanistreet, I. G., and McCarthy, T. S. (1993). The Okavango Fan and the classification of subaerial fan systems. **Sedimentary Geology**. 85(1–4): 115-133. doi: http://dx.doi.org/10.1016/0037-0738(93)90078-J.

Sutthirat, C., Charusiri, P., Farrar, E., and Clarke, A. H. (1994). New 40Ar/39Ar geochronology and characteristics of some Cenozoic basalts in Thailand. In **The Proceedings of the International Symposium on Stratigraphic Correlation of Southeast, Asia.** Bangkok, Thailand.

Sutthirat, C., Droop, G. T. R., Henderson, C. M. B., and Manning, D. A. C. (1999). Petrography and mineral chemistry of xenoliths and xenocrysts in Thai corundum-related basalts: Implications for the upper mantle and lower crust beneath Thailand. In **The Symposium on Mineral, Energy and Water Resources of Thailand: Towards the Year 2000**. Bangkok, Thailand.

Swezey, C. (1998). The Identification of Eolian Sands and Sandstones. **Comptes Rendus de l'Académie des Sciences - Series IIA - Earth and Planetary Science**. 327(8): 513-518. doi: http://dx.doi.org/10.1016/S1251-8050(99)80032-9

Sun, S.S., and McDonough, W. F. (1989). Chemical and isotopic systematics of oceanic basalts:implications for mantle composition and processes. **Geological Society of London, Special Publications.** 42: 313-345.

Taylor, S. R., and McLennan, S. M. (1985). **The Continental Crust: Its Composition and Evolution.** Oxford: Blackwell Scientific Publications.

Taylor, S. R., and McLennan, S. M. (1995). The geochemical evolution of the continental crust. **Reviews of Geophysics**. 33(2): 241-265. doi: 10.1029/95rg00262

Teerarungsigul, N., Raksaskulwong, L., and Khantaprab, C. (1999). Reconsidation of the lithostratigraphy of non-marine Mesozoicrocks in Thung Yai- Khong Thom area, southern Thailand. In **The Symposium on Mineral, Energy, and Water Resources of Thailand: toward the year 2000**. Bangkok, Thailand.

Thassanapak, H., Feng, Q., Grant-Mackie, J., Chonglakmani, C., and Thanee, N. (2011). Middle Triassic radiolarian faunas from Chiang Dao, Northern Thailand. **Palaeoworld**. 20(2011): 179–202.

Thomas, M. (1994). **Geomorphology in the tropics: a study of weathering and denudation in low latitudes.** Chichester: wiley & sons.

Todd, S. P. (1996). Process deduction from fluvial sedimentary structures. In P. A. Carling and M. R. Dawson (Eds.). In **Advances in Fluvial Dynamics and Stratigraphy** (pp. 299–350). Chichester, UK: Wiley.

Tucker, M. E. (1988). **Techniques in sedimentology**. Oxford: Blackwell scientific publication.

Tucker, M. E. (2003). **Sedimentary Rocks in the Field**. West Sussex, England: John Wiley and Sons.

Tunbridge, I. P. (1984). Facies model for a sandy ephemeral stream and clay playa complex; the Middle Devonian Trentishoe Formation of North Devon, U.K. **Sedimentology.** 31(5): 697-715. doi: 10.1111/j.1365-3091.1984.tb01231.x

Udchachon, M., Thassanapak, H., Feng, Q., and Chonglakmani, C. (2011). Geochemical constraints on the depositional environment of Upper Devonian radiolarian cherts from Loei, north-eastern Thailand. **Frontiers of Earth Sciences**. 5(2): 178–190.

Ueno, K., and Charoentitirat, T. (2011). Carborniferous and Permian. In M. F. Ridd, A. J. Barber and M. J. Crow (Eds.). **The Geology of Thailand**. United Kingdom: The Geological Society of London.

Ueno, K., and Hisada, K. (2001). The Nan-Uttaradit-Sa Kaeo Suture as a Main Paleo-Tethyan Suture in Thailand: Is it Real? **Gondwana Research**. 4(4): 804-806. doi: http://dx.doi.org/10.1016/ S1 342-937X(05)70590-6

Upton, D.R. 1999. **A regional fission track study of Thailand: implications for thermal history and denudation**. Unpublished PhD thesis, University of London, United Kingdom.

Utha-Aroon, C. (1993). Continental origin of the Maha Sarakham evaporites, northeastern Thailand. **Journal of Southeast Asian Earth Sciences**. 8(1– 4): 193-203. doi: 10.1016/0743-9547(93)90021-g

Vermeesch, P., 2012, On the visualisation of detrital age distributions. **Chemical Geology**. (312-313): 190-194. doi: 10.1016/j.chemgeo.2012.04.021

Ward, D. E., and Bunnag, D. (1964). Stratigraphy of the Mesozoic Khorat Group in Northeastern Thailand. **Report of Investigation** (pp. 95): Department of Mineral Resources.

Weltje, G. J. (1994). **Provenance and dispersal of sand-size sediments: reconstruction of dispersal patterns and sources of sand-sized sediments by means of inverse modelling techniques**. Unpublished PhD thesis, Universiteit Utrecht, Nederlands.

Wieldchowsky, C.C., and Young, J.D. (1985). Regional facies variation in Permian rocks of the Phetchabun Fold and Thrust Belt, Thailand. In P. Thanvarachorn,S. Hokjaroen, and W. Youngme (eds.). In **Proceedings on Geology and Mineral Resources Development of the Northeastern Thailand** (pp 41-56). Khon Kaen University, Khon Kaen, Thailand.

Wonganan, N., and Caridroit, M. (2005). Middle and Upper Devonian radiolarian fauna from Chiang Dao area, Chiang Mai Province, northern Thailand. **Micropaleontology.** 51: 39–57.

Wongwanich, T., and Burrett, C. (1983). The Lower Paleozoic of Thailand. **Journal of the Geological Society of Thailan.** 6: 21-29.

Wongwanich, T., Burrett, C. F., Chaodumrong, P., and Tansathein, W. (1990). Lower to Mid Palaeozoic stratigraphy of mainland Satun province, southern Thailand. **Journal of Southeast Asian Earth Sciences**. 4(1): 1–9.

Wongwanich, T., and Boucot, A. J. (2011). Devonian. In M. F. Ridd, A. J. Barber and M. J. Crow (Eds.). **The Geology of Thailand**. United Kingdom: The Geological Society of London.

Wu, Y., and Zheng, Y. (2004). Genesis of zircon and its constraints on interpretation of U-Pb age. **Chinese Science Bulletin**. 49: 1554 -1569.

Yang, J., Du, Y., Cawood, P. A., and Xu, Y. (2012). Modal and Geochemical Compositions of the Lower Silurian Clastic Rocks In North Qilian, Nw China:

Implications For Provenance, Chemical Weathering, and Tectonic Setting. **Journal of Sedimentary Research**. 82(2): 92-103. doi: 10.2110/jsr.2012.6

Yang, W., Feng, Q., and Shen, S. (2008). Permian Radiolarians, Chert and Basalt from the Nan Suture Zone, Northern Thailand. In **The Proceedings of the International Symposia on Geoscience Resources and Environments of Asian Terranes (GREAT 2008), 4th IGCP 516,and 5th APSEG**. Bangkok, Thailand.

Yang, W., Feng, Q., Shen, S., and Chonglakmani, C. (2009). Constraints of U-Pb zircon dating on the evolution of the Nan-Uttaradit suture zone in northern Thailand. **Acta Geoscientica Sinica**. 30: 88-89.

Young, G. M., and Nesbitt, H. W. (1998). Processes controlling the distribution of Ti and Al in weathering profiles, siliciclastic sediments and sedimentary rocks. **Journal of Sedimentary Research.** 68(3): 448-455. doi: 10.2110/jsr.68.448

Zhu, B., Kidd, W. S. F., Rowley, D. B., Currie, B. S., and Shafique, N. (2005). Age of Initiation of the India-Asia Collision in the East-Central Himalaya. **The Journal of Geology**. 113: 265–285.

APPENDIX A

PALEOCURRENTS PATTERN

Table A.1. Paleocurrents pattern after tectonic tilt correction.

Formation	Unit	Attitude (Dip/Dip direction)
Phu Khat	Upper	20/210, 10/210, 30/225, 25/210, 30/205, 25/215, 15/205, 10/230, 15/240, 10/210, 10/220, 10/180, 15/190, 15/170, 10/180, 20/180, 30/160, 30/170
	Middle	20/145, 15/120, 20/080, 15/160, 15/140, 20/130, 1/170, 15/130, 10/140, 10/270, 20/130, 10/090, 15/080, 20/090, 20/080
	Lower	30/065, 25/070, 30/065
Khao Ya Puk	Upper	35/190, 30/195, 35/185, 30/180, 35/190, 30/180, 30/180, 30/180, 35/165, 35/220, 20/325, 30/215, 35/215, 35/215, 35/220
	Middle	30/205, 35/175, 35/175, 20/215, 30/195, 30/200, 25/180, 25/185, 25/200, 25/185

APPENDIX B

FRAMEWORK GRAINS COUNTING

Table B.1. Framework grains composition counting

Fm.	Unit	Sample No.	*Quartz*		*Feldspar (K+P)*	*Lithic fragment*		*Count*	*Qt-F-L(%)*			*Qm-F-Lt(%)*		
			Qm	*Qp*		*Ls*	*Lv*		*Qt*	*F*	*L*	*Qm*	*F*	*Lt*
Phu Khat Fm.	Upper	5.4	176	10	17	20	92	315	59	5.4	35.5	55.8	5.4	38.7
		5.3	175	11	17	18	85	306	60.8	5.5	33.6	57.2	5.5	37.2
		4.2	153	18	11	23	105	310	55.2	3.5	41.3	49.4	3.5	47.1
		4.1	238	7	31	27	129	432	56.6	7.2	36.3	55	7.2	37.9
		1.5	178	26	6	22	129	361	56.5	1.7	41.8	49.3	1.7	49
		1.4	212	10	29	35	105	392	56.5	7.4	35.8	54	7.4	38.3
		1.2	159	15	20	14	109	317	54.9	6.3	38.8	50.2	6.3	43.5
		1.1	174	13	34	31	118	370	50.5	9.2	40.3	47	9.2	43.8
	Middle	10	176	15	8	10	128	337	56.7	2.4	41	52.2	2.4	45.5
		8	180	11	20	16	73	300	63.7	6.7	29.6	60	6.7	33.3
		7	226	7	15	10	89	347	67.1	4.3	28.5	65.1	4.3	30.5
		6	163	24	14	15	116	332	56.2	4.2	39.5	49	4.2	46.7
		5	162	19	15	28	55	279	64.9	5.4	29.7	58.1	5.4	36.5
		3	165	28	17	27	68	305	63.3	5.6	31.2	54.1	5.6	40.4
		2	183	20	8	20	98	329	61.7	2.4	35.9	55.6	2.4	42
		1	220	15	10	23	95	363	64.7	2.8	32.5	60.6	2.8	36.6
		3.6	215	21	24	15	93	368	64.1	6.5	29.3	58.4	6.5	35
		3.4	289	15	3	5	99	411	73.6	0.8	25.2	70	0.8	28.8
		3.2	180	23	14	24	62	303	67	4.6	28.4	59.4	4.6	36
	Lower	16	200	13	13	17	120	363	58.6	3.6	37.7	55	3.6	41.3
		15	196	16	14	25	119	370	57.3	3.8	39	53	3.8	43.3
		11	200	20	11	22	128	381	57.7	2.9	39.4	52.5	2.9	44.6
		2.4	205	10	12	9	122	358	60.1	3.4	36.5	57.3	3.4	39.3
		2.1	185	16	10	17	122	350	57.4	2.9	39.6	52.8	2.9	44.2
		7.2	165	26	33	26	100	350	54.5	9.4	36	47.1	9.4	43.4
		7.1	200	17	17	9	114	357	60.7	4.7	34.4	56	4.7	39.1
		18	195	19	10	24	133	381	56.2	2.6	41.3	51.2	2.6	46.3
		17	187	23	18	21	135	384	54.7	4.7	40.5	48.7	4.7	46.5
		5.2	190	23	33	41	90	377	56.5	8.8	34.8	50.4	8.8	40.9
		5.1	124	25	30	9	93	281	53	10.6	36.2	44	10.6	45.2
		21	163	21	16	22	100	322	57.1	5	37.9	50.6	5	44.4
		20	213	25	5	28	115	386	61.7	1.3	37.1	55.2	1.3	43.6
		19	207	14	24	17	86	348	63.5	6.9	29.6	59.5	6.9	33.6
		6.4	150	15	8	7	75	255	64.7	3.1	32.1	58.8	3.1	38
		6.2	150	24	30	26	87	317	54.9	9.5	35.6	47.3	9.5	43.2
		6.1	230	15	31	19	100	395	62	7.8	30.1	58.2	7.8	33.9

Table B.1. Framework grains composition counting (Continued)

Fm.	**Unit**	**Sample No.**	***Quartz***		***Feldspar (K+P)***	***Lithic fragment***		***Count***	***Qt-F-L(%)***			***Qm-F-Lt(%)***		
			Qm	***Qp***		***Ls***	***Lv***		***Qt***	***F***	***L***	***Qm***	***F***	***Lt***
Khao Ya Puk Fm.	**Upper**	35	230	15	8	15	45	313	78.3	2.6	19.2	73.3	2.6	24
		34	297	23	14	10	84	428	74.7	3.3	21.9	69.3	3.3	27.3
		33	190	21	15	33	65	324	65.1	4.6	30.2	58.6	4.6	36.7
		32	239	20	12	19	65	355	72.9	3.4	23.7	67.3	3.4	29.3
		31	235	18	20	12	67	352	71.7	5.7	22.5	66.7	5.7	27.5
		30	268	22	12	29	48	379	76.5	3.2	20.4	70.7	3.2	26.2
		29	247	22	6	9	51	335	80.3	1.8	17.9	73.7	1.8	24.5
		28	220	7	12	12	35	286	79.3	4.2	16.4	76.9	4.2	18.8
		27	305	13	24	10	90	442	72	5.5	22.5	69	5.5	25.5
		26	266	9	23	9	47	354	77.5	6.5	15.8	75	6.5	18.3
		25	232	10	14	8	89	353	68.5	4	27.5	65.7	4	30.3
		22	225	19	7	3	28	282	86.5	2.5	11	80	2.5	17.7
		4.3	250	12	19	6	29	317	82.6	6	11.3	79	6	15
	Middle	36	258	31	15	9	15	328	88.1	4.6	7.2	78.6	4.6	16.7
		4.4	267	18	26	7	11	330	86.4	7.8	5.7	81	7.8	11.2

APPENDIX C

GEOCHEMICAL DATA

Table C.1. Geochemistry of sandstone of the Phu Khat and the Khao Ya Puk Formations

Fm.	**Up-Phk**		**Mid-Phk**		**Low-Phk**								**Up-Kyp**		**Mid-Kyp**
Sample No.	CK_M76-4	CK_M90-3	NH_B12	NH_B17	KM23B12	KM23B16	CK_M86-2	KM40B3	KM40B5	KM40B13	KM40B26	KM40B34	Kyp-1	Kyp-3	Kyp-2
Major elememts (wt%)															
SiO2	83.72	82.65	82.3	74.02	84.66	78.54	77.47	87.91	89.28	88.21	89.6	84.54	92.05	93.47	94.33
TiO2	0.40	0.31	0.32	0.39	0.36	0.38	0.49	0.37	0.22	0.29	0.20	0.54	0.23	0.15	0.13
Al2O3	5.97	6.07	5.87	7.86	6.98	6.00	7.65	5.61	5.22	5.37	5.06	7.11	3.79	3.39	2.87
Fe2O3(t)	2.32	2.28	2.09	2.89	2.63	2.53	3.26	1.85	1.39	2.30	1.53	3.02	1.37	0.92	0.82
FeO	0.61	0.75	0.46	1.14	0.14	0.07	0.82	0.07	0.07	0.25	0.25	0.14	nil	nil	0.04
MnO	0.08	0.03	0.04	0.07	0.03	0.14	0.05	0.02	0.02	0.05	0.01	0.04	0.01	0.01	<0.01
MgO	0.84	0.84	0.89	1.01	0.68	0.73	1.14	0.53	0.38	0.50	0.37	0.63	0.21	0.16	0.19
CaO	1.59	2.30	2.68	5.08	0.35	4.64	3.11	0.06	0.04	0.05	0.03	0.07	0.07	0.03	0.03
Na2O3	0.88	0.61	0.72	1.20	0.77	0.68	0.91	0.36	<0.1	<0.1	<0.1	0.10	<0.1	<0.1	<0.1
K2O	1.39	1.47	1.30	1.69	1.16	0.87	1.43	1.47	1.66	1.04	1.34	1.51	0.64	0.31	0.32
P2O5	0.07	0.03	0.06	0.09	0.06	0.05	0.04	0.01	0.01	0.01	0.01	0.02	0.01	0.02	0.01
LOI	2.50	3.09	3.45	5.40	1.98	5.17	4.16	1.61	1.35	1.74	1.51	2.03	1.31	1.28	1.05
H2O	0.12	0.09	0.14	0.16	0.22	0.14	0.15	0.07	0.22	0.28	0.20	0.20	0.20	0.16	0.15
Trace elements (ppm)															
Sc	4.97	4.58	4.82	5.81	6.66	5.96	7.64	4.22	3.10	4.89	3.03	6.86	2.65	3.64	1.96
Co	82.47	70.80	129.60	45.16	202.80	73.17	153.30	168.60	102.70	208.00	127.00	143.90	106.20	143.50	207.70
V	45.77	44.51	44.32	45.58	49.76	57.05	68.07	42.48	31.42	43.71	35.25	53.85	22.98	17.15	21.91
Rb	57.48	63.97	51.40	69.66	50.60	35.42	62.96	66.31	70.07	47.03	66.31	66.95	27.17	12.54	13.65
Zr	375.80	150.70	182.10	151.60	170.60	176.90	277.70	328.70	126.90	112.10	156.10	423.50	243.30	106.00	94.20
Nb	11.47	4.28	4.54	6.79	5.05	6.71	5.03	5.81	3.38	3.18	2.87	6.98	3.89	2.83	1.58
Hf	11.35	4.39	5.02	4.39	4.74	5.26	7.72	9.79	3.83	3.21	4.75	12.00	6.74	3.06	2.65
Ta	5.16	1.00	1.02	1.47	1.15	2.44	0.97	1.24	0.92	0.87	1.09	1.19	1.32	1.38	0.96
Pb	10.26	7.78	7.21	8.31	6.22	23.12	9.32	8.45	8.27	6.52	7.71	7.35	6.91	8.03	3.41
Th	11.73	6.16	6.18	8.13	12.83	7.13	7.24	8.11	5.32	4.56	5.85	8.61	5.80	4.16	3.52
U	2.37	1.22	1.27	1.73	1.88	1.89	1.75	1.44	1.01	1.05	1.13	1.77	1.01	0.71	0.59
Cr	43.83	37.39	32.41	49.83	36.28	38.81	52.80	33.19	20.45	33.87	26.41	44.47	19.02	11.21	9.55

Table C.1. Geochemistry of sandstone of the Phu Khat and the Khao Ya Puk Formations (Continued)

Fm.	Up-Phk		Mid-Phk		Low-Phk			
Sample No.	CK_M76-4	CK_M90-3	NH_B12	NH_B17	KM23B12	KM23B16	CK_M86-2	KM40B3
Ba	296.95	182.30	200.45	238.85	191.95	380.65	161.55	241.70
Ni	18.95	14.55	18.24	16.25	25.62	17.46	22.83	17.94
Sr	53.17	49.10	50.01	73.29	49.33	66.24	72.27	34.84
Th/Sc	2.36	1.35	1.28	1.40	1.93	1.20	0.95	1.92
Th/U	4.94	5.04	4.87	4.70	6.81	3.77	4.14	5.64
Zr/Sc	75.64	32.92	37.78	26.09	25.62	29.68	36.35	77.95
La/Th	2.04	2.55	2.66	2.56	2.37	2.59	2.70	2.30
REE (ppm)								
La	23.98	15.69	16.44	20.82	30.37	18.46	19.54	18.69
Ce	46.15	28.12	30.36	35.80	56.28	32.78	34.85	34.43
Pr	5.50	3.47	3.73	4.88	6.68	4.06	4.41	4.75
Nd	20.06	13.03	13.84	18.80	23.47	14.92	16.40	18.17
Sm	3.98	2.55	2.79	3.68	4.10	2.99	3.24	3.74
Eu	0.73	0.53	0.55	0.79	0.51	0.62	0.66	0.74
Gd	3.61	2.17	2.27	3.29	3.00	2.55	2.75	2.99
Tb	0.57	0.38	0.37	0.55	0.44	0.45	0.44	0.48
Dy	3.45	2.19	2.22	3.15	2.43	2.56	2.67	2.66
Ho	0.70	0.43	0.42	0.65	0.49	0.52	0.52	0.49
Er	1.90	1.26	1.23	1.75	1.35	1.45	1.53	1.49
Tm	0.30	0.19	0.20	0.28	0.22	0.23	0.24	0.22
Yb	1.88	1.18	1.19	1.64	1.38	1.36	1.51	1.38
Lu	0.27	0.17	0.17	0.23	0.18	0.19	0.21	0.19
LaN/YbN	9.14	9.54	9.95	9.09	15.79	9.75	9.27	9.69
GdN/YbN	1.59	1.52	1.59	1.65	1.80	1.55	1.50	1.78
Eu/Eu*	0.58	0.68	0.64	0.68	0.42	0.67	0.66	0.65

Fm.	Low-Phk (cont.)				Up-Kyp		Mid-Kyp
Sample No.	KM40B5	KM40B13	KM40B26	KM40B34	Kyp-1	Kyp-3	Kyp-2
Ba	248.65	183.90	230.50	206.70	165.40	131.65	31.20
Ni	13.65	18.61	12.51	22.75	7.13	7.61	9.43
Sr	27.60	21.16	19.38	28.56	23.16	14.35	11.25
Th/Sc	1.72	0.93	1.93	1.25	2.19	1.14	1.79
Th/U	5.25	4.36	5.19	4.86	5.75	5.83	5.95
Zr/Sc	40.99	22.91	51.52	61.73	91.71	29.12	48.01
La/Th	2.35	3.18	2.32	2.89	2.33	3.24	2.77
REE (ppm)							
La	12.51	14.52	13.59	24.89	13.52	13.51	9.75
Ce	22.25	26.83	23.35	51.33	21.72	25.40	17.08
Pr	2.74	3.22	3.28	5.81	2.58	4.39	2.01
Nd	9.88	12.06	12.62	21.58	8.35	18.71	6.75
Sm	2.02	2.27	2.54	4.03	1.53	4.63	1.20
Eu	0.47	0.48	0.58	0.79	0.28	1.05	0.21
Gd	1.77	1.98	2.36	3.43	1.30	4.43	1.14
Tb	0.30	0.31	0.38	0.55	0.19	0.71	0.19
Dy	1.77	1.81	2.09	3.21	1.24	4.16	1.12
Ho	0.35	0.35	0.41	0.64	0.26	0.81	0.23
Er	0.98	1.00	1.13	1.78	0.79	2.11	0.64
Tm	0.15	0.17	0.18	0.29	0.12	0.31	0.11
Yb	0.95	0.99	1.03	1.83	0.86	1.85	0.65
Lu	0.14	0.14	0.15	0.25	0.12	0.26	0.09
LaN/YbN	9.43	10.48	9.47	9.76	11.34	5.23	10.77
GdN/YbN	1.53	1.65	1.90	1.55	1.26	1.98	1.45
Eu/Eu*	0.74	0.68	0.72	0.63	0.59	0.70	0.53

Table C.2. Correlation coefficient (r) of major element of sandstone of the Phu Khat and the Khao Ya Puk Formations

	$Si0_2$	***Tio_2***	***Al_2O_3***	***Fe_2O_3***	***Feo***	***MnO***	***MgO***	***CaO***	***Na_2O***	***K_2O***	***P_2O_5***
$Si0_2$	1.00										
Tio_2	-0.75	1.00									
Al_2O_3	-0.89	0.87	1.00								
Fe_2O_3	-0.87	0.93	0.95	1.00							
Feo	-0.77	0.44	0.95	0.60	1.00						
MnO	-0.71	0.53	0.48	0.58	0.30	1.00					
MgO	-0.94	0.78	0.88	0.58	0.82	0.57	1.00				
CaO	-0.89	0.44	0.58	0.58	0.70	0.75	0.77	1.00			
Na_2O	-0.87	0.56	0.72	0.67	0.79	0.58	0.88	0.82	1.00		
K_2O	-0.61	0.62	0.79	0.62	0.57	0.18	0.66	0.30	0.44	1.00	
P_2O_5	-0.78	0.47	0.63	0.58	0.68	0.60	0.75	0.76	0.92	0.34	1.00

APPENDIX D

U-Pb DETRITAL ZIRCON DATING DATA

Table D.1. U–Pb isotopic data for detrital zircon grains of the upper Khao Ya Puk Formation (Up-Kyp) determined by LA-ICP-MS

Grain No.	Pb (ppm)	U (ppm)	Th/U	Ratios				Ages (Ma)				Best Age	±2s
				Pb206/ U238	± s.e.	Pb207/ Pb206	± s.e.	Pb206/ U238	± 2s	Pb207/ Pb206	± 2s		
G1	152.3	306.6	0.55	0.4367	0.0024	0.1593	0.0017	2335.7	21.8	2448.6	36.4	2448.56	36.4
G2	17.4	158.3	1.07	0.0881	0.0005	0.0593	0.0010	544.0	6.3	577.0	74.7	543.99	6.28
G3	25.7	114.7	0.66	0.1976	0.0011	0.0792	0.0010	1162.3	12.3	1176.1	50.3	1176.14	50.3
G4	9.9	71.6	0.88	0.1154	0.0009	0.0699	0.0019	704.1	10.2	926.6	110.2	704.15	10.17
G5	41.1	95.7	1.54	0.3080	0.0018	0.1069	0.0013	1730.9	18.0	1746.7	45.2	1746.71	45.2
G6	33.5	662.4	0.49	0.0475	0.0003	0.0523	0.0007	299.1	3.3	297.7	60.9	299.09	3.32
G7	83.8	138.8	0.79	0.4945	0.0029	0.1816	0.0020	2590.2	24.8	2667.8	36.9	2667.81	36.9
G8	3.7	131.5	0.73	0.0247	0.0002	0.0569	0.0032	157.1	2.5	488.4	237.9	157.10	2.52
G9	28.9	298.2	1.08	0.0776	0.0005	0.0574	0.0008	481.6	5.4	508.1	62.4	481.60	5.38
G10	38.6	130.4	0.89	0.2635	0.0015	0.1007	0.0012	1507.5	15.6	1636.5	44.3	1636.49	44.3
G11	14.5	618.8	1.15	0.0184	0.0001	0.0510	0.0012	117.7	1.5	239.5	105.3	117.66	1.52
G12	55.9	248.4	0.66	0.1985	0.0011	0.0785	0.0009	1167.3	12.0	1160.3	45.9	1160.31	45.9
G13	31.0	143.2	1.01	0.1758	0.0010	0.0747	0.0010	1044.2	11.3	1059.9	52.6	1059.90	52.6
G14	54.7	274.1	0.39	0.1883	0.0011	0.0765	0.0009	1112.1	11.7	1109.0	47.7	1108.97	47.7
G15	102.1	431.9	0.86	0.1986	0.0011	0.0783	0.0009	1167.6	12.0	1153.5	44.8	1153.48	44.8
G16	72.5	136.0	0.72	0.4511	0.0026	0.1674	0.0019	2400.3	23.4	2532.2	37.7	2532.21	37.7
G17	173.8	365.3	0.57	0.4192	0.0023	0.1559	0.0017	2256.9	21.3	2411.6	36.6	2411.56	36.6
G18	63.2	344.1	0.18	0.1855	0.0011	0.0779	0.0010	1096.7	11.6	1144.1	48.2	1144.07	48.2
G19	78.9	325.1	1.04	0.1957	0.0011	0.0770	0.0009	1152.1	12.0	1120.9	46.5	1120.93	46.5
G20	58.6	236.7	0.78	0.2122	0.0012	0.0802	0.0010	1240.7	13.0	1202.6	47.4	1202.65	47.4
G21	11.7	42.0	1.45	0.2040	0.0015	0.0811	0.0019	1196.9	15.7	1224.4	89.7	1224.35	89.7
G22	16.1	537.1	0.44	0.0284	0.0002	0.0504	0.0013	180.3	2.4	212.1	115.0	180.34	2.38
G23	4.3	201.4	0.89	0.0178	0.0002	0.0550	0.0031	113.7	1.9	411.4	239.4	113.74	1.90
G24	103.8	307.2	0.32	0.3211	0.0018	0.1119	0.0012	1795.1	17.7	1830.3	39.9	1830.34	39.9

Table D.1. U–Pb isotopic data for detrital zircon grains of the upper Khao Ya Puk Formation (Up-Kyp) determined by LA-ICP-MS (Continued)

Grain No.	Pb (ppm)	U (ppm)	Th/U	Ratios				Ages (Ma)				Best Age	±2s
				Pb206/ U238	± s.e.	Pb207/ Pb206	± s.e.	Pb206/ U238	± 2s	Pb207/ Pb206	± 2s		
G25	21.6	57.6	3.05	0.2033	0.0013	0.0815	0.0014	1193.1	13.7	1234.0	64.2	1234.01	64.2
G26	23.2	278.1	1.05	0.0674	0.0004	0.0542	0.0009	420.2	4.8	380.2	71.8	420.17	4.83
G27	36.9	996.4	1.02	0.0302	0.0002	0.0531	0.0008	191.9	2.3	332.2	70.5	191.93	2.25
G28	19.4	551.1	0.84	0.0300	0.0002	0.0521	0.0009	190.5	2.3	288.9	80.4	190.55	2.25
G29	53.4	132.6	0.53	0.3588	0.0021	0.1226	0.0014	1976.6	20.0	1994.3	41.5	1994.26	41.5
G30	3.1	163.9	0.74	0.0164	0.0002	0.0571	0.0040	104.7	1.9	495.0	293.5	104.67	1.90
G31	20.6	226.0	0.46	0.0857	0.0005	0.0577	0.0009	530.3	6.1	519.9	68.6	530.29	6.06
G32	10.2	45.3	0.87	0.1878	0.0012	0.0795	0.0016	1109.7	13.5	1185.1	79.1	1185.11	79.1
G33	112.1	508.6	0.49	0.2034	0.0011	0.0799	0.0009	1193.5	12.2	1193.8	43.9	1193.78	43.9
G34	22.2	548.8	0.57	0.0370	0.0002	0.0523	0.0009	234.1	2.7	296.8	78.1	234.09	2.74
G35	22.6	348.0	0.34	0.0638	0.0004	0.0576	0.0009	398.5	4.6	516.1	69.0	398.45	4.61
G36	38.5	233.3	0.58	0.1505	0.0009	0.0727	0.0009	903.8	9.7	1004.5	50.3	1004.49	50.3
G37	34.3	267.4	1.59	0.0918	0.0005	0.0597	0.0009	565.9	6.4	592.7	61.7	565.94	6.38
G38	54.0	143.2	0.83	0.3172	0.0019	0.1138	0.0014	1776.1	18.4	1860.8	43.3	1860.80	43.3
G39	25.7	689.3	0.74	0.0326	0.0002	0.0500	0.0008	207.0	2.4	192.7	72.1	206.99	2.37
G40	24.5	304.9	0.46	0.0758	0.0005	0.0581	0.0009	470.9	5.4	534.3	66.0	470.88	5.39
G41	10.0	461.0	0.77	0.0189	0.0001	0.0493	0.0014	120.4	1.5	164.0	126.1	120.45	1.52
G42	20.3	186.3	1.10	0.0865	0.0005	0.0586	0.0010	534.5	6.2	552.6	73.8	534.51	6.17
G43	13.1	95.1	1.91	0.0914	0.0006	0.0597	0.0016	563.7	7.6	593.1	110.5	563.69	7.56
G44	19.9	192.5	1.02	0.0840	0.0005	0.0562	0.0011	519.9	6.4	459.5	87.2	519.89	6.42
G45	12.9	53.2	0.83	0.2050	0.0013	0.0804	0.0014	1202.1	14.1	1206.3	69.0	1206.33	69.0
G46	12.5	109.7	1.46	0.0825	0.0006	0.0574	0.0015	511.3	6.8	506.2	115.8	511.27	6.79
G47	85.8	268.5	0.62	0.2826	0.0016	0.0995	0.0011	1604.5	16.2	1614.8	42.1	1614.75	42.1
G48	156.2	423.0	0.58	0.3269	0.0019	0.1117	0.0013	1823.5	18.1	1826.9	40.5	1826.93	40.5
G49	6.6	57.1	1.08	0.0930	0.0007	0.0657	0.0022	573.3	8.1	795.9	136.5	573.31	8.14

Table D.1. U–Pb isotopic data for detrital zircon grains of the upper Khao Ya Puk Formation (Up-Kyp) determined by LA-ICP-MS (Continued)

Grain No.	Pb (ppm)	U (ppm)	Th/U	Ratios				Ages (Ma)				Best Age	±2s
				Pb206/ U238	± s.e.	Pb207/ Pb206	± s.e.	Pb206/ U238	± 2s	Pb207/ Pb206	± 2s		
G50	75.3	136.0	0.85	0.4508	0.0026	0.1619	0.0018	2398.8	23.1	2475.9	37.7	2475.91	37.7
G51	12.2	64.3	1.12	0.1516	0.0010	0.0743	0.0014	909.9	11.0	1049.4	76.6	1049.36	76.6
G52	57.1	665.2	0.27	0.0860	0.0005	0.0588	0.0007	531.8	5.8	560.4	52.7	531.78	5.82
G53	47.3	195.3	1.17	0.1899	0.0011	0.0761	0.0009	1120.6	11.9	1097.4	48.8	1097.44	48.8
G54	33.4	845.9	0.99	0.0327	0.0002	0.0505	0.0007	207.5	2.4	216.2	67.7	207.49	2.37
G55	52.8	167.3	0.62	0.2789	0.0016	0.0990	0.0012	1585.8	16.3	1605.9	43.9	1605.93	43.9
G56	28.0	621.0	0.86	0.0385	0.0002	0.0519	0.0008	243.5	2.9	281.4	69.6	243.53	2.86
G57	28.8	97.9	0.89	0.2456	0.0015	0.0918	0.0012	1415.5	15.3	1462.2	50.1	1462.22	50.1
G58	14.0	69.4	0.71	0.1775	0.0013	0.0808	0.0018	1053.0	14.3	1215.4	85.3	1215.37	85.3
G59	3.0	32.4	0.03	0.1002	0.0008	0.0661	0.0032	615.8	9.6	809.2	194.0	615.76	9.61
G60	11.9	251.2	1.18	0.0370	0.0002	0.0513	0.0012	234.3	2.9	255.7	105.5	234.33	2.86
G61	16.7	62.7	1.33	0.2013	0.0013	0.0822	0.0015	1182.4	14.2	1249.8	68.0	1249.81	68.0
G62	89.9	208.1	0.65	0.3771	0.0022	0.1375	0.0016	2062.5	20.9	2196.0	40.6	2195.95	40.6
G63	394.0	698.8	1.04	0.4438	0.0025	0.1604	0.0018	2367.7	22.4	2459.6	37.2	2459.57	37.2
G64	29.2	64.9	0.93	0.3663	0.0023	0.1276	0.0017	2012.0	21.7	2065.4	45.8	2065.45	45.8
G65	72.5	153.9	0.58	0.4124	0.0025	0.1424	0.0017	2225.9	22.4	2256.8	40.4	2256.84	40.4
G66	74.4	134.3	0.79	0.4561	0.0027	0.1560	0.0018	2422.4	23.9	2412.7	39.4	2412.65	39.4
G67	34.7	143.2	0.45	0.2264	0.0013	0.0866	0.0011	1315.7	14.0	1351.8	47.5	1351.83	47.5
G68	94.3	176.2	0.55	0.4647	0.0027	0.1648	0.0019	2460.5	23.7	2505.8	37.9	2505.82	37.9
G69	22.1	564.5	0.47	0.0370	0.0002	0.0534	0.0010	234.4	3.0	345.8	86.7	234.40	2.98
G70	142.1	394.4	0.46	0.3295	0.0019	0.1123	0.0013	1835.8	18.2	1836.5	40.8	1836.48	40.8
G71	28.0	127.6	0.82	0.1870	0.0012	0.0799	0.0012	1104.8	12.7	1195.5	57.8	1195.51	57.8
G72	22.5	124.8	0.62	0.1617	0.0010	0.0707	0.0012	966.2	11.4	947.6	67.4	947.59	67.4
G73	22.4	199.2	0.42	0.1058	0.0007	0.0654	0.0011	648.4	7.7	785.6	68.8	648.37	7.70
G74	7.1	256.2	0.86	0.0238	0.0002	0.0543	0.0020	151.3	2.3	381.4	156.9	151.31	2.27

Table D.1. U–Pb isotopic data for detrital zircon grains of the upper Khao Ya Puk Formation (Up-Kyp) determined by LA-ICP-MS (Continued)

Grain No.	Pb (ppm)	U (ppm)	Th/U	Ratios				Ages (Ma)				Best Age	±2s
				Pb206/ U238	± s.e.	Pb207/ Pb206	± s.e.	Pb206/ U238	± 2s	Pb207/ Pb206	± 2s		
G75	38.1	572.9	0.20	0.0680	0.0004	0.0551	0.0007	424.2	4.8	415.9	59.1	424.16	4.83
G76	32.5	671.9	0.73	0.0430	0.0003	0.0526	0.0009	271.3	3.2	310.7	73.0	271.34	3.21
G77	55.2	460.5	1.36	0.0899	0.0005	0.0578	0.0008	555.0	6.3	522.2	57.2	555.00	6.27
G78	6.9	181.8	1.24	0.0290	0.0002	0.0532	0.0022	184.0	2.9	338.6	183.4	183.97	2.88
G79	78.3	1412.1	0.33	0.0547	0.0003	0.0544	0.0007	343.1	3.9	387.2	55.9	343.07	3.91
G80	15.9	487.3	0.11	0.0345	0.0002	0.0513	0.0009	218.3	2.6	255.7	79.2	218.34	2.62
G81	31.0	840.3	0.60	0.0337	0.0002	0.0536	0.0010	213.6	2.6	355.5	80.7	213.60	2.62
G82	3.5	160.6	0.78	0.0187	0.0002	0.0527	0.0039	119.2	2.4	314.2	317.6	119.18	2.40
G83	46.0	335.7	0.27	0.1359	0.0008	0.0697	0.0009	821.4	9.1	918.9	51.6	821.44	9.08
G84	52.0	570.1	0.44	0.0871	0.0005	0.0583	0.0007	538.4	6.0	540.3	56.6	538.36	6.05
G85	8.8	223.2	0.52	0.0368	0.0002	0.0526	0.0014	232.9	3.0	310.7	117.3	232.91	2.98
G86	9.0	181.8	0.79	0.0426	0.0003	0.0522	0.0015	269.2	3.5	294.6	126.9	269.18	3.46
G87	24.8	81.7	0.78	0.2568	0.0016	0.0939	0.0013	1473.4	16.3	1506.3	52.2	1506.31	52.2
G88	44.9	252.9	0.69	0.1566	0.0009	0.0692	0.0009	937.6	10.5	904.1	55.3	904.11	55.3
G89	16.7	411.2	0.61	0.0366	0.0002	0.0498	0.0009	231.8	2.7	186.1	80.7	231.85	2.74
G90	2.6	118.0	0.44	0.0204	0.0002	0.0558	0.0038	130.1	2.3	445.6	287.9	130.06	2.27
G91	55.7	370.4	0.42	0.1428	0.0008	0.0687	0.0009	860.3	9.5	888.5	51.9	860.31	9.48
G92	77.3	297.6	0.24	0.2547	0.0015	0.0927	0.0011	1462.8	15.4	1481.4	45.7	1481.36	45.7
G93	87.8	263.5	0.67	0.2895	0.0017	0.1002	0.0012	1638.9	16.9	1627.1	44.0	1627.06	44.0
G94	13.0	96.8	1.23	0.1037	0.0007	0.0617	0.0015	636.2	8.4	664.1	99.6	636.17	8.41
G95	5.2	261.3	0.67	0.0177	0.0001	0.0488	0.0022	113.1	1.8	139.7	208.4	113.10	1.77
G96	4.9	230.5	0.93	0.0177	0.0001	0.0485	0.0024	112.9	1.8	125.2	221.5	112.91	1.77
G97	9.4	252.9	0.57	0.0343	0.0002	0.0511	0.0013	217.7	2.9	244.4	116.8	217.65	2.87
G98	145.3	213.7	1.43	0.4807	0.0028	0.1609	0.0019	2530.3	24.5	2464.8	39.4	2464.83	39.4
G99	21.9	880.6	0.42	0.0238	0.0001	0.0497	0.0008	151.6	1.8	180.5	74.4	151.56	1.76

Table D.1. U–Pb isotopic data for detrital zircon grains of the upper Khao Ya Puk Formation (Up-Kyp) determined by LA-ICP-MS (Continued)

Grain No.	Pb (ppm)	U (ppm)	Th/U	Ratios				Ages (Ma)				Best Age	±2s
				Pb206/ U238	± s.e.	Pb207/ Pb206	± s.e.	Pb206/ U238	± 2s	Pb207/ Pb206	± 2s		
G100	66.5	187.4	0.77	0.3007	0.0018	0.1052	0.0013	1695.0	17.5	1717.3	44.2	1717.29	44.2
G101	2.9	86.2	0.73	0.0295	0.0003	0.0462	0.0035	187.2	3.1	9.6	348.5	187.17	3.13
G102	34.5	228.8	0.81	0.1280	0.0008	0.0668	0.0009	776.6	8.8	832.8	56.8	776.56	8.80
G103	9.2	259.6	0.81	0.0302	0.0002	0.0525	0.0014	192.0	2.5	309.0	119.5	191.99	2.50
G104	15.0	86.2	1.11	0.1371	0.0009	0.0692	0.0012	828.2	9.8	905.9	68.1	828.19	9.75
G105	32.3	370.4	0.54	0.0801	0.0005	0.0568	0.0008	496.5	5.8	484.6	64.6	496.48	5.85
G106	7.5	19.6	0.15	0.3818	0.0028	0.1514	0.0025	2084.6	26.0	2362.0	56.0	2362.02	56.0
G107	40.8	176.8	0.77	0.1978	0.0012	0.0784	0.0010	1163.7	12.7	1156.0	50.6	1156.02	50.6
G108	7.0	39.2	1.50	0.1301	0.0009	0.0712	0.0020	788.5	10.7	964.0	110.7	788.49	10.72
G109	210.2	329.0	0.54	0.5385	0.0032	0.1923	0.0023	2777.3	26.6	2761.6	38.8	2761.59	38.8
G110	25.3	275.3	0.19	0.0930	0.0006	0.0658	0.0010	573.1	6.8	800.0	63.4	573.14	6.84
G111	19.9	312.2	0.35	0.0621	0.0004	0.0555	0.0009	388.1	4.6	432.0	69.1	388.14	4.61
G112	102.6	574.6	0.21	0.1825	0.0011	0.0764	0.0009	1080.3	11.7	1105.8	48.5	1105.83	48.5
G113	67.9	75.0	2.88	0.4920	0.0031	0.1613	0.0021	2579.2	26.7	2469.5	42.8	2469.54	42.8
G114	106.3	617.7	1.19	0.1350	0.0008	0.0656	0.0008	816.0	9.1	794.6	52.2	816.04	9.09
G115	1.6	34.7	0.25	0.0459	0.0005	0.0542	0.0064	289.1	6.3	378.1	493.1	289.05	6.29
G116	14.1	33.0	1.51	0.3057	0.0021	0.1106	0.0018	1719.6	20.5	1808.5	59.0	1808.47	59.0
G117	10.2	38.6	1.78	0.1823	0.0013	0.0780	0.0018	1079.4	14.1	1147.1	87.8	1147.13	87.8
G118	9.7	163.9	0.80	0.0507	0.0003	0.0506	0.0014	318.5	4.2	223.1	122.9	318.51	4.17
G119	47.4	579.1	0.25	0.0826	0.0005	0.0580	0.0008	511.9	5.8	528.6	59.6	511.86	5.84
G120	6.9	49.8	1.89	0.0922	0.0007	0.0610	0.0024	568.7	8.5	637.5	164.7	568.65	8.50
G121	85.6	142.1	1.22	0.4541	0.0027	0.1606	0.0020	2413.4	24.2	2461.6	41.4	2461.57	41.4
G122	11.0	111.9	0.47	0.0947	0.0006	0.0635	0.0013	583.5	7.3	723.3	88.0	583.51	7.30
G123	6.1	48.7	0.61	0.1128	0.0009	0.0644	0.0023	689.0	10.4	754.5	149.5	689.05	10.43
G124	26.4	166.2	0.71	0.1404	0.0009	0.0662	0.0011	846.8	10.2	811.8	68.7	846.81	10.18

Table D.1. U–Pb isotopic data for detrital zircon grains of the upper Khao Ya Puk Formation (Up-Kyp) determined by LA-ICP-MS (Continued)

Grain No.	Pb (ppm)	U (ppm)	Th/U	Ratios				Ages (Ma)				Best Age	±2s
				Pb206/ U238	± s.e.	Pb207/ Pb206	± s.e.	Pb206/ U238	± 2s	Pb207/ Pb206	± 2s		
G125	19.0	147.7	2.12	0.0830	0.0006	0.0636	0.0013	513.9	6.7	728.7	87.4	513.89	6.67
G126	8.1	413.5	0.69	0.0174	0.0001	0.0540	0.0021	111.4	1.8	370.6	168.3	111.39	1.77
G127	4.2	34.1	1.44	0.0916	0.0009	0.0651	0.0036	564.8	10.0	776.3	227.0	564.76	10.04
G128	2.7	68.8	0.45	0.0369	0.0004	0.0600	0.0040	233.7	4.4	603.6	274.3	233.65	4.35
G129	20.3	508.0	0.86	0.0339	0.0002	0.0505	0.0010	215.0	2.7	219.0	88.4	215.04	2.74
G130	55.4	297.6	0.29	0.1824	0.0011	0.0740	0.0010	1079.9	11.9	1041.7	51.9	1041.74	51.9
G131	3.6	158.9	0.80	0.0198	0.0002	0.0487	0.0030	126.1	1.9	134.9	276.0	126.08	1.90
G132	71.9	783.3	0.26	0.0918	0.0006	0.0582	0.0008	566.4	6.5	535.4	57.9	566.41	6.49
G133	14.8	377.6	0.57	0.0358	0.0002	0.0514	0.0011	227.0	3.0	260.1	97.4	227.00	2.99

Table D.2. U–Pb isotopic data for detrital zircon grains of the lower Phu Khat Formation (Low-Phk) determined by LA-ICP-MS

Grain No.	Pb (ppm)	U (ppm)	Th/U	Ratios				Ages (Ma)				Best Age	±2s
				Pb206/ U238	± s.e.	Pb207/ Pb206	± s.e.	Pb206/ U238	± 2s	Pb207/ Pb206	± 2s		
G1	179.2	519.5	0.22	0.3374	0.0038	0.1260	0.0015	1874.1	36.8	2042.2	20.4	2042.2	20.4
G2	20.5	460.7	0.74	0.0390	0.0005	0.0512	0.0010	246.3	5.6	247.6	18.3	246.3	5.6
G3	45.2	1243.4	0.45	0.0344	0.0004	0.0509	0.0007	217.8	4.9	236.8	15.7	217.8	4.9
G4	6.7	159.4	0.33	0.0414	0.0005	0.0533	0.0020	261.4	6.2	342.9	31.0	261.4	6.2
G5	61.9	332.3	0.55	0.1703	0.0019	0.0707	0.0009	1013.9	21.4	949.0	25.5	949.0	25.5
G6	128.7	239.3	0.47	0.4742	0.0054	0.1649	0.0019	2501.8	47.1	2506.0	31.3	2506.0	31.3
G7	9.4	109.9	0.79	0.0733	0.0009	0.0551	0.0018	455.8	10.6	414.3	31.6	455.8	10.6
G8	40.6	462.9	0.62	0.0788	0.0009	0.0572	0.0008	488.7	10.8	499.6	21.2	488.7	10.8

Table D.2. U–Pb isotopic data for detrital zircon grains of the lower Phu Khat Formation (Low-Phk) determined by LA-ICP-MS (Continued)

Grain No.	Pb (ppm)	U (ppm)	Th/U	Ratios				Ages (Ma)				Best Age	±2s
				Pb206/ U238	± s.e.	Pb207/ Pb206	± s.e.	Pb206/ U238	± 2s	Pb207/ Pb206	± 2s		
G9	125.8	1034.0	0.43	0.1153	0.0013	0.0640	0.0008	703.5	15.0	742.0	22.4	703.5	15.0
G10	38.6	303.0	0.27	0.1272	0.0015	0.0700	0.0010	772.1	16.7	927.5	27.2	772.1	16.7
G11	20.1	375.3	1.16	0.0423	0.0005	0.0518	0.0011	266.8	6.1	278.4	20.0	266.8	6.1
G12	54.5	276.9	0.51	0.1824	0.0021	0.0765	0.0010	1080.3	22.7	1107.7	27.4	1107.7	27.4
G13	3.2	115.9	0.73	0.0242	0.0003	0.0499	0.0042	154.1	4.0	191.7	39.2	154.1	4.0
G14	62.5	331.8	0.43	0.1777	0.0020	0.0746	0.0010	1054.2	22.0	1056.4	26.5	1056.4	26.5
G15	4.5	89.7	0.44	0.0482	0.0006	0.0604	0.0034	303.7	7.7	617.2	62.3	303.7	7.7
G16	22.7	307.3	0.64	0.0661	0.0008	0.0575	0.0011	412.9	9.3	512.3	25.4	412.9	9.3
G17	33.8	1405.0	0.03	0.0261	0.0003	0.0508	0.0009	166.0	3.8	230.4	16.8	166.0	3.8
G18	221.9	628.8	0.53	0.3180	0.0036	0.1101	0.0013	1779.8	34.9	1801.4	29.2	1801.4	29.2
G19	13.7	114.2	0.28	0.1190	0.0014	0.0703	0.0016	724.8	16.2	938.0	36.6	724.8	16.2
G20	90.4	206.2	0.72	0.3795	0.0043	0.1554	0.0019	2073.9	40.4	2405.9	32.2	2405.9	32.2
G21	52.8	118.0	0.56	0.3925	0.0045	0.1345	0.0017	2134.5	41.5	2157.5	32.2	2157.5	32.2
G22	246.2	402.0	0.50	0.5196	0.0058	0.1764	0.0021	2697.5	49.5	2619.7	31.4	2619.7	31.4
G23	17.6	44.1	0.74	0.3379	0.0040	0.1125	0.0019	1876.5	38.8	1839.5	38.8	1839.5	38.8
G24	154.6	453.6	0.55	0.3065	0.0035	0.1126	0.0013	1723.4	34.0	1841.6	29.8	1841.6	29.8
G25	32.8	739.8	0.82	0.0378	0.0004	0.0523	0.0009	239.1	5.3	299.0	18.8	239.1	5.3
G26	51.4	396.0	0.21	0.1315	0.0015	0.0708	0.0010	796.2	17.1	952.8	27.8	796.2	17.1
G27	12.0	229.5	0.80	0.0452	0.0005	0.0528	0.0015	284.7	6.5	318.1	24.7	284.7	6.5
G28	21.4	588.5	0.26	0.0362	0.0004	0.0529	0.0010	229.2	5.1	323.2	19.7	229.2	5.1
G29	128.5	371.5	0.31	0.3297	0.0037	0.1153	0.0014	1836.8	36.0	1885.0	30.3	1885.0	30.3
G30	16.9	361.2	0.65	0.0421	0.0005	0.0533	0.0012	266.0	6.1	342.4	22.3	266.0	6.1
G31	142.2	275.2	0.54	0.4517	0.0051	0.1610	0.0019	2402.6	45.0	2466.2	31.6	2466.2	31.6
G32	138.4	235.0	0.72	0.4861	0.0055	0.1666	0.0020	2553.6	47.5	2524.0	32.1	2524.0	32.1
G33	149.7	443.9	0.12	0.3376	0.0038	0.1168	0.0014	1875.1	36.4	1907.1	30.1	1907.1	30.1

Table D.2. U–Pb isotopic data for detrital zircon grains of the lower Phu Khat Formation (Low-Phk) determined by LA-ICP-MS (Continued)

Grain No.	Pb (ppm)	U (ppm)	Th/U	Ratios				Ages (Ma)				Best Age	±2s
				Pb206/ U238	± s.e.	Pb207/ Pb206	± s.e.	Pb206/ U238	± 2s	Pb207/ Pb206	± 2s		
G34	13.2	563.0	0.64	0.0211	0.0003	0.0500	0.0015	134.9	3.2	195.9	20.4	134.9	3.2
G35	86.9	241.0	0.48	0.3281	0.0037	0.1143	0.0015	1829.2	36.1	1868.4	31.4	1868.4	31.4
G36	25.1	132.2	0.80	0.1633	0.0019	0.0732	0.0012	974.8	20.7	1018.4	30.5	1018.4	30.5
G37	186.4	534.7	0.29	0.3336	0.0037	0.1154	0.0014	1855.9	36.1	1885.7	30.0	1885.7	30.0
G38	21.5	647.8	0.12	0.0349	0.0004	0.0514	0.0011	221.3	5.0	258.8	18.9	221.3	5.0
G39	9.6	140.9	0.71	0.0605	0.0008	0.0587	0.0022	378.7	9.1	557.1	41.4	378.7	9.1
G40	7.8	193.6	0.67	0.0360	0.0005	0.0558	0.0022	227.7	5.6	442.8	38.2	227.7	5.6
G41	17.6	488.5	0.34	0.0356	0.0004	0.0506	0.0011	225.3	5.1	221.3	18.0	225.3	5.1
G42	39.1	430.3	0.43	0.0868	0.0010	0.0592	0.0009	536.4	11.6	575.2	23.1	536.4	11.6
G43	70.6	367.7	0.49	0.1781	0.0020	0.0736	0.0010	1056.4	21.9	1031.1	26.5	1031.1	26.5
G44	8.9	323.1	0.72	0.0245	0.0003	0.0551	0.0018	155.9	3.6	414.3	32.2	155.9	3.6
G45	85.7	124.6	0.44	0.5883	0.0067	0.2223	0.0028	2982.6	54.1	2997.7	33.5	2997.7	33.5
G46	6.6	170.8	0.57	0.0355	0.0005	0.0585	0.0026	225.1	5.6	546.7	47.1	225.1	5.6
G47	4.5	118.6	0.52	0.0357	0.0005	0.0546	0.0032	226.1	5.7	395.9	48.5	226.1	5.7
G48	50.1	246.4	0.74	0.1768	0.0020	0.0746	0.0010	1049.2	21.8	1056.4	27.4	1056.4	27.4
G49	248.6	377.5	1.44	0.4706	0.0053	0.1637	0.0020	2486.1	46.0	2494.4	32.2	2494.4	32.2
G50	51.3	305.1	0.35	0.1628	0.0018	0.0713	0.0010	972.5	20.3	966.9	26.6	966.9	26.6
G51	78.2	148.5	1.13	0.4117	0.0047	0.1570	0.0021	2222.6	42.7	2423.4	33.8	2423.4	33.8
G52	79.6	451.5	0.77	0.1514	0.0017	0.0698	0.0009	909.0	18.9	923.4	25.6	923.4	25.6
G53	11.8	31.0	0.54	0.3397	0.0040	0.1184	0.0021	1885.1	38.8	1931.9	40.9	1931.9	40.9
G54	48.2	87.0	0.80	0.4550	0.0052	0.1594	0.0021	2417.4	45.6	2449.4	33.6	2449.4	33.6
G55	10.0	254.0	0.62	0.0356	0.0004	0.0495	0.0016	225.8	5.2	173.5	19.9	225.8	5.2
G56	35.6	107.2	0.78	0.2817	0.0032	0.0988	0.0014	1600.0	32.1	1601.4	32.6	1601.4	32.6
G57	44.0	294.3	0.83	0.1266	0.0014	0.0642	0.0010	768.6	16.3	747.6	25.3	768.6	16.3
G58	7.7	196.4	0.45	0.0375	0.0004	0.0522	0.0019	237.1	5.5	293.3	27.7	237.1	5.5

Table D.2. U–Pb isotopic data for detrital zircon grains of the lower Phu Khat Formation (Low-Phk) determined by LA-ICP-MS (Continued)

Grain No.	Pb (ppm)	U (ppm)	Th/U	Ratios				Ages (Ma)				Best Age	±2s
				Pb206/ U238	± s.e.	Pb207/ Pb206	± s.e.	Pb206/ U238	± 2s	Pb207/ Pb206	± 2s		
G59	70.0	125.1	0.43	0.4929	0.0055	0.1727	0.0022	2583.3	47.8	2583.6	33.4	2583.6	33.4
G60	214.3	442.2	1.63	0.3409	0.0038	0.1134	0.0014	1891.0	36.4	1855.1	30.9	1855.1	30.9
G61	59.9	96.3	0.59	0.5197	0.0059	0.1857	0.0024	2697.7	49.7	2704.0	34.0	2704.0	34.0
G62	29.5	739.8	0.69	0.0354	0.0004	0.0512	0.0010	224.1	5.0	248.0	18.0	224.1	5.0
G63	8.4	77.2	1.13	0.0864	0.0010	0.0574	0.0021	534.0	12.2	505.0	38.8	534.0	12.2
G64	61.8	177.9	0.41	0.3216	0.0036	0.1083	0.0014	1797.7	35.1	1770.7	31.9	1770.7	31.9
G65	7.0	34.8	0.72	0.1776	0.0022	0.0766	0.0024	1053.7	23.6	1111.1	51.8	1111.1	51.8
G66	9.4	347.6	0.54	0.0249	0.0003	0.0497	0.0017	158.5	3.6	182.9	20.9	158.5	3.6
G67	4.8	119.7	0.27	0.0402	0.0005	0.0608	0.0029	254.3	6.2	631.8	55.1	254.3	6.2
G68	5.0	115.9	0.45	0.0412	0.0005	0.0571	0.0031	260.0	6.6	495.8	51.8	260.0	6.6
G69	382.1	789.8	0.23	0.4540	0.0050	0.1579	0.0020	2413.1	44.6	2433.3	32.9	2433.3	32.9
G70	17.5	59.8	0.69	0.2556	0.0030	0.0969	0.0017	1467.1	30.4	1565.3	37.8	1565.3	37.8
G71	117.7	613.6	0.70	0.1712	0.0019	0.0704	0.0010	1018.9	21.0	940.3	26.2	940.3	26.2
G72	16.8	140.3	1.16	0.0942	0.0011	0.0612	0.0014	580.3	13.0	646.3	32.1	580.3	13.0
G73	9.8	250.8	0.95	0.0324	0.0004	0.0530	0.0019	205.7	4.9	327.9	29.5	205.7	4.9
G74	22.6	551.6	0.72	0.0360	0.0004	0.0505	0.0010	228.2	5.1	215.8	17.3	228.2	5.1
G75	138.7	397.1	0.26	0.3369	0.0037	0.1136	0.0015	1871.8	36.1	1858.1	31.7	1858.1	31.7
G76	15.6	404.1	0.48	0.0362	0.0004	0.0541	0.0013	229.4	5.2	375.6	24.1	229.4	5.2
G77	304.4	415.0	1.36	0.5187	0.0057	0.1743	0.0022	2693.8	48.7	2599.6	33.7	2599.6	33.7
G78	6.8	243.1	0.66	0.0251	0.0003	0.0547	0.0021	159.6	3.8	400.8	35.4	159.6	3.8
G79	62.6	1286.4	0.54	0.0449	0.0005	0.0533	0.0008	283.3	6.2	339.5	18.0	283.3	6.2
G80	26.1	877.9	0.32	0.0294	0.0003	0.0520	0.0011	186.7	4.3	285.8	20.3	186.7	4.3
G81	5.5	125.6	0.55	0.0399	0.0005	0.0531	0.0025	252.4	6.0	333.9	36.1	252.4	6.0
G82	94.1	108.8	0.54	0.7175	0.0080	0.3086	0.0041	3486.8	60.1	3513.9	35.4	3513.9	35.4
G83	32.8	812.1	0.64	0.0360	0.0004	0.0520	0.0009	228.2	5.0	287.2	18.1	228.2	5.0

Table D.2. U–Pb isotopic data for detrital zircon grains of the lower Phu Khat Formation (Low-Phk) determined by LA-ICP-MS (Continued)

Grain No.	Pb (ppm)	U (ppm)	Th/U	Ratios				Ages (Ma)				Best Age	±2s
				Pb206/ U238	± s.e.	Pb207/ Pb206	± s.e.	Pb206/ U238	± 2s	Pb207/ Pb206	± 2s		
G84	18.6	625.5	0.28	0.0296	0.0003	0.0506	0.0011	187.9	4.3	224.0	18.6	187.9	4.3
G85	16.5	451.5	0.51	0.0340	0.0004	0.0520	0.0011	215.7	4.7	285.8	20.2	215.7	4.7
G86	18.3	229.0	0.63	0.0715	0.0008	0.0588	0.0014	444.9	10.1	561.2	30.7	444.9	10.1
G87	113.9	250.2	0.43	0.4149	0.0046	0.1554	0.0021	2237.4	42.2	2405.8	34.7	2405.8	34.7
G88	53.1	218.7	0.52	0.2224	0.0025	0.0876	0.0013	1294.6	26.2	1373.1	31.1	1373.1	31.1
G89	105.8	629.3	0.49	0.1566	0.0017	0.0703	0.0010	937.7	19.4	938.0	26.9	938.0	26.9
G90	38.4	99.0	0.71	0.3319	0.0037	0.1159	0.0017	1847.4	36.1	1893.3	34.8	1893.3	34.8
G91	1358.8	19052.5	0.01	0.0775	0.0010	0.0575	0.0031	480.9	11.7	510.0	53.3	480.9	11.7
G92	74.0	411.8	0.35	0.1733	0.0019	0.0734	0.0011	1030.2	21.2	1025.0	28.6	1025.0	28.6
G93	55.0	242.6	1.63	0.1597	0.0018	0.0696	0.0011	955.2	19.8	917.2	28.2	917.2	28.2
G94	250.4	590.7	0.10	0.4220	0.0047	0.1606	0.0022	2269.4	42.3	2462.3	34.6	2462.3	34.6
G95	126.8	439.5	0.37	0.2754	0.0031	0.1111	0.0015	1568.0	30.8	1818.1	32.9	1818.1	32.9
G96	37.3	458.5	1.50	0.0591	0.0007	0.0546	0.0011	370.3	8.2	397.1	23.1	370.3	8.2
G97	9.0	260.0	0.22	0.0351	0.0004	0.0587	0.0019	222.4	5.2	554.5	37.4	222.4	5.2
G98	7.7	142.0	0.74	0.0481	0.0006	0.0589	0.0021	303.0	7.1	564.1	40.8	303.0	7.1
G99	168.2	294.3	0.44	0.5024	0.0056	0.1803	0.0025	2623.9	47.6	2655.3	35.4	2655.3	35.4
G100	3.8	144.7	0.88	0.0225	0.0003	0.0503	0.0039	143.2	3.8	208.9	38.8	143.2	3.8
G101	40.4	236.1	0.40	0.1633	0.0018	0.0732	0.0012	975.0	20.4	1018.9	31.2	1018.9	31.2
G102	25.5	62.0	1.31	0.3145	0.0038	0.1111	0.0021	1762.7	37.0	1817.8	42.2	1817.8	42.2
G103	1.3	47.3	0.98	0.0235	0.0004	0.0513	0.0099	149.8	4.7	255.7	96.7	149.8	4.7
G104	31.1	59.3	0.47	0.4630	0.0053	0.1645	0.0025	2452.7	46.8	2502.5	38.2	2502.5	38.2
G105	5.6	85.9	0.79	0.0567	0.0007	0.0561	0.0028	355.8	8.8	455.9	46.6	355.8	8.8
G106	59.9	182.2	0.47	0.3023	0.0034	0.1101	0.0017	1702.7	33.5	1801.1	34.9	1801.1	34.9
G107	13.0	344.9	0.61	0.0344	0.0004	0.0521	0.0013	218.2	4.9	289.8	21.9	218.2	4.9

Table D.3. U–Pb isotopic data for detrital zircon grains of the Middle Phu Khat Formation (Mid-Phk) determined by LA-ICP-MS

Grain No.	Pb (ppm)	U (ppm)	Th/U	Ratios				Ages (Ma)				Best Age	±1s
				Pb206/ U238	± s.e.	Pb207/ Pb206	± s.e.	Pb206/ U238	± 1s	Pb207/ Pb206	± 1s		
NH01T-1	106	247	0.31	0.20623	0.00299	0.07911	0.00205	1209	16	1175	45	1175	45
NH01T-2	71	112	0.80	0.1346	0.00174	0.07263	0.00286	814	10	1004	78	1004	78
NH01T-3	43.2	442	0.89	0.02064	0.00039	0.05404	0.0031	132	2	373	125	132	2
NH01T-4	90	173	0.52	0.15449	0.00236	0.0752	0.0022	926	13	1074	56	926	13
NH01T-5	73.0	306	0.43	0.08586	0.00119	0.05957	0.00196	531	7	588	66	531	7
NH01T-7	23.7	138	1.19	0.02215	0.0006	0.04605	0.00521	141	4	-	224	141	4
NH01T-8	112	587	0.21	0.09842	0.00126	0.06867	0.00188	605	7	889	53	605	7
NH01T-9	352	374	0.44	0.347	0.00417	0.11211	0.00227	1920	20	1834	32	1834	32
NH01T-10	253	380	0.69	0.18083	0.00231	0.07263	0.00162	1072	13	1004	40	1004	40
NH01T-11	121	1383	0.41	0.03237	0.00035	0.06017	0.00157	205	2	610	44	205	2
NH01T-12	310	252	0.65	0.30289	0.00442	0.11658	0.00187	1706	22	1904	30	1904	30
NH01T-13	479	246	0.69	0.49389	0.00584	0.1592	0.00188	2587	25	2447	16	2447	16
NH01T-14	846	530	0.68	0.41991	0.00366	0.15049	0.00124	2260	17	2351	10	2351	10
NH01T-15	352	102	1.31	0.53579	0.00539	0.17379	0.0021	2766	23	2594	13	2594	13
NH01T-17	52.1	185	0.80	0.05722	0.00086	0.06554	0.00305	359	5	792	90	359	5
NH01T-20	167	150	0.44	0.25405	0.00638	0.13023	0.00669	1459	33	2101	93	2101	93
NH01T-21	28.1	172	0.56	0.04498	0.0006	0.06666	0.00325	284	4	827	92	284	4
NH01T-23	41.7	238	0.58	0.03494	0.00051	0.04605	0.00321	221	3	-	154	221	3
NH01T-24	51.2	354	0.19	0.08014	0.00085	0.05897	0.00172	497	5	566	61	497	5
NH01T-25	95	98.5	0.36	0.4034	0.00451	0.13857	0.00207	2185	21	2209	22	2209	22
NH02T-01	110.08	274.73	1.23	0.08691	0.00155	0.05931	0.00323	537	9	579	78	537	9
NH02T-02	287.78	528.26	0.33	0.29588	0.00362	0.09812	0.00216	1671	18	1589	26	1589	26
NH02T-03	99.41	707.36	0.60	0.04426	0.00065	0.05674	0.00463	279	4	482	186	279	4
NH02T-04	451.34	887.72	0.21	0.33498	0.00336	0.11493	0.00212	1862	16	1879	21	1879	21
NH02T-06	304.30	949.43	0.34	0.17274	0.00239	0.07022	0.00181	1027	13	935	34	935	34

Table D.3. U–Pb isotopic data for detrital zircon grains of the Middle Phu Khat Formation (Mid-Phk) determined by LA-ICP-MS (Continued)

Grain No.	Pb (ppm)	U (ppm)	Th/U	Ratios				Ages (Ma)				Best Age	±1s
				Pb206/ U238	± s.e.	Pb207/ Pb206	± s.e.	Pb206/ U238	± 1s	Pb207/ Pb206	± 1s		
NH02T-07	135.43	646.68	0.35	0.1057	0.0019	0.06652	0.00262	648	11	823	60	648	11
NH02T-08	265.03	643.49	0.52	0.16653	0.0021	0.07494	0.00203	993	12	1067	34	993	12
NH02T-09	327.53	2791.13	0.62	0.04015	0.00054	0.05574	0.00166	254	3	442	48	254	3
NH02T-10	161.26	1999.55	0.33	0.04004	0.00066	0.05339	0.00301	253	4	346	131	253	4
NH02T-13	137.57	1302.23	1.00	0.02546	0.00038	0.05189	0.00226	162	2	281	74	162	2
NH02T-14	42.95	241.71	0.37	0.08616	0.00141	0.0643	0.00366	533	8	751	84	533	8
NH02T-15	575.60	315.56	1.04	0.47342	0.00672	0.16171	0.00386	2499	29	2474	24	2474	24
NH02T-16	263.38	654.62	0.93	0.1748	0.00217	0.0781	0.00224	1038	12	1150	40	1150	40
NH02T-17	230.69	553.17	1.24	0.09129	0.00148	0.0614	0.00216	563	9	653	53	563	9
NH02T-18	79.75	833.99	0.71	0.0305	0.0005	0.05498	0.00291	194	3	411	89	194	3
NH02T-19	184.86	1334.95	0.32	0.06597	0.00086	0.0557	0.00167	412	5	441	44	412	5
NH02T-20	91.60	731.86	0.78	0.03714	0.0006	0.04813	0.00308	235	4	106	111	235	4
NH02T-23	33.52	201.85	0.41	0.0788	0.00188	0.05319	0.00401	489	11	337	136	489	11
NH02T-24	205.44	4330.74	0.13	0.03825	0.00059	0.05066	0.00184	242	4	225	86	242	4
NH02T-25	302.61	445.02	0.18	0.45993	0.00672	0.16074	0.00312	2439	30	2463	20	2463	20
NH02T-26	70.51	558.43	0.41	0.05465	0.00082	0.05259	0.00361	343	5	311	159	343	5
NH02T-27	222.11	1518.79	0.72	0.04524	0.00063	0.05428	0.00156	285	4	383	44	285	4
NH02T-28	144.72	695.69	0.58	0.07201	0.00099	0.06182	0.00248	448	6	668	62	448	6
NH03T-02	134.31	67.33	2.06	0.18644	0.00267	0.08955	0.00283	1102	14	1416	34	1416	34
NH03T-03	803.11	330.12	0.91	0.50095	0.00561	0.1815	0.00299	2618	24	2667	15	2667	15
NH03T-04	117.37	502.44	0.45	0.07818	0.00093	0.06048	0.00174	485	6	621	41	485	6
NH03T-05	12.50	53.42	0.77	0.04735	0.00151	0.08974	0.00674	298	9	1420	83	298	9
NH03T-07	91.02	147.64	1.17	0.09039	0.0015	0.0634	0.0034	558	9	722	70	558	9
NH03T-08	10.92	82.38	0.47	0.04095	0.001	0.06325	0.00519	259	6	717	116	259	6
NH03T-09	13.91	105.86	1.02	0.02152	0.00057	0.06374	0.00536	137	4	733	134	137	4

Table D.3. U–Pb isotopic data for detrital zircon grains of the Middle Phu Khat Formation (Mid-Phk) determined by LA-ICP-MS (Continued)

Grain No.	Pb (ppm)	U (ppm)	Th/U	Ratios				Ages (Ma)				Best Age	±1s
				Pb206/ U238	± s.e.	Pb207/ Pb206	± s.e.	Pb206/ U238	± 1s	Pb207/ Pb206	± 1s		
NH03T-10	38.94	635.73	0.60	0.01751	0.00028	0.04433	0.00209	112	2	-53	76	112	2
NH03T-11	78.91	271.22	0.68	0.07192	0.00107	0.05164	0.00212	448	6	270	64	448	6
NH03T-12	99.04	161.14	1.04	0.11839	0.00193	0.0614	0.00199	721	11	653	45	721	11
NH03T-13	52.29	216.06	0.97	0.03743	0.00074	0.05461	0.00661	237	5	396	276	237	5
NH03T-16	149.61	372.16	0.79	0.08477	0.00103	0.06281	0.00187	525	6	702	45	525	6
NH03T-17	216.56	160.13	1.26	0.20259	0.00283	0.07498	0.00212	1189	15	1068	40	1068	40
NH03T-18	195.58	91.95	0.79	0.34462	0.0057	0.11526	0.00571	1909	27	1884	91	1884	91
NH03T-19	89.02	523.73	0.74	0.03697	0.00054	0.05435	0.00402	234	3	385	171	234	3
NH03T-21	211.40	282.95	1.01	0.13536	0.00189	0.06992	0.002	818	11	926	35	818	11
NH03T-22	63.27	387.06	0.29	0.07953	0.00154	0.05874	0.00203	493	9	558	48	493	9
NH03T-23	30.14	197.18	0.71	0.03599	0.0006	0.05571	0.00319	228	4	441	97	228	4
NH03T-24	13.11	66.13	0.63	0.04243	0.00101	0.05743	0.0092	268	6	508	358	268	6
NH03T-25	155.85	388.73	0.16	0.26289	0.00226	0.11218	0.00216	1505	12	1835	23	1835	23
NH03T-26	52.34	728.95	0.22	0.03549	0.00042	0.05496	0.00182	225	3	410	58	225	3
NH03T-27	100.35	796.69	0.42	0.02617	0.00033	0.05128	0.00457	167	2	253	204	167	2
NH03T-28	181.31	139.66	0.90	0.2566	0.00379	0.09966	0.00266	1472	19	1618	31	1618	31

BIOGRAPHY

Mr. Pradit Nulay was born in Khon Kaen Province, Thailand on August 22, 1979. He received bachelor degree of science in the field of Geotechnology from the Faculty of Technology, Khon Kaen University in 2001. After he graduated he has been working in the field of environmental geology and geohazard, for the Environmental Geology and Geohazard Division, Department of Mineral Resources since 2001. In 2009, he got a scholarship from the Royal Thai Government to continue his post-graduate study leading to the master degree of science in the field of Engineering Geology at the University of Portsmouth, United Kingdom and graduated in 2010. His interests are field of geology and applied geology as he has attended Ph.D. study at the Suranaree University of Technology.