GEOLOGY AND PETROCHEMISTRY OF VOLCANIC ROCKS IN THE LAM SONTHI AREA, LOP BURI PROVINCE

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A Thesis Submitted in Partial Fulfillment of the Requirements
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ธรณีวิทยาและศิลาเคมีของหินภูเขาไฟในพื้นที่ลำสนธิ จังหวัดลพบุรี

น.ส.เสาวภาพ อุทัยรัตน์

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิทยาศาสตรมหาบัณฑิต
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Thesis Title	GEOLOGY AND PETROCHEMISTRY OF VOLCANIC ROCKS IN THE LAM SONTHI AREA, LOP BURI PROVINCE
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Field of Study	Geology
Thesis Advisor	ABHISIT SALAM, Ph.D.

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เสาวภาพ อุทัยรัตน์ : ธรณีวิทยาและศิลาเคมีของหินภูเขาไฟในพื้นที่ลำสนธิ จังหวัดลพบุรี. (GEOLOGY AND PETROCHEMISTRY OF VOLCANIC ROCKS IN THE LAM SONTHI AREA, LOP BURI PROVINCE) อ.ที่ปรึกษาหลัก : อ. ดร. อภิสิทธิ์ ซาลำ

พื้นที่ศึกษาตั้งอยู่ที่อำเภอลำสนธิ จังหวัดลพบุรี ตอนกลางของประเทศไทย ธรณีวิทยาในพื้นที่ประกอบด้วย 5 หน่วยหินเรียงตามลำดับชั้นหินจากล่างขึ้นบน ดังนี้ หน่วยหินที่ 1 หินทรายแป้งเขารวก (Unit I: Khao Ruak siltstone) เทียบสัมพันธ์ได้กับหมวดหินเขาลวก อายุเพอร์เมียนตอนต้น หน่วยหินที่ 2 หินกรวดมนเขาแผงม้า (Unit II: Khao Phaeng Ma conglomerate) หน่วยหินที่ 3 หินภูเขาไฟเขารวก (Unit III: Khao Ruak volcanics) หน่วยหินที่ 4 หินกรวดมนโพลีมิติกลำสนธิ (Unit IV: Lam Sonthi polymictic conglomerate) และ หน่วยหินที่ 5 หินทรายกุดตาเพชร (Unit V: Kuttaphet sandstone) เทียบสัมพันธ์ได้กับหมวดหินภูกระดึง อายุจูแรสซิกตอนต้น นอกจากนี้ยังพบหินภูเขาไฟวางตัวอยู่ด้านบนของหน่วยหินกรวดมนโพลีมิติกได้แก่ หินภูเขาไฟกุดตาเพชรและหินภูเขาไฟโคกคลีซึ่งมีลักษณะเป็นหินกรวดเหลี่ยมอินเตอมิเดียตโพลีมิติก (polymictic intermediate breccia) จากการแบ่งชนิดหินโดยลักษณะทางศิลาวรรณนาพบว่าหินภูเขาไฟดังกล่าวมีปริมาณแร่ควอตซ์น้อยว่าร้อยละ 20 จึงจัดให้เป็นหินแอนดีไซต์ กรวดที่พบภายในหินภูเขาไฟกุดตาเพชรประกอบด้วยหินแพลจิโอเคลสแอนดีไซต์ และหินไพรอกซีน-แพลจิโอเคลสแอนดีไซต์ ในขณะที่กรวดที่พบภายในหินภูเขาไฟโคกคลีประกอบด้วยหินแพลจิโอเคลสแอนดีไซต์ และหินฮอร์นเบลนด์-แพลจิโอเคลสแอนดีไซต์ กรวดของหินภูเขาไฟกุดตาเพชรและหินภูเขาไฟโคกคลีที่มีขนาดใหญ่ได้ถูกคัดเลือกเพื่อนำมาศึกษาองค์ประกอบทางเคมีด้วยเครื่องมือ XRF และ ICP-MS เพื่อหาปริมาณธาตุองค์ประกอบหลักและปริมาณธาตุร่องรอย จากนั้นนำผลที่ได้มาเปรียบเทียบกับหินไพรอกซีน-แพลจิโอเคลสแอนดีไซต์ที่เป็นลาวาจากหน่วยหินภูเขาไฟเขารวก ผลการศึกษาธรณีเคมีพบว่ากรวดหินภูเขาไฟเหล่านี้มีองค์ประกอบเป็นหินแอนดีไซต์ ยกเว้นตัวอย่างหินแพลจิโอเคลสแอนดีไซต์ จากหินภูเขาไฟกุดตาเพชรที่มีองค์ประกอบทางเคมีเป็นหินเดไซต์/ไรโอไลต์ อย่างไรก็ตามตัวอย่างหินภูเขาไฟทั้งหมดจัดเป็นหินแคลก์-แอลคาไลน์ และจากแผนภาพที่ใช้ค่าของธาตุไทเทเนียม (Ti)-เซอร์โคเนียม (Zr) พบว่าหินเหล่านี้มีต้นกำเนิดสัมพันธ์กับธรณีแปรสัณฐานบริเวณแนวโค้งภูเขาไฟ และลักษณะกราฟสัดส่วนธาตุร่องรอยต่อหินบะซอลต์สันเขากลางสมุทรชนิด N (N-MORB normalized patterns) แสดงค่าผิดปกติเชิงลบของธาตุไนโอเบียม (Nb) และแทนทาลัม (Ta) บ่งบอกว่าหินภูเขาไฟในพื้นที่ลำสนธิมีความเกี่ยวข้องกับการมุดตัวของเปลือกโลก ผลวิเคราะห์ธรณีเคมีของกรวดหินภูเขาไฟจากหินภูเขาไฟกุดตาเพชร (หินไพรอกซีน-แพลจิโอเคลแอนดีไซต์) และหินภูเขาไฟโคกคลี (หินแพลจิโอเคลสแอนดีไซต์ และหินฮอร์นเบลนด์-แพลจิโอเคลสแอนดีไซต์) มีความคล้ายกันกับลาวาจากหน่วยหินภูเขาไฟเขารวก บ่งชี้ว่าหินภูเขาไฟเหล่านี้มาจากต้นกำเนิดเดียวกัน ยกเว้นตัวอย่างหินแพลจิโอเคลสแอนดีไซต์ จากหินภูเขาไฟกุดตาเพชร

สาขาวิชา	ธรณีวิทยา	ลายมือชื่อนิสิต	
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Saowaphap Uthairat : GEOLOGY AND PETROCHEMISTRY OF VOLCANIC ROCKS IN THE LAM SONTHI AREA, LOP BURI PROVINCE. Advisor: ABHISIT SALAM, Ph.D.

Lam Sonthi area is in Lop Buri province, central Thailand. Stratigraphically, the geology of the area consists of five rocks units; Unit I: Khao Ruak siltstone which is correlated to Khao Luak Formation (Early Permian), Unit II: Khao Phaeng Ma conglomerate, Unit III: Khao Ruak volcanics, Unit IV: Lam Sonthi polymictic conglomerate, and Unit V: Kuttaphet sandstone which is correlated to Phu Kradung Formation (Early Jurassic). In addition, the volcanic rocks, which are named as Kuttaphet volcanics and Khok Khli volcanics, could be found in the top of Unit IV as the polymictic intermediate breccia. Petrographic classification identifies the volcanic rocks according to their mineral constituents that quartz is found less than 20 %, so they are named as andesite. Clasts of Kuttaphet volcanics consist of plagioclase andesite and pyroxene-plagioclase andesite while clasts of Khok Khli volcanics consist of plagioclase andesite and hornblende-plagioclase andesite. The selected large clasts of these 2 volcanics were geochemically analyzed for major oxides and some trace elements using XRF and ICP-MS, then compared to the pyroxene-plagioclase andesite which is lava from Khao Ruak volcanics. Geochemistry of all samples suggests that the volcanic rocks in this area are andesite excluding plagioclase andesite clasts of Kuttaphet volcanics are composing of dacite/rhyolite. However, all samples are identified as calc-alkaline affinity and plotting of Ti-Zr suggests that they could have been originated in the volcanic arc setting and the N-MORB normalized patterns show negative Nb and Ta which could be suggest that the volcanic rocks in the Lam Sonthi area is associated with subduction zone. Geochemical similarities indicate that the clasts of Kuttaphet volcanics (which is pyroxene-plagioclase andesite) and Khok Khli volcanics (which are plagioclase andesite and hornblende-plagioclase andesite) were derived from the similar magma source of the Khao Ruak volcanics excluding plagioclase andesite clasts of Kuttaphet volcanics.

Field of Study:	Geology	Student's Signature ....
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Saowaphap Uthairat

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Chapter 1
Introduction

1.1 General statement

The distribution of volcanic rocks in Thailand has been reported in two main periods, 1) Pre-Cenozoic and 2) Cenozoic volcanic rocks. These volcanic depositions are well known for associating with mineral resources of the country. The important examples of mineral resources are Chatree gold-silver deposit, Khao Panom Pha gold skarn, Khao Lek iron-copper skarn, and Khao Thap Kwai iron skarn located on the central part of Thailand. To understand the volcanic stratigraphy, facies architecture, geochemistry and tectonic setting of the volcanic rocks could be useful in integrating data for mineral exploration because many mineral deposits are associated with both plutonic and volcanic rocks. In Thailand and its adjacent areas, Pre-Cenozoic volcanic rocks are of particularly important. The Pre-Cenozoic volcanic belts are mapped into four belts namely, 1) Chaing Rai-Chiang Mai volcanic belt, 2) Chaing Khong-Lampang-Tak volcanic belt, 3) Nan- Uttaradit suture and Sa Kaeo suture, and 4) Loei-Phetchabun-Nakhon Nayok volcanic belt.

The Lam Sonthi area locates in the center of the Loei-Phetchabun-Nakhon Nayok volcanic belt (LPN). Several versions of geologic map of the Lam Sonthi area were published through the time. The first map was published by Geological Survey Division, Department of Mineral Resources (DMR) (Nakornsri, 1977) AMPHOE BAN MI map sheet. The geology in the area composes of Khao Luak Formation, Ratburi Group which represented the Permian sedimentary rock, Huai Hin Lat Formation, the Triassic rock and Phu Kradung Formation, the Jurassic rock. After that, another geologic map of Lop Buri province by DMR (Vimuktanandana and Thiyaphairach, 2007) was proceeded. The Khao Luak Formation was changed namely to the Permian rock of Saraburi Group and the undifferentiated volcanic rocks have been presented into this geologic map. The least version of geologic map that covered Lam Sonthi area is presented by Department of Geology, Chulalongkorn University (2016 and 2020). However, the more details of geology in Lam Sonthi area are still not cleared for example petrographic description of rock, geochemical data, and some volcanic outcrops are still not presented in the previous studies before. Therefore, the insufficient details bring about to the study in this area in order to fulfill geology information in the Lam Sonthi area.

1.2 Location and accessibility

Lam Sonthi study area is in Lam Sonthi district, Lop Buri province in the south-central Thailand. The study area closes to the boundary between Lop Buri province and Chaiyaphum province. It is presented on a topographic map scale 1:50,000 series L7018 sheet 5239I named AMPHOE THEP SATHIT, edition 2-RTSD by Royal Thai Survey Department (Fig. 1.1).

The study area locates about 236 kilometers, northeast from Bangkok. The area can be accessed by the car using the national highway No. 1 (or Phahonyothin Road) from Bangkok to Saraburi province, then turning right onto the highway No. 21 (or Lop Buri-Lom Sak road) before reaching the Lop Buri town to Lam Sonthi district. Within the survey area, accessibility can be done by using the rural roads. It usually spends about 3 hours and a half driving from Bangkok to the area.

1.3 Physiography

Lam Sonthi area mostly consists of flat plain with elevations ranging from 95 to 135 meters above mean sea level. The area is located between the Khao Ruak mountain range in the west and the Khao Phang Hoei mountain range which is the border of Khorat plateau in the east. The highest point in the western is about 425 meters which is one peak of Khao Ruak mountain. Furthermore, there are the smaller mountains that parallel to the Khao Ruak mountains in the south-east which are Khao Saming and Khao Phaeng Ma mountains. All the mountain is aligned in the northeast-southwest direction excluding Khao Phang Hoei mountain that aligned in the north-south direction.

The plain areas are typically used for agriculture and settlements. Reservoirs also present in the study area. The largest reservoir is called Kuttaphet reservoir. The other reservoirs are Sap Langka reservoir and Huai Hin Rang reservoir. The rivers and tributaries are narrow flowing from Khao Ruak mountain to the lower plain area.

1.4 Objective

The aim of this research is to define the characteristics of volcanic rocks in Lam Sonthi area and their relationship with other sedimentary rock units.

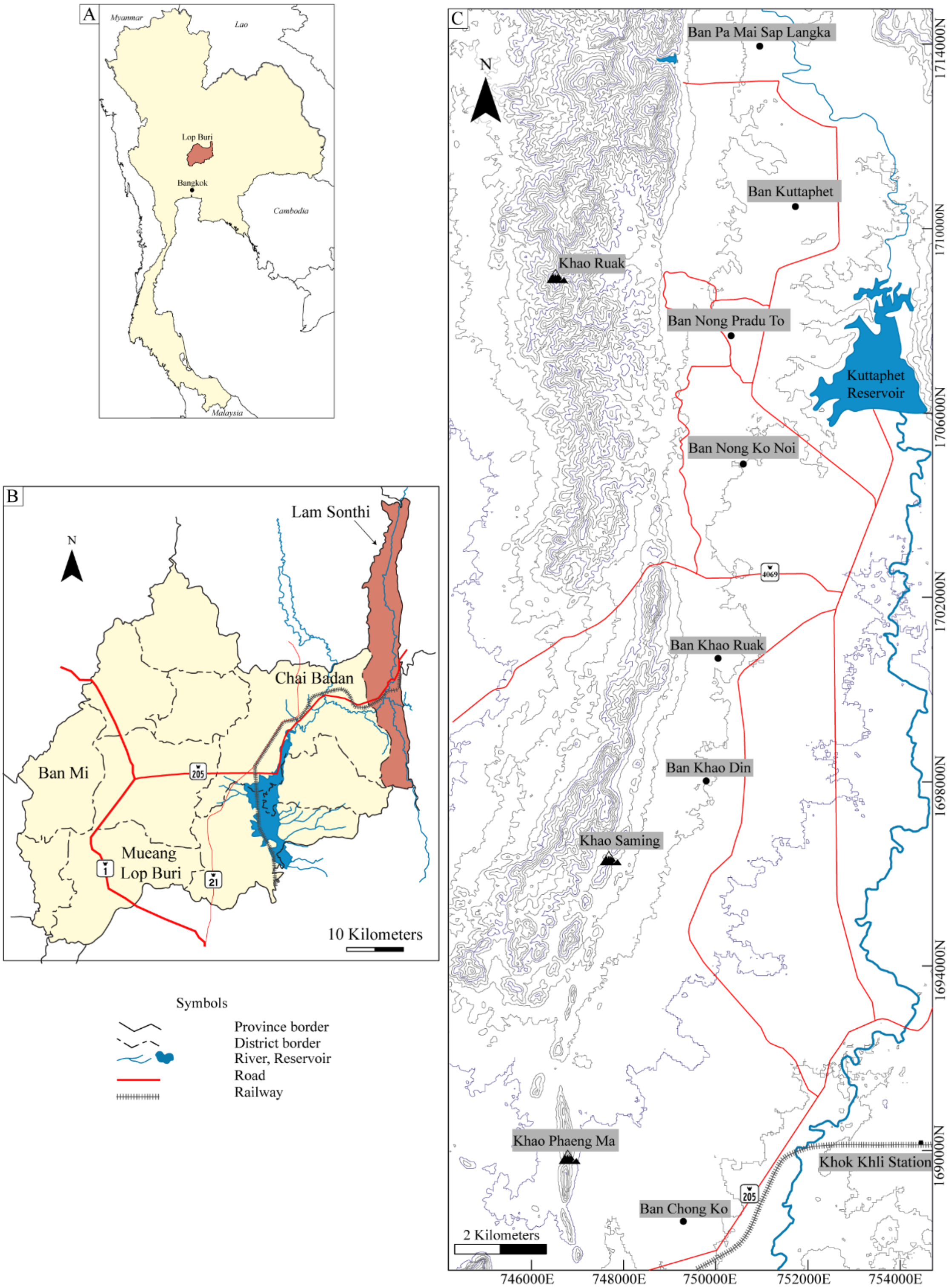

Fig. 1.1 Topographic map of study area showing landforms and routes within Lam Sonthi area.

1.5 Scope of study

This study focuses on the field investigation and field sample collections. Field survey was conducted in two times. The first time was undertaken during 15 to 20 February 2019 and the second time was undertaken during 28 November to 2 December 2019. Detailed of petrography and geochemistry including major oxide, trace elements, and rare earth elements are conducted to clarify their characteristics and their relationship between rocks in the area.

1.6 Methodology

Methodology of this study consist of five steps as describe below.

1.6.1 Literature review

The study started with the reviewing of previous works in the field of tectonic setting and regional geology, mostly focused on rock units. The volcanic rocks in Thailand are also focused.

1.6.2 Field investigation

Geological field investigation includes geological field mapping and collecting geological data from the study area. This process is to verify the geologic boundaries of each unit and to construct the stratigraphic column in the area where the section available. Then, sampling the representative rock for the petrographic study and geochemistry analysis are followed.

1.6.3 Laboratory investigation

(a) Petrographic study examines rock samples on a micro scale to identify the mineral composition, then classifies rock type and confirms the stratigraphic section. The rock would be slab-cut to make a thin section and study under a polarizing microscope.

(b) Geochemical study would be carried out, in order to analyze major elements by using X-Ray Fluorescence (XRF) and selected the representative samples for trace and rare earth elements analysis by using Inductively Coupled Plasma-Mass Spectrometry (ICP-MS).

1.6.4 Discussion and summary

Results of Field investigation, petrographic study and geochemistry analysis were interpreted. The geology, stratigraphy and tectonic setting in the study area would be discussed and concluded.

1.6.5 Thesis writing

Thesis writing, presentation and draft publication for the international journal would be carried out.

1.7 Thesis organization

This thesis is divided into 6 chapters as below:

Chapter 1 (Introduction) provides general statement of this thesis and the general information of Lam Sonthi area, objective, scope of this study, and summarizing methods.

Chapter 2 (Tectonic setting and Regional geology) provides the regional tectonic setting in Thailand, review of volcanic rocks in Thailand and the regional geology.

Chapter 3 (Geology of Lam Sonthi area) presents the characteristic of rock units in Lam Sonthi area including their outcrop scale and petrography.

Chapter 4 (Petrography of volcanic rocks) details the petrography of volcanic rocks, especially lava and clasts selecting for geochemical analysis.

Chapter 5 (Geochemistry of volcanic rocks) presents the geochemical data of the volcanic rock including of major elements, trace elements, and rare earth elements.

Chapter 6 (Discussion and Summary) involves discussion and summary of the study.

Chapter 2
Tectonic setting and Regional Geology

2.1 Introduction

This chapter reviews the tectonic setting, volcanic rocks, and regional geology of the Lam Sonthi area.

2.2 Tectonic setting

Thailand includes two major terranes, Sibumasu (part of it previous known as Shan-Thai (Bunopas, 1981) terrane in the west and Indochina terrane in the east (Fig. 2.1). These two terranes are separated by Sukhothai Arc (or Sukhothai Fold Belt-SFB) on the eastern edge of Sibumasu terrane and Loei Fold Belt (LFB) on the western edge of Indochina terrane. The Sibumasu terrane comprises part of Shan state of Myanmar, north and western Thailand, Malaysia peninsular and Sumatra. The Indochina terrane includes Lao, part of Thailand, Cambodia, Vietnam (south of Song Ma suture), eastern of Malaysia peninsular (Bunopas, 1981; Sone and Metcalfe, 2008) (Fig. 2.1).

The Sibumasu terrane rifted off the Australia sector of Gondwana in the early Permian. It is supported by the evidence of diamictite from Kaeng Krachan Group which was deposited in the glacial environment and could be correlated with Gondwana glacial stratigraphy (Metcalfe, 1988). The Indochina and South China terranes were from north-eastern Gondwana in the early Paleozoic and rifted from Gondwana in the Silurian or Devonian (Hutchison, 1989). The Paleo-Tethys between Sibumasu and Indochina terranes is represented by Inthanon zone (Sone and Metcalfe, 2008). The Paleo-Tethys subducted beneath Sukhothai Arc in Early Permian while Nan-Sa Kaeo back arc basin was opening (Ueno and Hisada, 2001). The collision of Sibumasu and Indochina took place in the Late Triassic and resulted in the closure of Paleo-Tethys. The Sra Kaeo Suture is a continuation of the same suture of Nan-Uttaradit suture, representing back-arc basin (Wakita and Metcalfe, 2005). Based on U-Pb zircon age data and whole rock chemistry, the Loei Fold Belt (LFB) has a complex magmatic history and that widespread of Permo-Triassic magmatism both in SFB and LFB because of subduction-related magmatism. The magmatic rocks of the

LFB are predominantly of I-type affinity (Zaw et al., 2007). The subduction of oceanic crust underneath the Sukhothai Arc occurred during Late Permian, resulting in the emplacement of volcanic rocks (ranging in composition from basalt to rhyolite) and plutonic rocks (granite to diorite of I-type affinity).

The Sibumasu and Indochina Terranes collided and accreted by the Late Triassic to Early Jurassic. It caused the Paleo-Tethys closure and post-collision magmatism followed as represented by granitic rocks in SFB and LFB (Barr and Charusiri, 2011; Jungyusuk and Khositanont, 1992; Zaw et al., 2014). Later on, the collision between India and Eurasia plates during Cenozoic occurred and this resulted in the formation of Cenozoic basins in Thailand. It also activated the magmatism as the Cenozoic volcanic rocks and developing of the strike-slip faults such as Red River, Three Pagoda, and Mae Ping Faults (Jungyusuk and Khositanont, 1992; Macdonald and Barr, 1978; Morley, 2014).

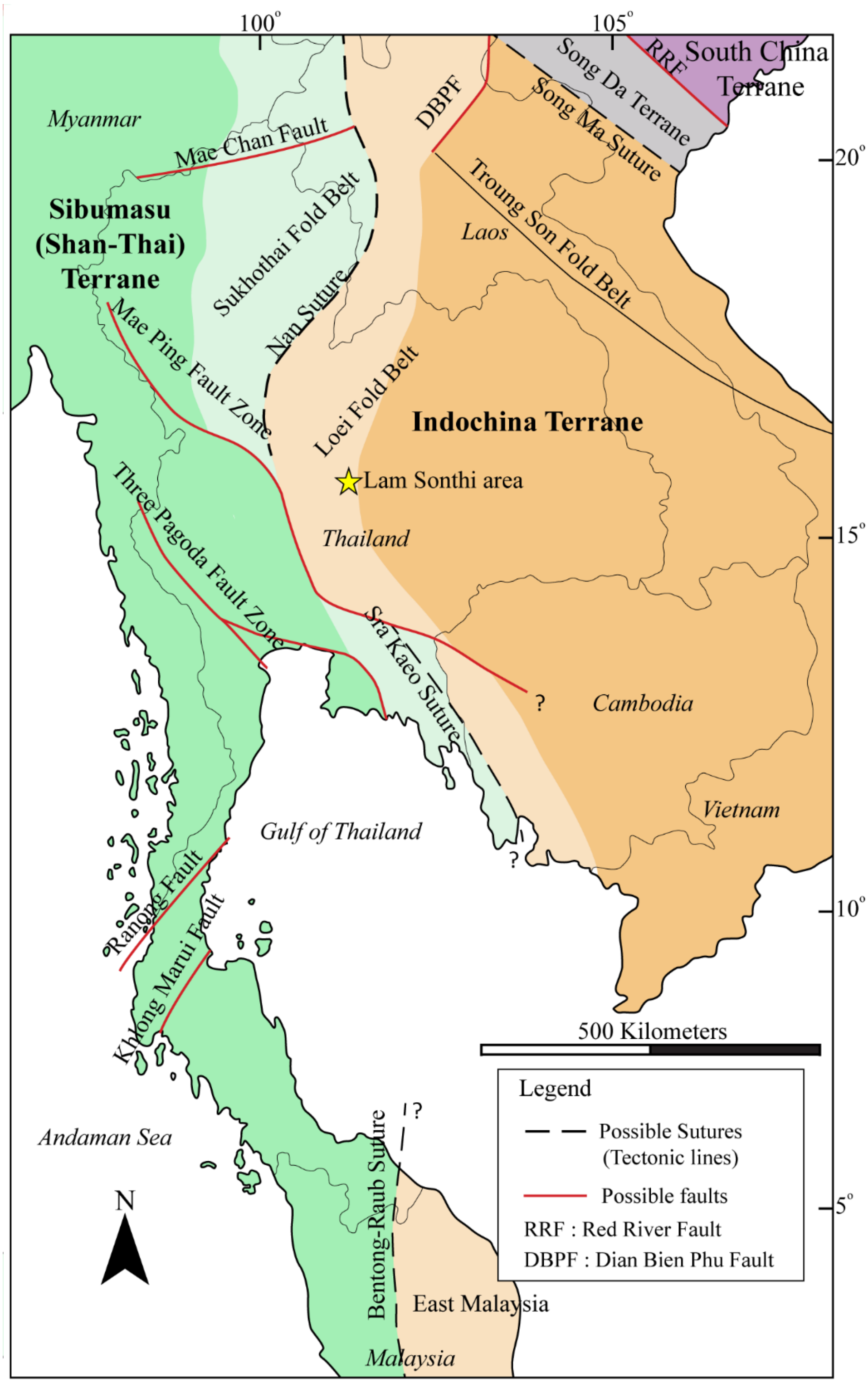

Fig. 2.1 Tectonic map showing the major tectonic terranes and suture zones of Thailand and the surrounding regions (modified after Metcalfe, 2009; Sone and Metcalfe, 2008).

2.3 Volcanic belts in Thailand

The volcanic rocks in Thailand can be divided into 2 groups based on the time of eruptions namely, Pre-Cenozoic volcanic rocks and the Cenozoic volcanic rocks. In this review only Pre-Cenozoic volcanics will be described. The Pre-Cenozoic volcanic rocks can be sub-divided into 4 belts including Chiang Rai-Chiang Mai volcanic belt, Chiang Khong-Lampang-Tak volcanic belt, Nan-Uttaradit suture and Sa Kaeo suture zone, and Loei-Phetchabun-Nakhon Nayok volcanic belt (Fig. 2.2) (Barr and Charusiri, 2011; Jundee et al., 2017; Jungyusuk and Khositanont, 1992; Panjasawatwong et al., 2006).

Chiang Rai-Chiang Mai volcanic belt extends in the north-south direction from the western Chiang Rai to the eastern Chiang Mai province (Fig. 2.2). It consists of tuff, agglomerate, basalt, porphyritic basalt, and cumulate gabbro (McDonald and Barr, 1978). Geochemically, these volcanic rocks are classified as the tholeiitic and transitional alkalic basalt (Barr et al., 1990). Phajuy (2008) suggested that there are two volcanic activities in this belt during the Silurian-Devonian and the Carboniferous to Late Triassic. The $^{40}Ar/^{39}Ar$ dating of basaltic samples was reported as 282 Ma and suggested that this belt might be represented the main Paleo-Tethys suture (Wang et al., 2017).

Chiang Khong-Lampang-Tak volcanic belt locates in the central part of Sukhothai Arc (Singharajwarapan and Berry, 2000) (Fig. 2.2). It extends from Chiang Khong district in Chiang Rai province toward the western Phrae, eastern Lampang and Tak provinces. It is correlated with the volcanic rocks in the Lincang-Jinhong volcanic belt in Yunnan as they have similar ages (Barr et al., 2000; Yang, Mo, and Zhu, 1994), geochemistry and tectonic setting. Composition of volcanic rocks in this belt is ranging from felsic to intermediate. The rocks consist of rhyolite, dacite, andesite, tuff, and agglomerate which could be subdivided into 2 groups namely, Permo-Triassic and upper Triassic to lower Jurassic based on stratigraphic correlation (Jungyusuk and Khositanont, 1992). Srichan (2009) studied the geochemical characteristics of volcanic rocks in Chiang Khong and concluded that they were erupted in the continental margin volcanic arc setting. However, the tectonic setting could be in post-collisional extensional setting based on the dominance of felsic lavas and the mainly non-marine associated sediments. The coherent rocks were dated as the Late Triassic age (223-230 Ma) (Srichan, Crawford, and Berry, 2009).

Nan–Uttaradit and Sa Kaeo suture extends southward from Nan province to Uttaradit and Sa Kaeo provinces (Fig. 2.2). It consists mainly of ophiolitic mafic and ultramafic rocks, these rocks in Nan-Uttaradit suture were interpreted to have formed in back-arc or inter-arc basin (Barr and Macdonald, 1987). The mafic-ultramafic igneous rocks in Nan-Uttaradit suture comprise oceanic-island basalts, back-arc basin basalts-andesites, island-arc basalts-andesite, and supra-subduction mafic cumulates in mélange during Carboniferous to Permo-Triassic time (Panjasawatwong and Yaowanoiyothin, 1993). The other mélange block was reported in Sa Kaeo suture which might be correlated with the Nan-Uttaradit suture as evidenced of an accretionary complex. This zone consists of basaltic pillow lava, hyaloclastite, chert, limestone, and serpentinite which formed in ocean environment and were collided by the east-dipping subduction during the Late Permian (Chutakositkanon and Hisada, 2008). Lately, the zircon U-Pb age of gabbro and meta-basalt from Nan-Uttaradit suture was reported as 311±10 Ma and the crystallization age of rock were 316 Ma which can be compared with ophiolitic rocks formed in the Ailaoshan- Jinshajiang Ocean in China (Yang et al., 2016).

Loei–Phetchabun–Nakhon Nayok volcanic belt is partly confined to the western edge of Khorat Plateau or western edge of Indochina terrane extending southward from Loei, Phetchabun, Nakhon Nayok, and Sa Kaeo (Fig 2.2). The volcanic rocks in this belt consist lava, tuff, and agglomerate with wide composition range from mafic to felsic and can be classified as calc-alkaline affinity representing arc related volcanism (Bunopas, 1981; Intasopa and Dunn, 1994; Kosuwan, 2004). Some mid-oceanic ridge basalt (MORB)-like tholeiitic basalts and microgabbro dykes have also been recorded in some areas (Panjasawatwong et al., 2006). The Loei volcanic rocks are present in the northern part of this belt. The rocks are separated into 3 zones: western, central and eastern zones which are composed of Devonian rhyolite, Middle Devonian-Lower Carboniferous basalt and Permo-Triassic andesite respectively. The age data indicate that the volcanism occurred in two magmatic episodes at approximately 374 and 361 Ma. Trace element and isotopic compositions of the rhyolites suggest that they were generated by partial melting of continental crust at 374 Ma (Intasopa, 1993). Panjasawatwong (2006) studied the central Loei volcanic rocks and presented that the volcanics in this area consist transitional tholeiitic to calc-alkaline affinity. The central Loei volcanic rocks are comprised of MORBs and oceanic island-arc lava which might erupted in an oceanic environment. Mafic volcanic rocks and hypabyssal rocks in the Chon Daen-Wang Pong area are considered to be southern extension of the western Loei volcanic rocks. The volcanic rocks consist tholeiite basalt-andesite to calc-alkaline andesite. They were suggested to have formed in a volcanic arc environment (Boonsoong, Panjasawatwong, and Metparsopsan, 2011). Furthermore, Salam et al. (2014) studied the volcanic stratigraphy and their geochemical characteristics in Chatree deposit located between Phichit and Phetchabun provinces and interpreted the evolution of the volcanic rocks in the Chatree deposit area. There are the Late Permian Suite 1 volcanic units are sourced from a more depleted mantle relative to the overlying Early Triassic Suite 2 volcanic units. The Late Permian Suite 1 unit was suggested to have formed immediately after the beginning of subduction and at the creation of a new island arc, whereas the less depleted Early Triassic Suite 2 unit was erupted during ongoing subduction once the system had achieved a steady state. In addition, the magmatic events in the Chatree region were recognized: 1) the carboniferous volcanism and plutonism (320-310 Ma), 2) the magmatism of volcanic complex (260-238 Ma) with associated with plutonism (249-244 Ma), and 3) post-collision plutonism (220-200 Ma) (Salam et al., 2014). The southern part of Loei-Nakhon Nayok volcanic belts includes the volcanic rocks of Khao Yai volcanics (Kosuwan, 2004). The volcanic rocks are chiefly distributed in the Saraburi-Nakhon Nayok area, and they are interpreted as calc-alkaline rocks which are suggested to have erupted in an active continental margin. The rhyolite of Khao Yai volcanics was dated and reported their U-Pb zircon age as 207 Ma which was interpreted to be in orogenic setting (Arboit et al., 2016).

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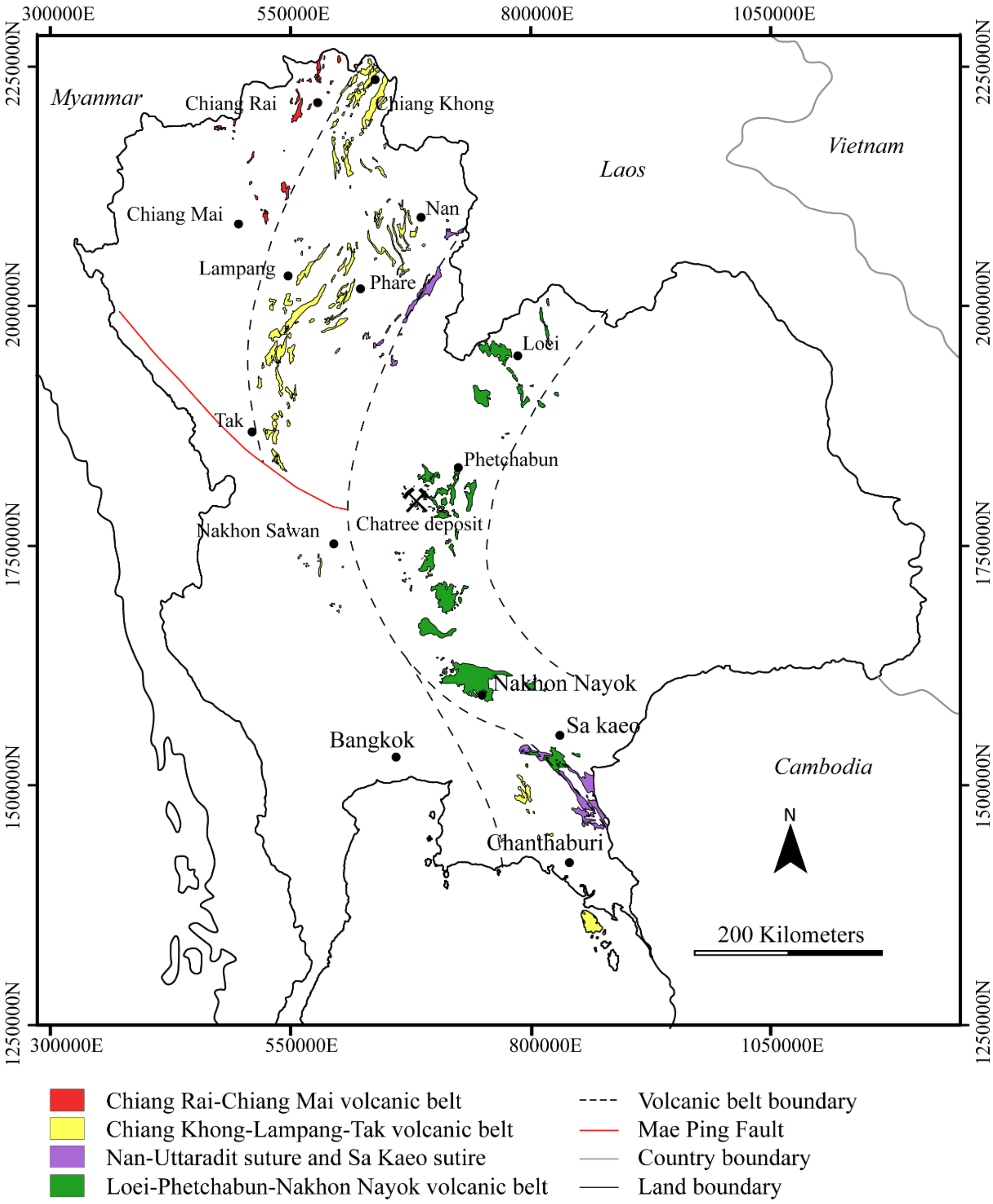

Fig. 2.2 The distribution of Pre-Jurassic volcanic rocks in Thailand (after Jungyusuk and Khositanont, 1992; Panjasawatwong et al., 2006; Kosuwan et al., 2017)

2.4 Regional geology

Regional geology of the Lam Sonthi area in this study is mainly based on the geological map of Ban Mi (Nakornsri, 1977) and compilation with the other geological maps in the area including the geologic maps of Lop Buri province (Vimuktanandana and Thiyaphairach, 2007) and Lam Sonthi produced by 3rd years students of the Department of Geology, Chulalongkorn University (2016 and 2020). The rocks presenting in the study area are described from older to younger below (Fig. 2.3).

2.4.1 Permian Rocks

The Permian rocks in Lam Sonthi area are the oldest rock unit as represented by Khao Luak Formation (Nakornsri, 1977) of geological map scaled of 1: 250,000 of Amphoe Ban Mi map sheet, Lop Buri province. This formation was previously grouped within Ratburi Group. However, Bunopas (1981) defined a new definition of the Ratburi Group as the Permian limestone distributing in the western and southern Thailand, while the Saraburi Group is mixed of limestone and clastic rock that distribute in the eastern side of lower Chao Phraya central plain and the western edge of Khorat plateau. Thus, the Khao Luak Formation is now assigned within the Saraburi Group. Bunopas (1981) also proposed that Saraburi Group consists of three rock units from older to younger which are Khao Luak Formation (Nakornsri, 1977), Saraburi Limestone, and Dan Sai Shale.

The Khao Luak Formation composes of argillaceous rocks such as brown shale to slaty shale, pale brown sandstone with medium-grained sand and interbedded limestone. The crystalline limestone lens is often included in the formation. The total thickness of formation is approximately 1,500 meters. The fossil of coral *Pseudohuangia* sp. was found and inferred as Lower Permian age (Nakornsri, 1981). The type section of the formation is at Khao Ruak mountains, Lam Sonthi district, northeastern of Lop Buri province. The lower part of this section consists of tuffaceous sandstone and the upper part of the section consists of interbedded shale and sandstone with thin beds of limestone. The well bedded strata have been overturned and cut by rhyolite dikes (Assavapatchara, 2006). It is folded with trending to north - south and dipping into both east and west directions but they are dominantly west dipping in this section. (Bunopas, 1981; Nakornsri, 1977). It extends from

Phetchabun southward to Khao Ruak mountains. The Khao Luak Formation is considered being the southern continuation of the Nam Duk Formation and it is a southern part of the Nam Duk basin (Ueno and Charoentitirat, 2011).

2.4.2 Triassic rocks

The Triassic rocks in Lam Sonthi and its adjacent areas are reported as Huai Hin Lat Formation (Nakornsri, 1977)**.** It includes conglomerates which are characterized by poor sorted, rounded to sub-rounded with pebble size clasts. Their clasts comprise mainly limestone carried fusulinids and coral. The Huai Hin Lat Formation is reported that it is unconformably underlain by Khao Luak Formation at Nong Bua Daeng district, Chaiyaphum province (northward out of Fig. 2.3) and overlain by rhyolite and tuff at Chai Badan district, Lop Buri province (southwestward out of Fig. 2.3). The rocks are generally conformably overlain by rocks of Phu Kradung Formation (Nakornsri, 1981)**.**

The study of Huai Hin Lat Formation (Chonglakmani and Sattayarak, 1978) at the type section concluded that the Huai Hin Lat Formation is the basement of Khorat Group. It is unconformity with limestone of Permian rocks. It composes of 2 members in lower sequence and 3 members in upper sequence in which the lower sequence is represented by the volcaniclastic rocks. Pho Hai Member that is the lowest in lower sequence includes tuff, agglomerate, rhyolite, and andesite which are intercalation of sandstone and conglomerate. The other member of lower sequence is Sam Khaen Member which is the limestone conglomerate and usually known as basal conglomerate. The upper sequence generally consists of sedimentary rocks such as shale, sandstone, argillaceous limestone with some volcanic rock intercalations (Chonglakmani and Sattayarak, 1978).

2.4.3 Jurassic rocks

The Jurassic rocks in Lam Sonthi and its adjacent area are sedimentary rocks of Khorat Group which includes Phu Kradung, Phra Wihan, and Sao Khau Formations. Nakornsri (1977) reported that Phu Kradung Formation in this area is friable purplish-red calcareous siltstones cross bedded with fine to medium grained sandstone. Phra Wihan Formation is white to light brown with medium-grained sandstone. It is interbedded with siltstone. Sao Khua Formation is grey with fine- to medium-grained sandstone and greenish-grey siltstone. The sandstone commonly shows cross-bedding structure.

2.4.4 Igneous rocks

Nakornsri (1981) also reported that volcanic rocks mostly are rhyolite and tuff with less andesite and agglomerate. Rhyolite and andesite erupted and deposited between Tak Fa Formation and Khorat Group eastward out of Fig. 2.3. Lately, basalts were also found in the northernmost part in the area thus they were identified as younger age. Later, the new geological map of DMR was published which includes the Lam Sonthi area (Vimuktanandana and Thiyaphairach, 2007). The map shows that Lam Sonthi area also composes of 4 rock units same as before. However, there are some difference between these two maps. The Khao Luak Formation was mapped as Saraburi Group, Huai Hin Lat Formation was mapped same as previous geological map version, Phu Kradung Formation was mapped covering whole plain area and the undifferentiated volcanic rocks of Permo-Triassic volcanic rocks were presented (Vimuktanandana and Thiyaphairach, 2007).

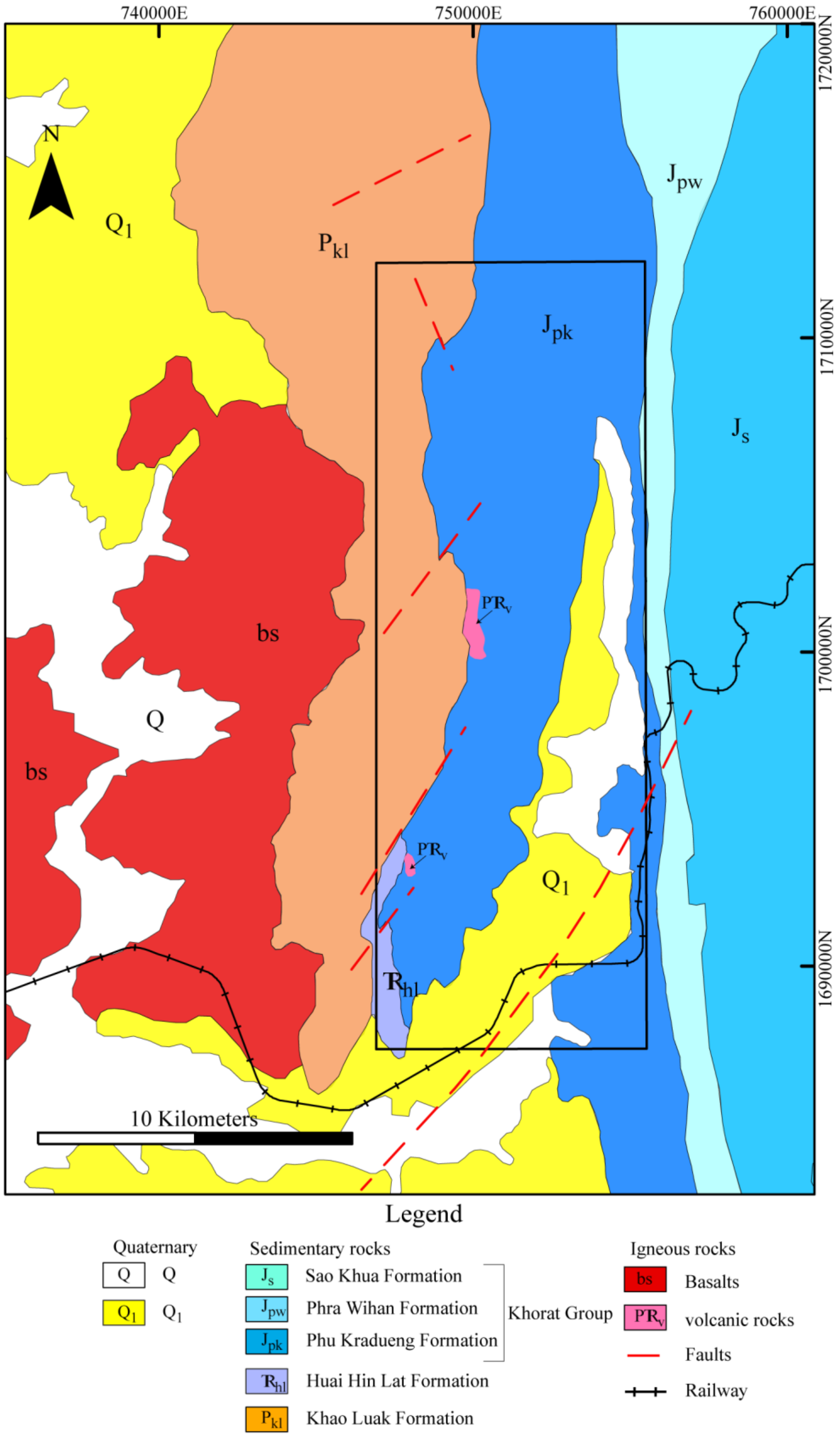

Fig. 2.3 The geological map of Amphoe Ban Mi (modified from Nakornsri, 1977; Vimuktanandana and Thiyaphairach, 2007).

Chapter 3
Geology of Lam Sonthi area

3.1 Introduction

This chapter details the geology of Lam Sonthi area, Lop Buri province. Mapping was based on the pre-existing geological scale 1: 250,000 of Department of Mineral Resources (1976, 2007) and geological map compiled by 3rd years students of Department of Geology, Chulalongkorn University (2016, 2020) aimed to improve geological boundaries and rock units. Details of each unit were present below.

3.2 Geology of Lam Sonthi area

The oldest rocks in Lam Sonthi area are sedimentary rocks of inferred Permian to Upper Triassic age (Nakornsri, 1981). Some volcanic rocks identified in the area consists of andesite, rhyolite, and tuff of inferred Permo-Triassic were reported in area (Vimuktanandana and Thiyaphairach, 2007), however no details were provided. Based on field investigation during this study, the rocks in the Lam Sonthi area can be divided into five units namely Unit I: Khao Ruak siltstone, Unit II: Khao Phaeng Ma conglomerate, Unit III: Khao Ruak volcanics, Unit IV: Lam Sonthi polymictic conglomerate, and Unit V: Kuttaphet sandstone (Fig. 3.1).

3.2.1 Unit I: Khao Ruak siltstone

Unit I: Khao Ruak siltstone can be correlated with the Khao Luak Formation (Nakornsri, 1977, 1981). It consists predominantly of siltstone, mudstone with minor shale, and limestone lenses. It is locally constituted tuffaceous siltstone and sandstone. The fine-grained clastic rocks (mudstone and siltstone) are characterized by laminated, thin to medium beds. Calcareous siltstone is occasionally show thick beds. Limestone occurs as lenses interbedded or intercalated with mudstone and siltstone. This unit distributes in the western part of the Lam Sonthi area, in which it covers large part of the Khao Ruak mountain range (Fig. 3.1).

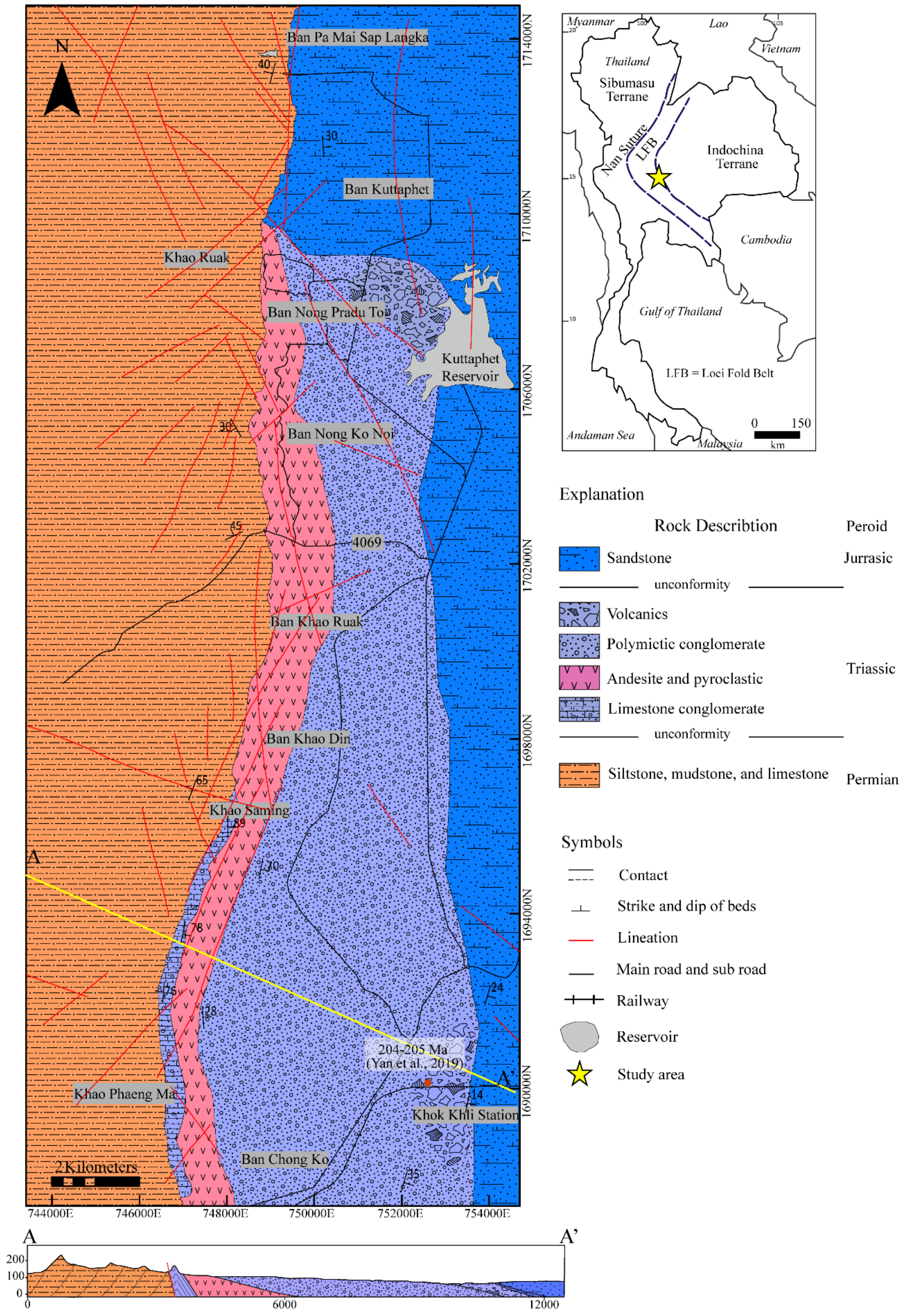

Fig. 3.1 Geological map of Lam Sonthi area, Lop Buri province.

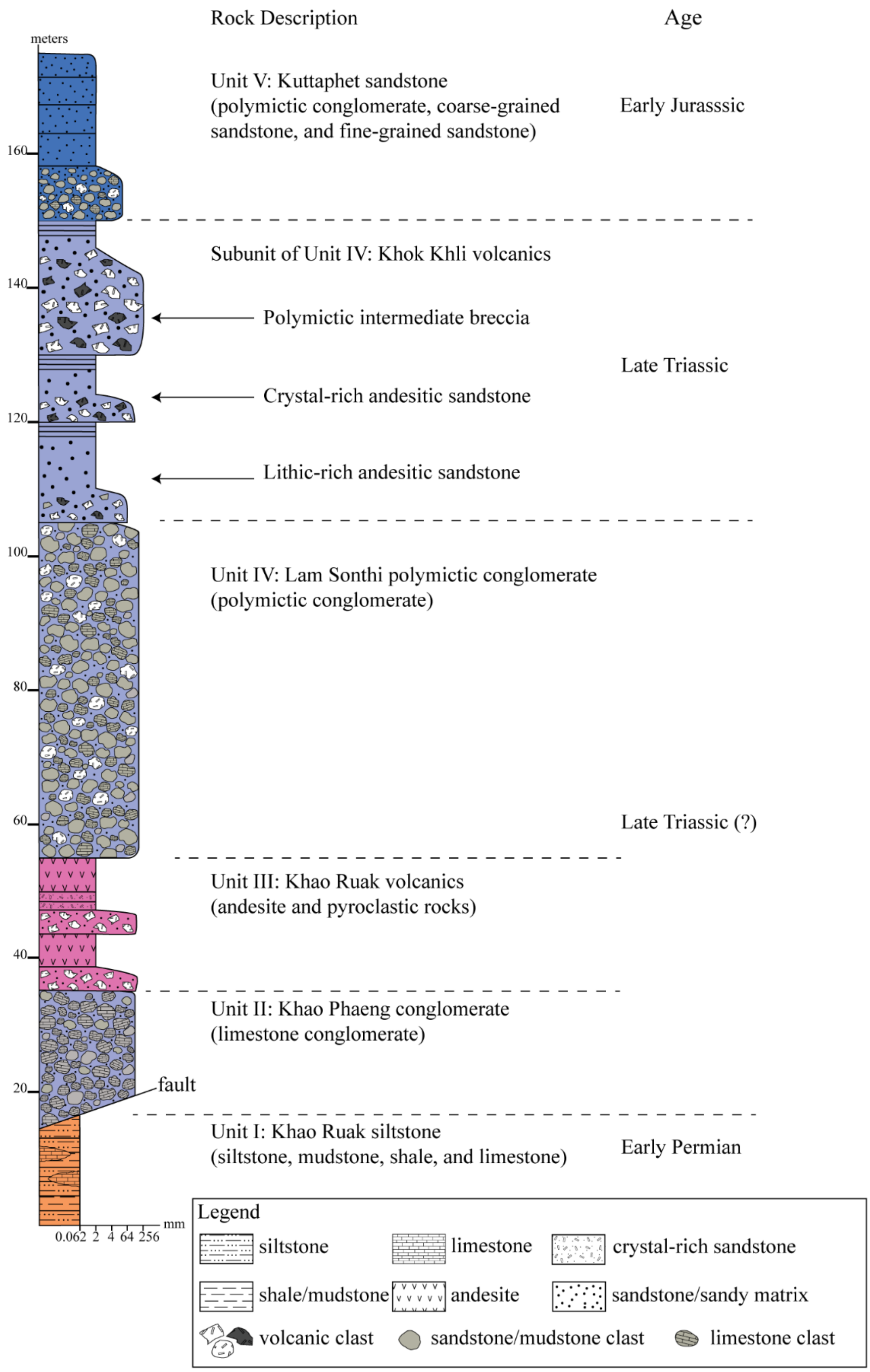

Fig. 3.2 Simplified composite stratigraphic column of Lam Sonthi area.

This unit's general strike is approximately northeast-southwest with predominantly east-dipping on the eastern flank of Khao Ruak mountains, while west-dipping is more common on the western side of the mountain. This unit is generally folded and interpreted as overturn strata. The Khao Ruak siltstone is best observed along the eastern side of the Khao Ruak mountains, especially at the road cut (Road No. 4069) at a latitude of 748660E and longitude of 1702700N that cut through the Khao Ruak mountains (Fig. 3.3A). The thickness of the sequence at this road cut is about 20 meters. At the bottom of the section, the rock is characterized by at least 5 meters thick of massive beds of green tuffaceous siltstone and overlaying by siliceous siltstone in which the contact can be observed at the western side of the section (up the slope). At the upper part of the section, the rock is overlain by medium to thick beds of calcareous siltstone interbedded with thin shale beds (Fig. 3.3B).

In addition to the tuffaceous siltstone at the lower part of the section, the rock is greenish-grey to green and has an exfoliation texture similar to those found in volcanic rocks. Black granules ranging from 2-4 mm in size could be observed. Under the microscope, the rock shows sphere quartz grained in the very fine-grained matrix (Fig. 3.4A and B).

The siliceous siltstone that is overlaying the tuffaceous siltstone is greenish-grey to dark grey. It forms thick beds and has a thickness of 3.5 meters. Under the microscope, the siliceous siltstone constitutes mainly quartz grains with minor muscovite (Fig. 3.4C and D).

The calcareous siltstone at the uppermost of the section is interbedded with thin shale. The calcareous siltstone is greenish-brown to brown, composing mainly quartz and carbonate minerals (mainly calcite). Shale is brown to dark brown and generally occurs as thin layers interbedded with siltstone. Under the microscope, the calcareous siltstone constitutes mainly quartz and calcite with a small amount of plagioclase (Fig. 3.4E and F). The Khao Ruak siltstone is overlain by Khao Phaeng Ma conglomerate (Unit II) with fault contact at the southern part of the area, but it is overlain by Khao Ruak volcanics (Unit III) at the northern part of the area (Fig. 3.1).

Fig. 3.3 Characteristic of Khao Ruak siltstone unit. (A) Photograph of Khao Ruak roadcut section showing thick bed of siliceous siltstone and calcareous siltstone. (B) Photograph of calcareous siltstone interbedded with shale. (C) Photograph of siliceous siltstone.

Fig. 3.4 Characteristic of siltstones of Khao Ruak siltstone unit. (A) Photograph of tuffaceous siltstone showing rock fragments in matrix. (B) Photomicrograph of tuffaceous siltstone. (C) Photograph of siliceous siltstone. (D) Photomicrograph of siliceous siltstone. (E) Photograph of calcareous siltstone. (F) Photomicrograph of calcareous siltstone. Abbreviation; rf=Rock fragment.

3.2.2 Unit II: Khao Phaeng Ma conglomerate

The limestone conglomerate found in the southern part of the area is known as Khao Phaeng Ma conglomerate. This unit is best exposed from areas of Khao Saming to Khao Phaeng Ma forming a steep mountain. The unit strikes almost north-south with steep dipping. The Khao Phaeng Ma conglomerate typically consists about 70% of limestone clasts and 30% of mudstones in reddish brown sandy to silty matrix. It is poorly sorted and commonly clast-supported conglomerate. The clast size ranges from 5-15 cm or from pebble to cobble. Clasts are rounded to subrounded (Fig. 3.5A and B).

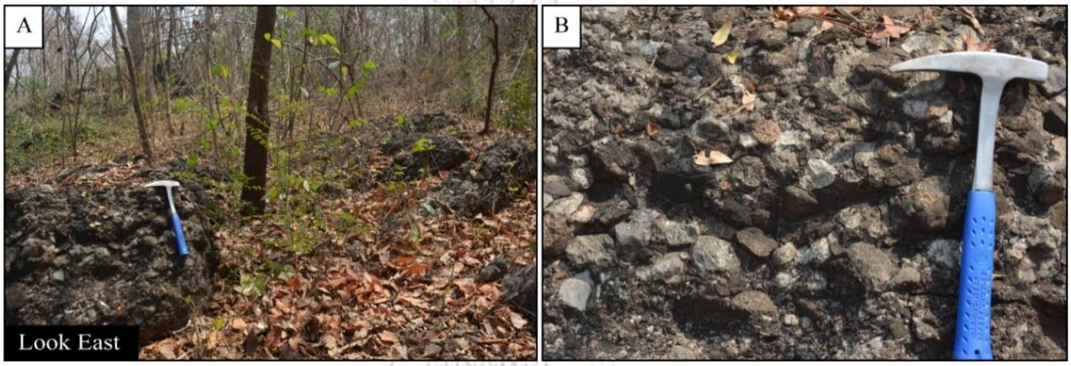

Fig. 3.5 Characteristic of Khao Phaeng Ma conglomerate unit. (A) Photograph of Khao Phaeng Ma conglomerate showing limestone conglomerate outcrops. (B) Photograph of limestone conglomerate zoomed up.

3.2.3 Unit III: Khao Ruak volcanics

In this study, this volcanic unit is preferred to name as “Khao Ruak volcanics” after the mountain in the area. Unit III is characterized by volcanic rocks consisting of andesite and andesitic tuff, and andesitic breccia. The unit strikes north-south, extending from Ban Nong Pradu To in the north to Ban Chong Ko in the south (Fig. 3.1). The Khao Ruak volcanics unit overlies on the Khao Ruak siltstone unit with presumably shallow easterly dipping. The rock cropped out in the east of the Khao Ruak mountains and extended several kilometers in a north-south trend. The outcrops sparsely expose in the plain area of the Lam Sonthi. The volcanic rocks of this unit are underlain by Khao Ruak siltstone unit, and Lam Sonthi polymictic conglomerate (Unit IV) overlies it. The terminology of volcanic rocks used in Khao Ruak volcanics is based on McPhie et al. (1993).

Andesitic breccia

Andesitic breccia has been identified at the north of Khao Ruak volcanic close to Ban Nong Pradu To, and in the south, the volcanic rock has been found near Ban Chong Ko. Clasts comprise andesite sit in a matrix of small lithic fragments, plagioclase, and devitrified glass (Fig. 3.6).

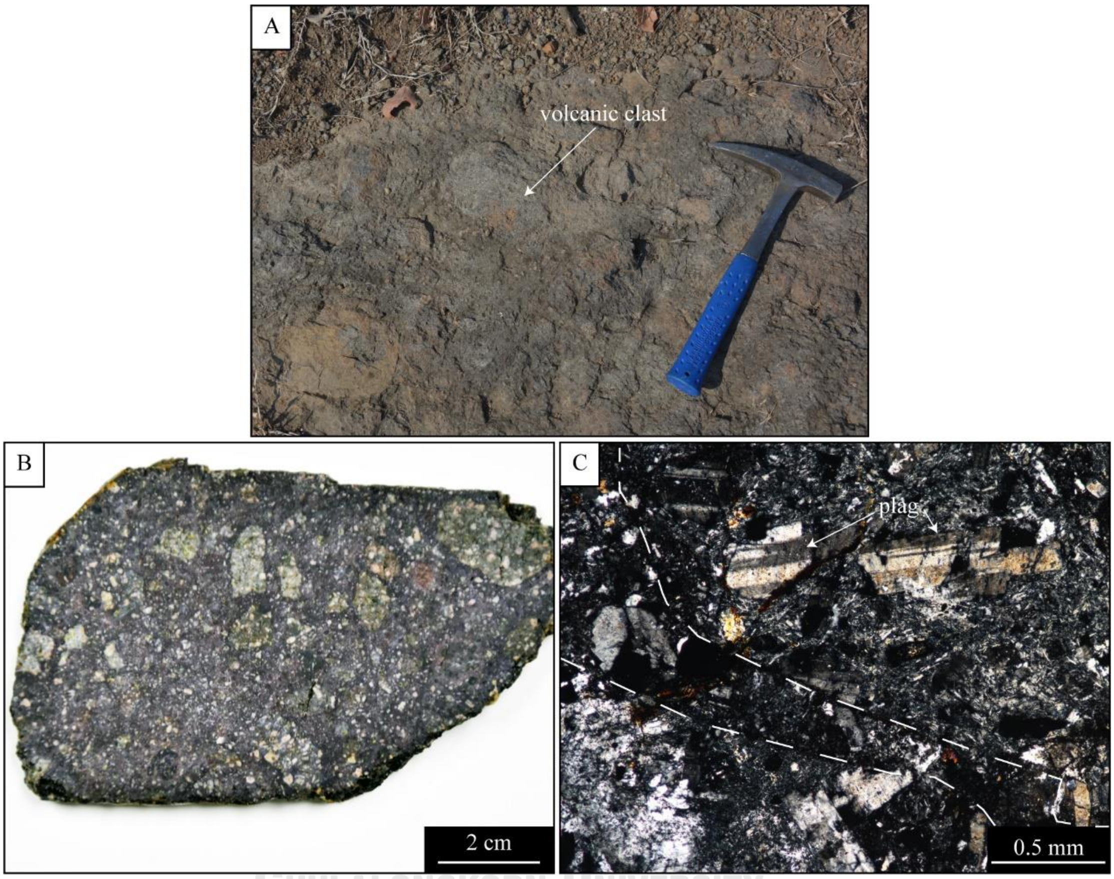

Fig. 3.6 Characteristic of andesitic breccia. (A) Photograph of andesitic breccia outcrop showing large volcanic clast are surrounded by matrix. (B) Photograph of andesitic breccia slab showing volcanic fragments and feldspars. (C) Photomicrograph of matrix showing small clasts of volcanic in glassy texture in the right of figure. Abbreviation; plag=Plagioclase

Hornblende andesitic breccia

Hornblende andesitic breccia crops out at Ban Nong Ko Noi in the northern part of study area and Ban Khao Din in central part of the area. This rock is greenish grey with predominantly of andesites clasts and crystals (Fig. 3.7A). Under microscope, the rock contains clasts in matrix composing of plagioclase and devitrified glass. Clasts size is typically 2-4 mm which some clast is about 1 cm. Their shapes are sub-angular to angular. Porphyritic andesite clasts consist mainly feldspar and hornblende phenocrysts in trachytic texture groundmass. The clasts can be classified as hornblende andesites (Fig. 3.7B and C).

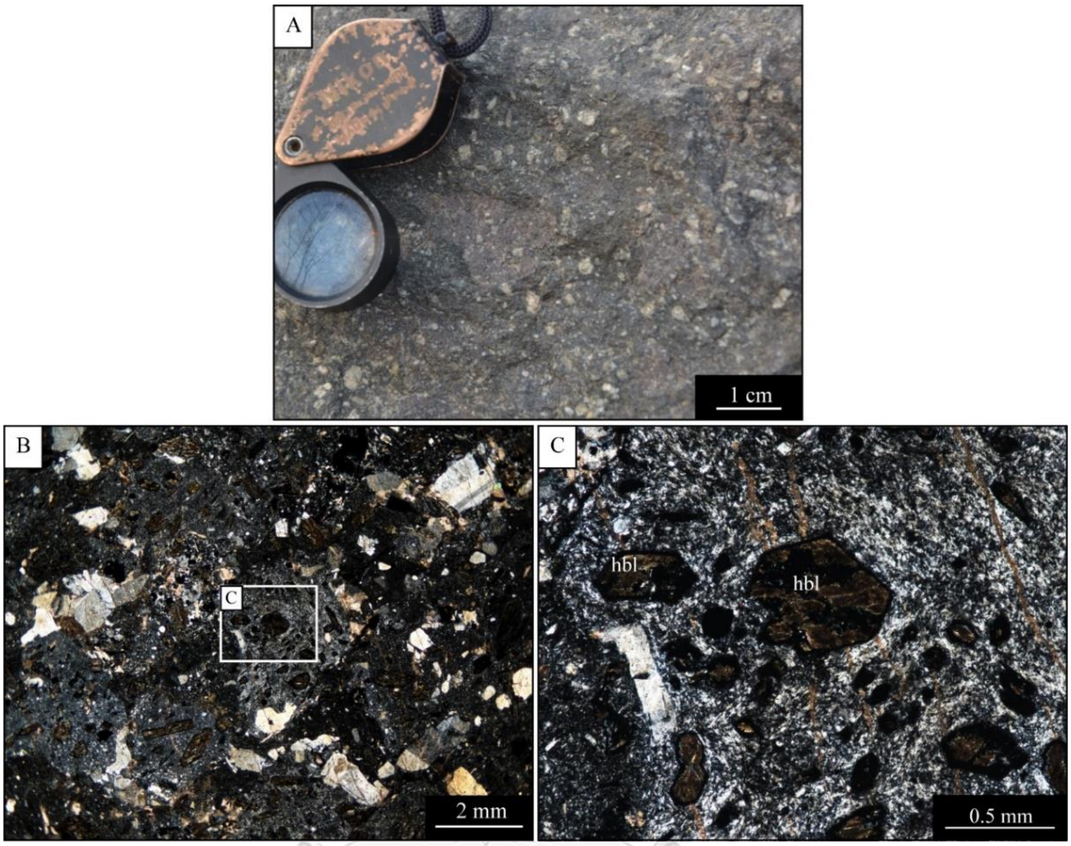

Fig. 3.7 Characteristic of hornblende andesitic breccia. (A) Photograph of rock showing the volcanic fragment is surrounded by feldspar phyric. (B) Photomicrograph of monomictic andesitic sandstone showing andesite clasts surrounded by plagioclase and glass in matrix. (C) Photomicrograph of andesite clast zoomed up showing hornblende phenocrysts in the trachytic texture. Abbreviation; hbl=Hornblende.

Crystal-rich andesitic sandstone

Crystal-rich andesitic sandstone can be observed at Ban Khao Ruak in the middle part of the Khao Ruak volcanics. The rock is pale brown, displaying layers similar to lamination (Fig. 3.8A and B). Under the microscope, the rock consists of plagioclase laths and devitrified glass. Plagioclase crystals are euhedral to subhedral, and their grain size is ranging from 0.2 to 0.5 mm (Fig. 3.8C).

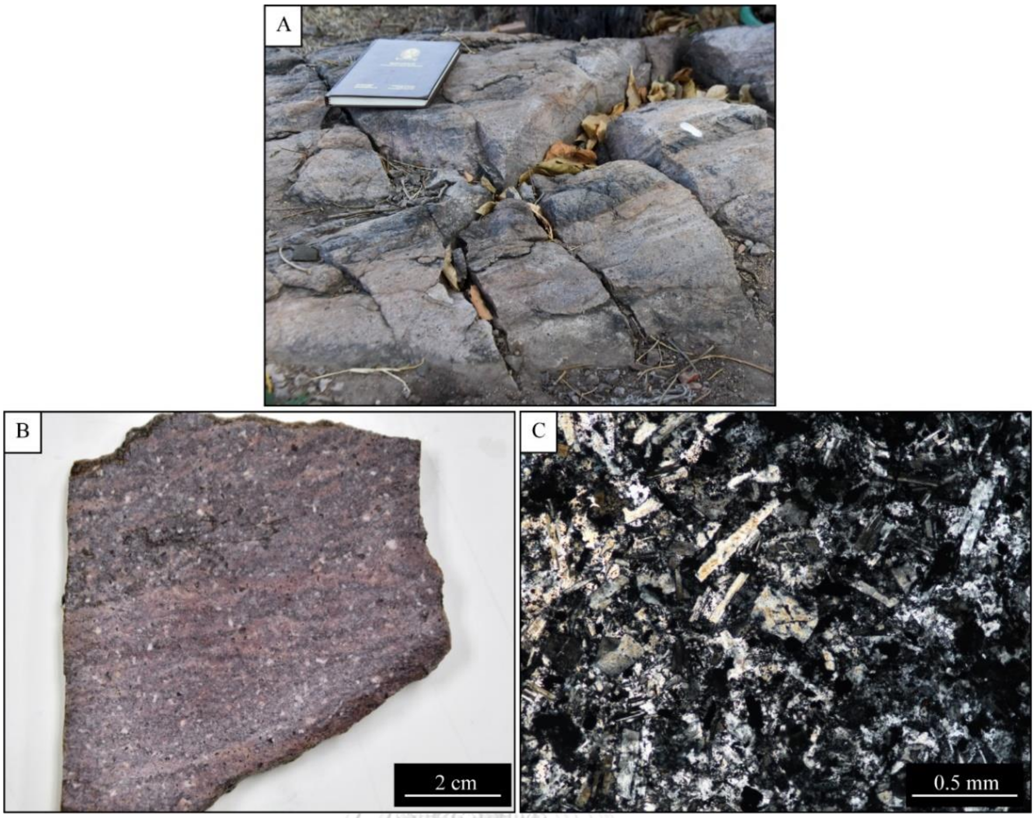

Fig. 3.8 Characteristic of crystal-rich andesitic sandstone. (A) Photograph of crystal-rich andesitic sandstone outcrop shows layering (B) Photograph of crystal-rich sandstone (C) Photomicrograph of crystal-rich andesitic sandstone showing plagioclase and glass material.

3.2.4 Unit IV: Lam Sonthi polymictic conglomerate

Unit IV is characterized by the rock of multiple clast types consisting of porphyritic andesite, limestone, sandstone, siltstone, and quartz vein fragments. This unit strikes north-south. Outcrops found in the areas slightly elevated from the flatted areas scattered through the study area center (Fig. 3.1). The outcrops of polymictic conglomerate are best observed in quarries and small farming reservoirs. Based on available outcrops, Lam Sonthi polymictic conglomerate is relatively uniform throughout the unit. Although grained size might vary from place to place, overall, the unit is made up only of the conglomerate. Lam Sonthi polymictic conglomerate extends in a north-south direction parallel to Khao Phang Hoei mountain, the western edge of the Khorat plateau.

In hand specimens, the rock is similar to the conglomerate of Khao Phaeng Ma conglomerate, and the main difference is that Lam Sonthi polymictic conglomerate has more variable clasts types as detailed above (Fig. 3.9A, B and C). Generally, the clasts' size is 3-15 cm, but it can be up to 20 cm in some places. They are sub-rounded to rounded and poorly sorted. They are clast-supported in which the matrix is red sandy grains with carbonate cemented. Under the microscope, the matrix shows poorly sorted with medium to coarse sand grained. The constituents are mainly rounded rock fragments that are fused by calcite (Fig. 3.9D).

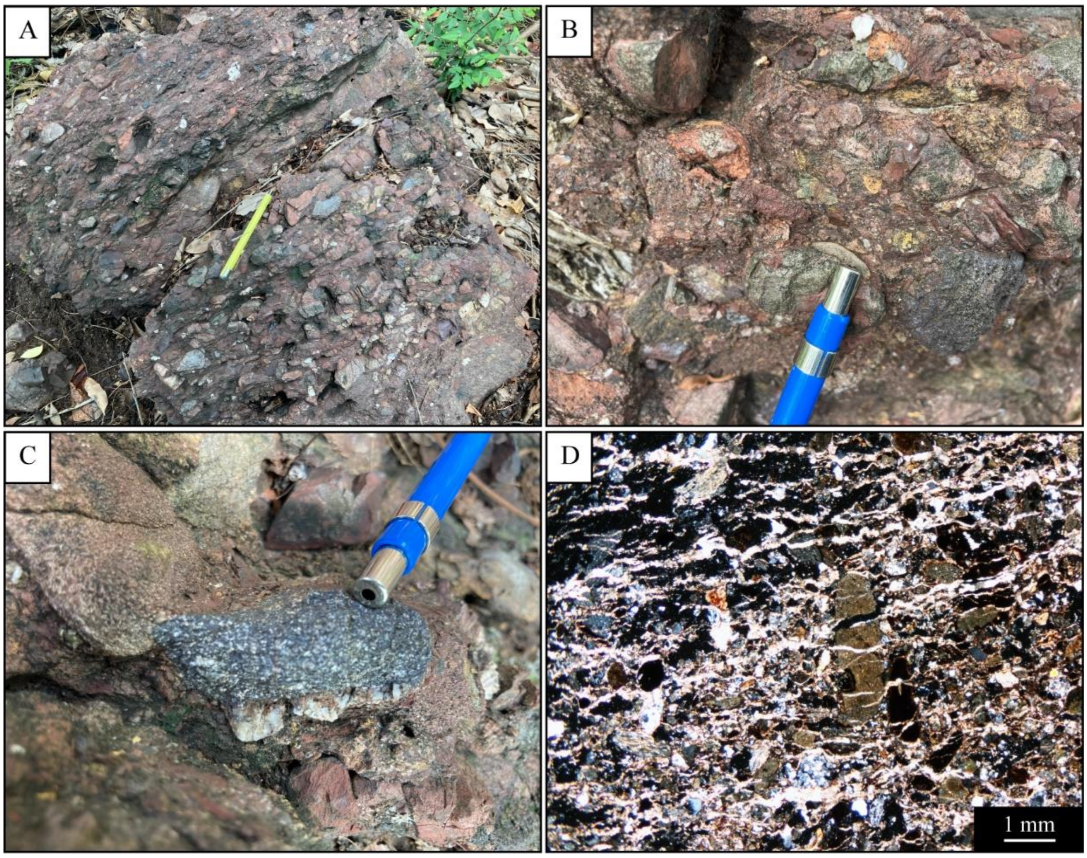

Fig. 3.9 Characteristic of Lam Sonthi polymictic conglomerate unit. (A) Photograph of polymictic conglomerate outcrop. (B) Photograph of clasts from polymictic conglomerate showing limestone and mudstone. (C) Photograph of porphyritic andesite. (D) Photomicrograph of red matrix showing sand size of grains fused by carbonate.

Also, at the top of this unit, volcanic outcrops were found at Kuttaphet reservoir (Fig. 3.10A) and Khok Khli railway station (Fig. 3.10B) as a local lens with no continuation to each other. At the Khok Khli railway station, the volcanics can be observed for a kilometer along the east-west section, both northern and partly southern sides of the road cut. The extension of this subunit is not known partly due to limited exposures to the north and south. The second-best exposures are at the Kuttaphet reservoir, where they crop on the western side of the Kuttaphet reservoir.

The volcanics at these two areas are characterized by polymictic intermediate breccia which consists andesite clasts surrounding by crystal-rich andesitic sandstone.

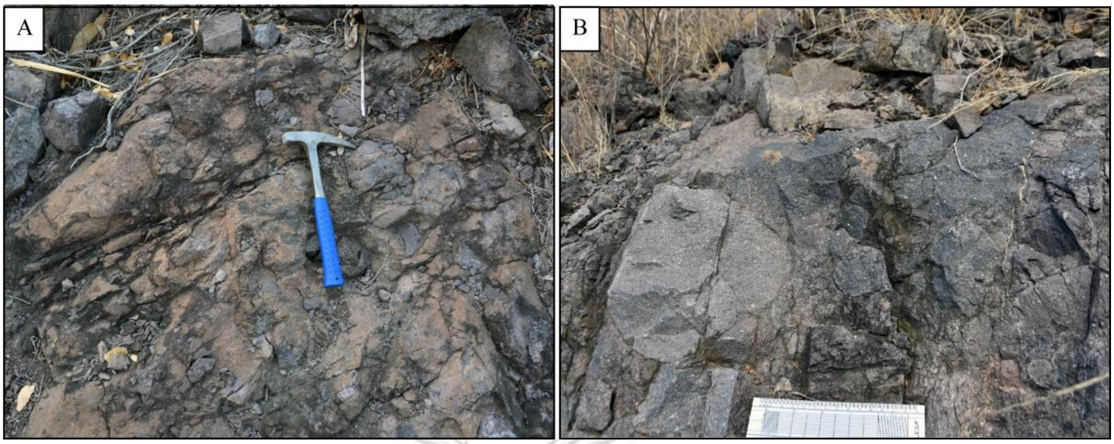

Fig. 3.10 Characteristic of volcanic outcrops. (A) Photograph of polymictic intermediate breccia at Kuttaphet reservoir. (B) Photograph of polymictic intermediate breccia at Khok Khli railway station.

3.2.5 Unit V: Kuttaphet Sandstone

Unit V is mapped as Phu Kradung Formation by DMR (Nakornsri, 1977; Vimuktanandana and Thiyaphairach, 2007). It is identified as non-marine clastic sedimentary rocks. It is distributed from the northeast and east of the area parallel with the north-south trending of Khao Phang Hoei mountain (Fig. 3.1). It is extending in the north-south direction from Ban Pa Mai Sap Langka (in the north) to Khok Khli railway station (in the south). This unit's general strike is slightly northeast-southwest, and they are sub-horizontal dipping to the east (about 5 to 10 degrees). Based on field information, the rocks are described below.

Polymictic conglomerate exposes in a narrow area between the volcanics at the Khok Khli station and the eastward extending of fine-grained sandstone. This unit's polymictic rock is characterized by multi clast types (e.g., andesite and mudstone) surrounded by a white sandy matrix cemented by calcium carbonate.

Coarse-grained sandstone exposes on the surface in the northward from fine-grained sandstone. The outcrop of coarse-grained sandstone shows that a bed of sandstone is almost horizontal dipping (Fig. 3.11A). Coarse-grained sandstone is pale red to brown with calcium carbonate cemented. The rock is well sorted. The grain size is ranged from medium- to coarse- sand (Fig. 3.11B). Petrographically, coarse-grained sandstone has grain size of 0.2-0.4 mm. It is grain supported. Its grain is sub-rounded to rounded. There are 65% quartz, 25% lithic, and 10% feldspar in composition (Fig. 3.11C). Lithic or rock fragments in coarse-grained sandstone can be identified as volcanic rock fragments. Coarse-grained sandstone can be classified as litharenite on the sandstone classification of Folk (1980).

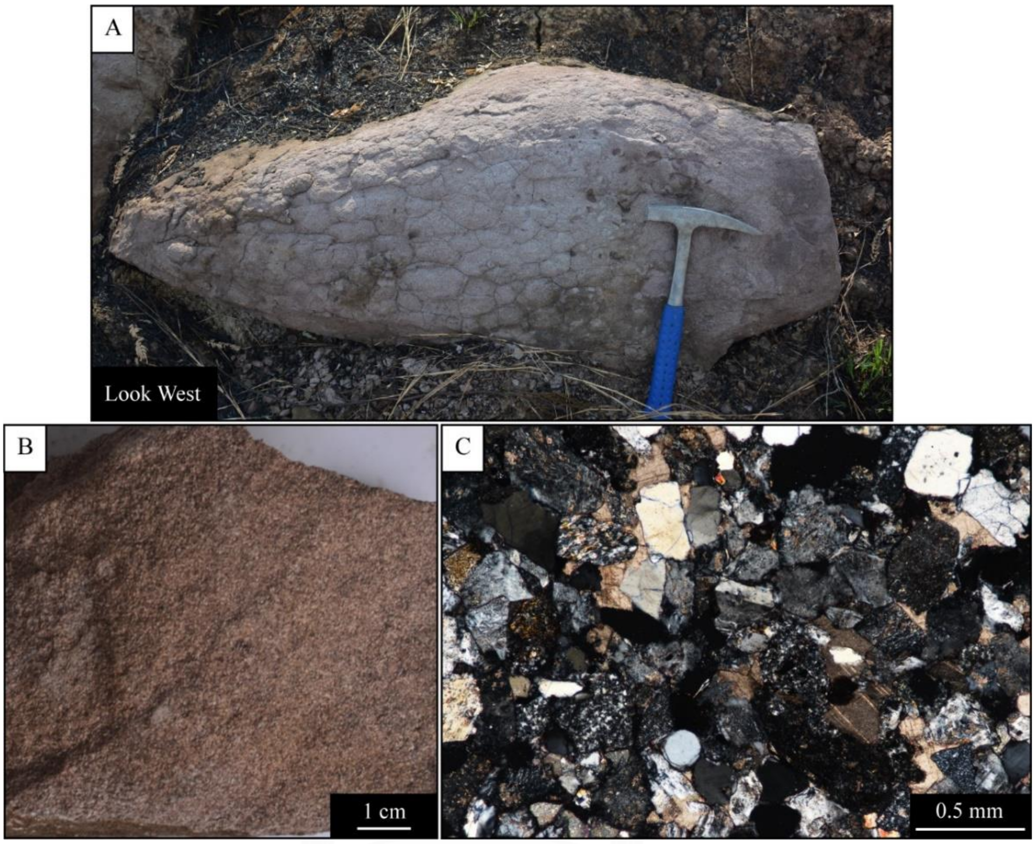

Fig. 3.11 Characteristic of coarse-grained sandstone. (A) Photograph of sandstone outcrop. (B) Photograph of sandstone hand specimen. (C) Photomicrograph of coarse-grained sandstone.

Fine-grained sandstone exposes on the surface in the north of the area closes to Ban Kuttaphet. The outcrop of fine-grained sandstone shows that a sandstone bed is almost horizontal dipping (Fig. 3.12A). The fine-grained sandstone is grey to dark-grey and well sorted. Its grain size ranges from fine to medium sand (Fig. 3.12B). Petrographically, sandstone has a grain size of 0.1-0.3 mm. It is grain supported. Its grain shape is angular to sub-angular. There are 70% quartz, 25% lithic, and 5% feldspar in composition. The other accessory minerals are biotite grains (Fig. 3.12C). Fine-grained sandstone can be classified as litharenite sandstone on the sandstone classification of Folk (1980).

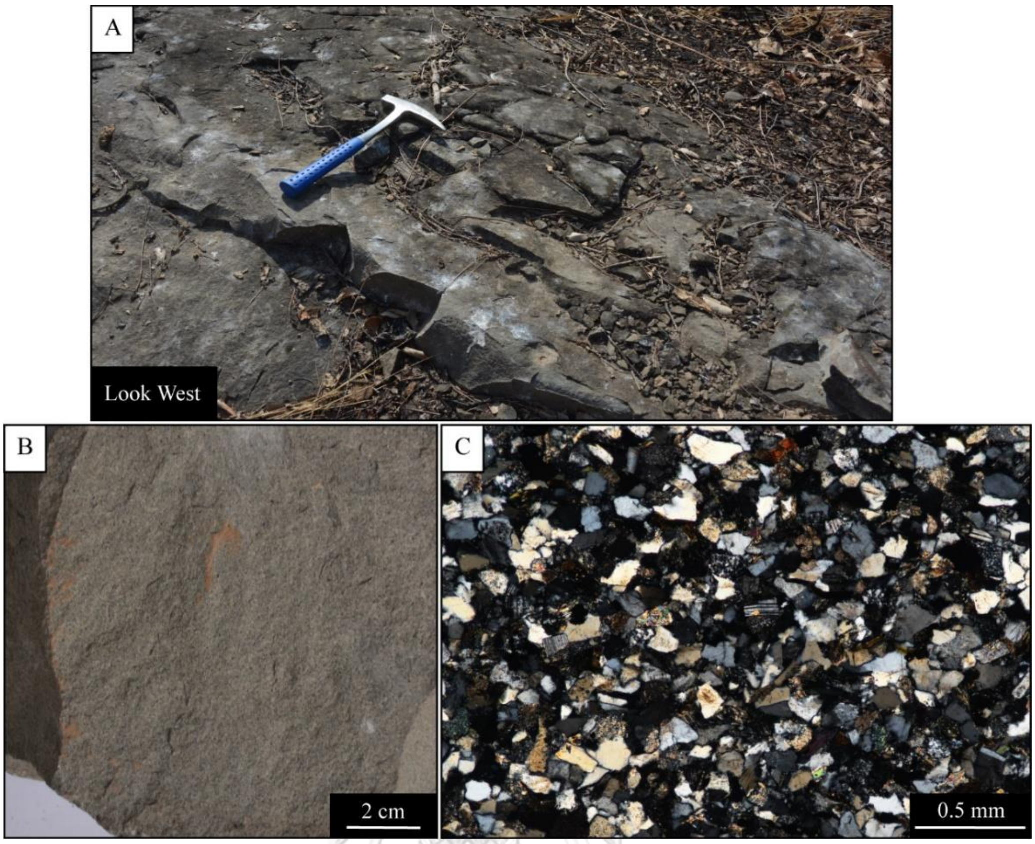

Fig. 3.12 Characteristic of fine-grained sandstone. (A) Photograph of sandstone outcrop. (B) Photograph of sandstone hand specimen. (C) Photomicrograph of fine-grained sandstone.

3.2.6 Igneous rock

Microdiorite intruded the Khao Ruak roadcut section (Fig.3.13A and B). The body of rock is about 5x11 m2. Microdiorite is greenish grey with phaneritic texture (Fig. 3.13C). Under microscope, it composes mainly plagioclase and chlorite. The plagioclase laths are euhedral to subhedral. The laths ranged from 0.2 - 05 mm (Fig. 3.13D).

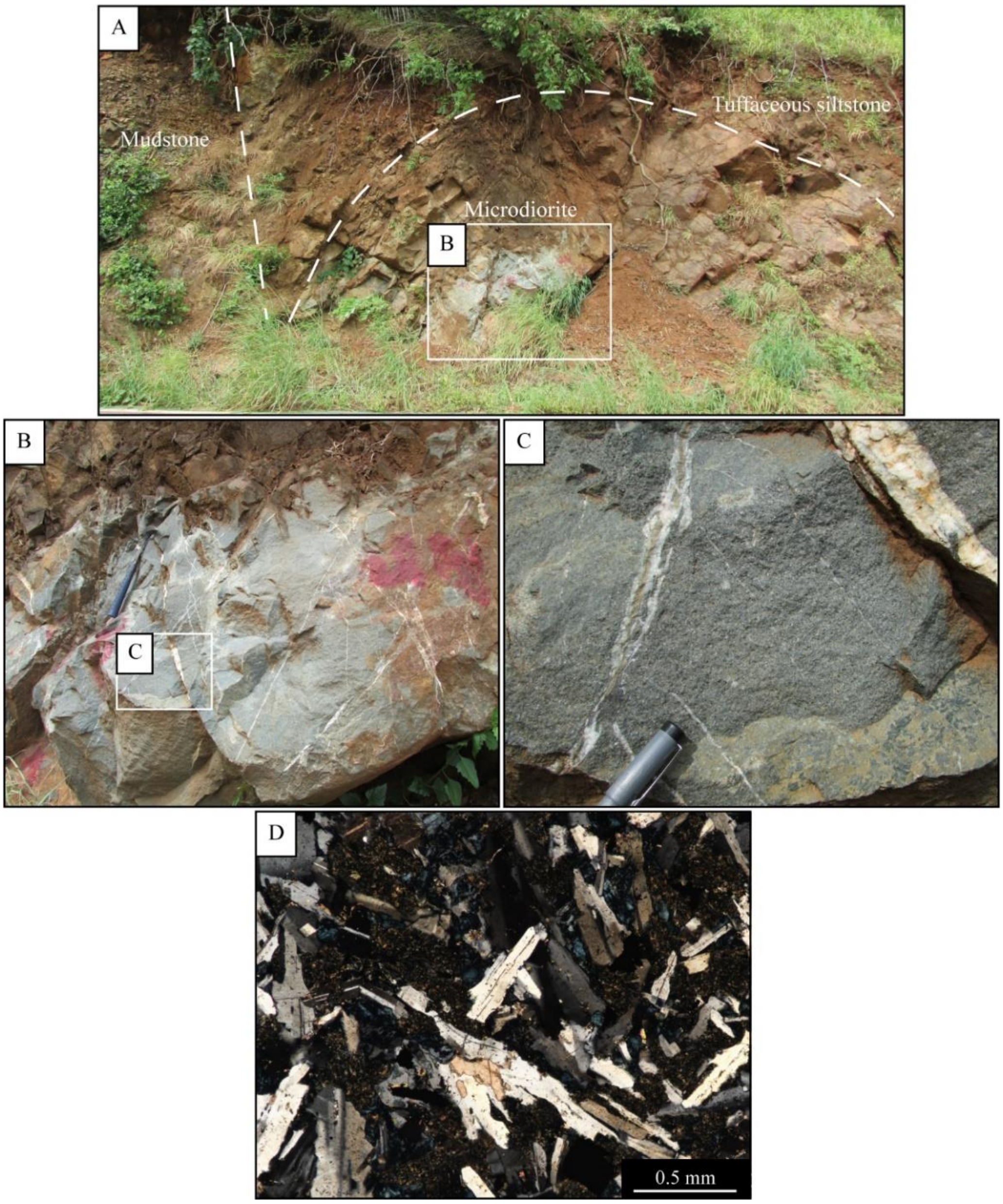

Fig. 3.13 Characteristic of microdiorite. (A) Photograph of Khao Ruak roadcut section showing intrusive body at the bottom of the section. (B) Photograph of microdiorite zoomed up. (C) Photograph of microdiorite zoomed up showing fine-grained texture. (D) Photomicrograph of microdiorite.

3.3 Stratigraphy of Khok Khli section

This part provides detailed volcanic stratigraphy of the Khok Khli section, which is best exposed at the Khok Khli railway station (Fig. 3.1). The rocks exposed in the east-west section about 1.1 kilometers long of the road cut. The section varies in thickness from 1-7 meters in height from the best of the drainage system. The composite stratigraphic section is estimated at 65 meters thick (Fig. 3.14).

Based on detailed observation, this volcanics sequence could be further sub-divided into three units from bottom to top, including Unit A: lithic-rich andesitic sandstone, Unit B: crystal-rich andesitic sandstone, and Unit C: polymictic intermediate breccia (Fig. 3.14). On the top of the Khok Khli volcanic sequence, it has sharp contact with Kuttaphet sandstone (Unit V), including polymictic conglomerate (possible basal conglomerate) and sandstone (Fig. 3.15). The descriptions of volcanics here are based on the definition of McPhie et al. (1993).

Fig. 3.14 Photograph of a part of the east-west Khok Khli volcanics section. Photo Looking north.

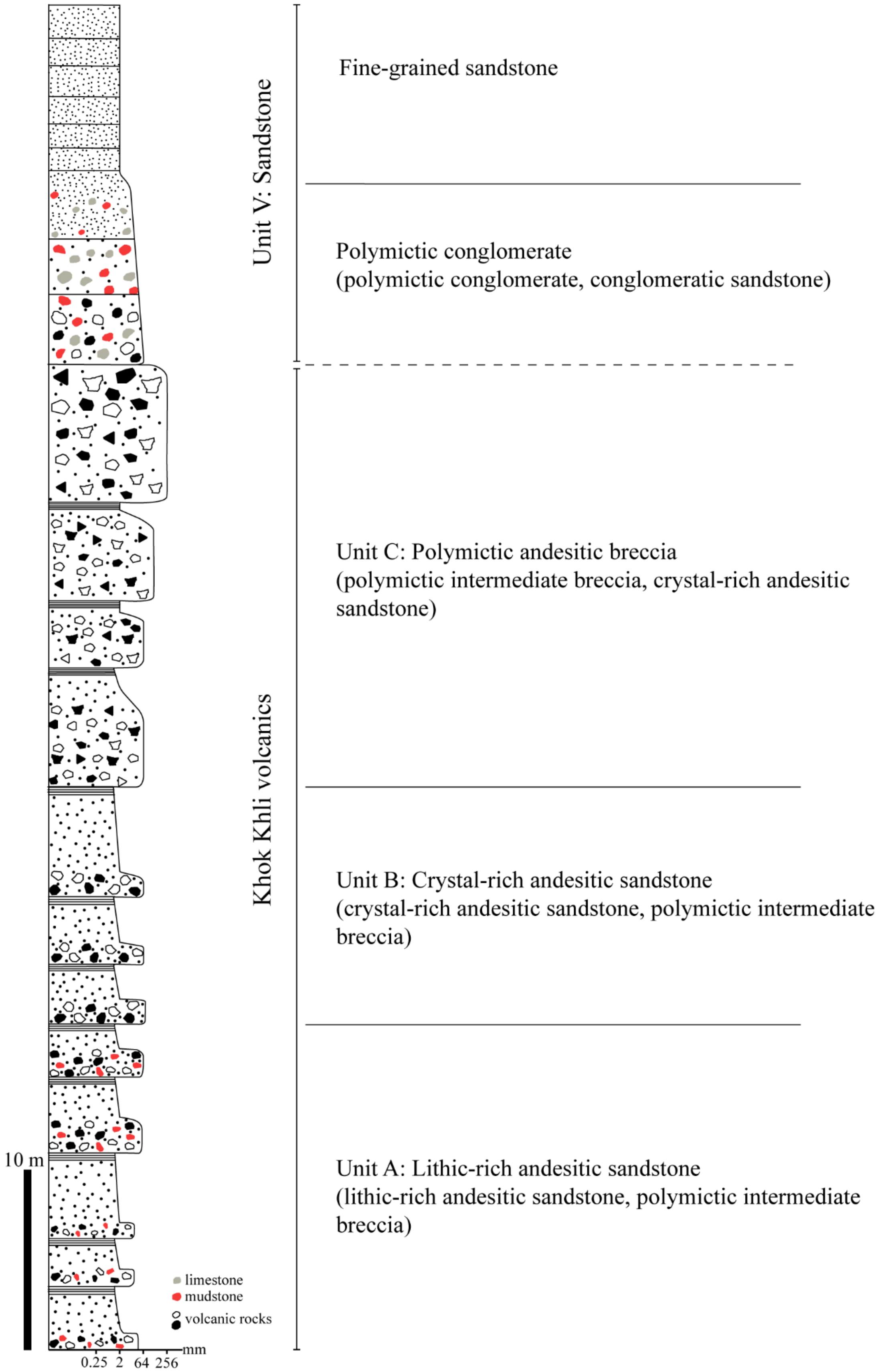

Fig. 3.15 Simplified composite stratigraphic column of Khok Khli section.

3.3.1 Unit A: lithic-rich andesitic sandstone

Unit A is the lowest unit of the Khok Khli section. Its thickness is about 15 meters, and it consists dominantly of lithic-rich andesitic sandstone and polymictic intermediate breccia. In the field, the lithic-rich andesitic sandstone is interbedded with polymictic intermediate breccia. This sandstone is pale red to purple, showing lamination (Fig. 3.16A) and occasionally shows graded bedding. It is medium- to coarse-grained sand-sized particles composing of quartz, feldspar, and rock fragments (Fig. 3.16B). The rock fragments include andesite angular to sub-angular shape and ranging in size from 0.3-1 mm (Fig. 3.16C). Under the microscope, the fine-grained matrix makes up of quartz, feldspar, and devitrified glass.

Polymictic breccia is a pale red to purple. It has matrix-supported with granule to pebble clasts size ranging from 0.3-2 cm (Fig. 3.17A). Most clasts are andesite, which has a sub-angular to sub-rounded shape and likely imbrication features (Fig. 3.17A). Mudstone clasts are present in small amounts but become an important characteristic feature of this unit. The clasts are surrounded by a fine-grained matrix, which is generally purplish-brown color. The matrix consists of feldspar, minor quartz, and fine andesite fragments (Fig. 3.17B).

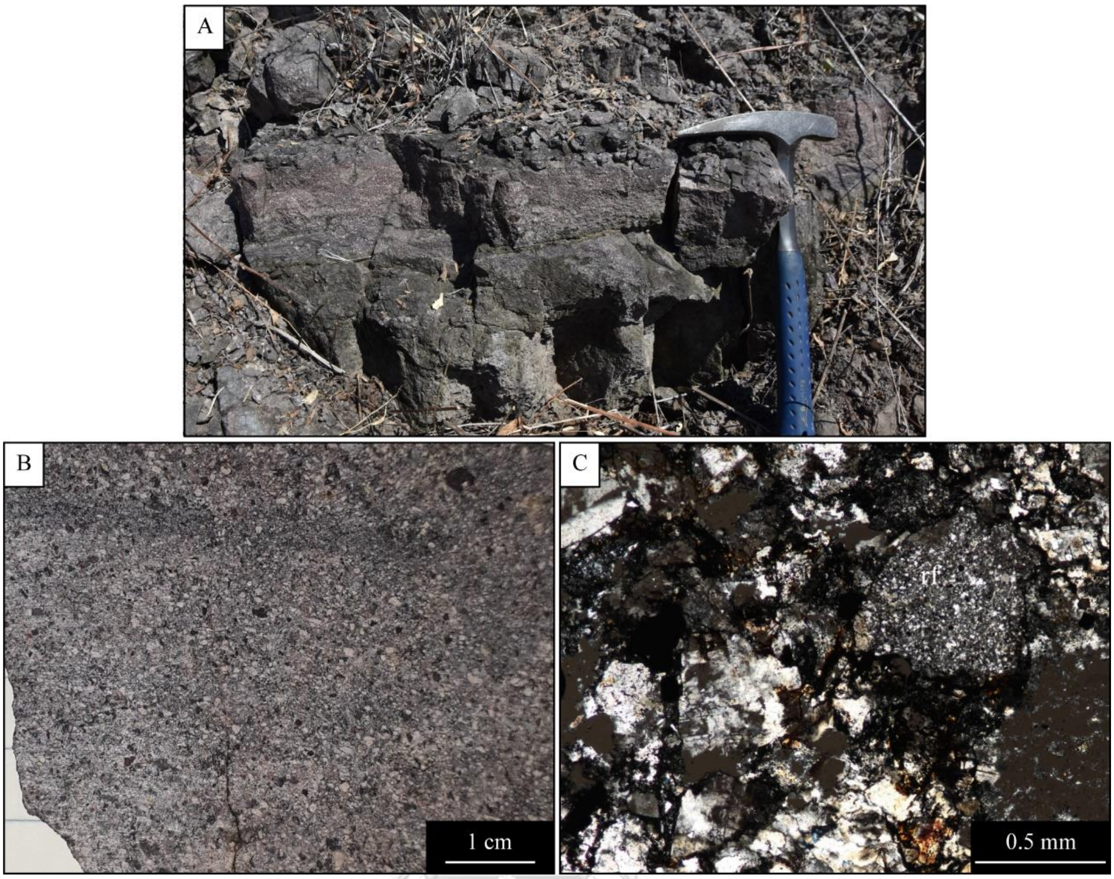

Fig. 3.16 Characteristic of lithic-rich andesitic sandstone unit. **(A)** Photograph of lithic-rich andesitic sandstone outcrop interbedded with polymictic intermediate breccia. **(B)** Photograph of lithic-rich andesitic sandstone showing grained size variation defining its bedding. **(C)** Photomicrograph of lithic-rich andesitic sandstone showing andesite rock fragment (top right corner) surrounded by feldspar rich portion (bottom left corner) sample coating by dark brown iron oxide. Abbreviation; rf=Rock fragment.

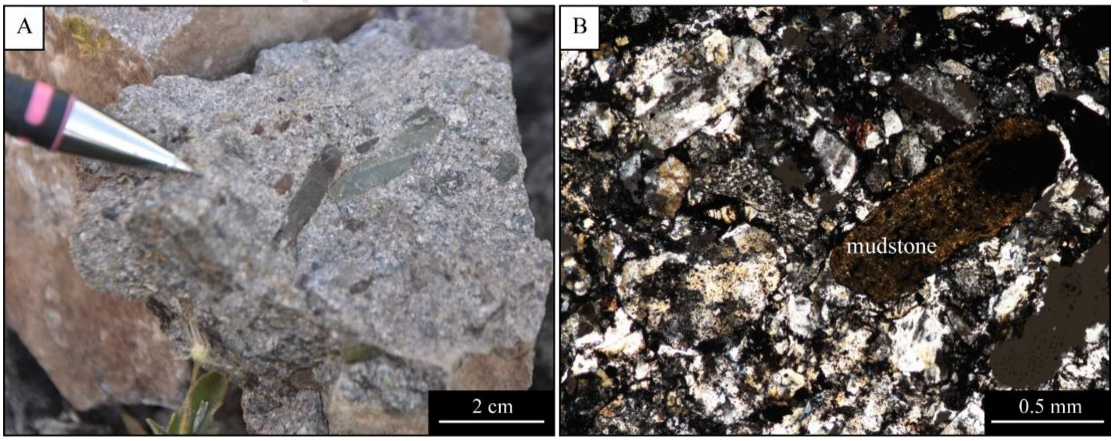

Fig. 3.17 Characteristic of lithic-rich andesitic sandstone unit. (A) Photograph of polymictic intermediate breccia showing mudstone clasts (some tabular shaped) in sandy matrix. (B) Photomicrograph of polymictic intermediate breccia showing mudstone clast surrounded by feldspar rich portion.

3.3.2 Unit B: Crystal-rich andesitic sandstone

Unit B is gradationally overlying on lithic-rich volcanic sandstone units. Its thickness is about 10 meters. This unit is composed dominantly of crystal-rich andesitic sandstone interbedded with polymictic intermediate breccia (Fig. 3.18). Crystal-rich andesitic sandstone is purplish-brown. It is characterized by fine- to medium-grained sand size (Fig. 3.18A). Under the microscope, the laminations of a rock show dark layers interbedded with thicker light layers which the grain size of dark layers is finer but the same composition (Fig. 3.18C). The crystal-rich andesitic sandstone consists of fine-grained plagioclase crystals, glass materials, and trace hornblendes. The plagioclase is euhedral to subhedral and ranges from 0.1-0.3 mm. The hornblende is euhedral to subhedral and ranges from 0.1-0.2 mm (Fig. 3.18D).

In the field, polymictic intermediate breccia is matrix-supported and interbedded with the crystal-rich andesitic sandstone. Clast size ranges from 8-10 cm. The clasts have a sub-angular to sub-rounded shape. They can be identified as porphyritic andesite (Fig. 3.18B).

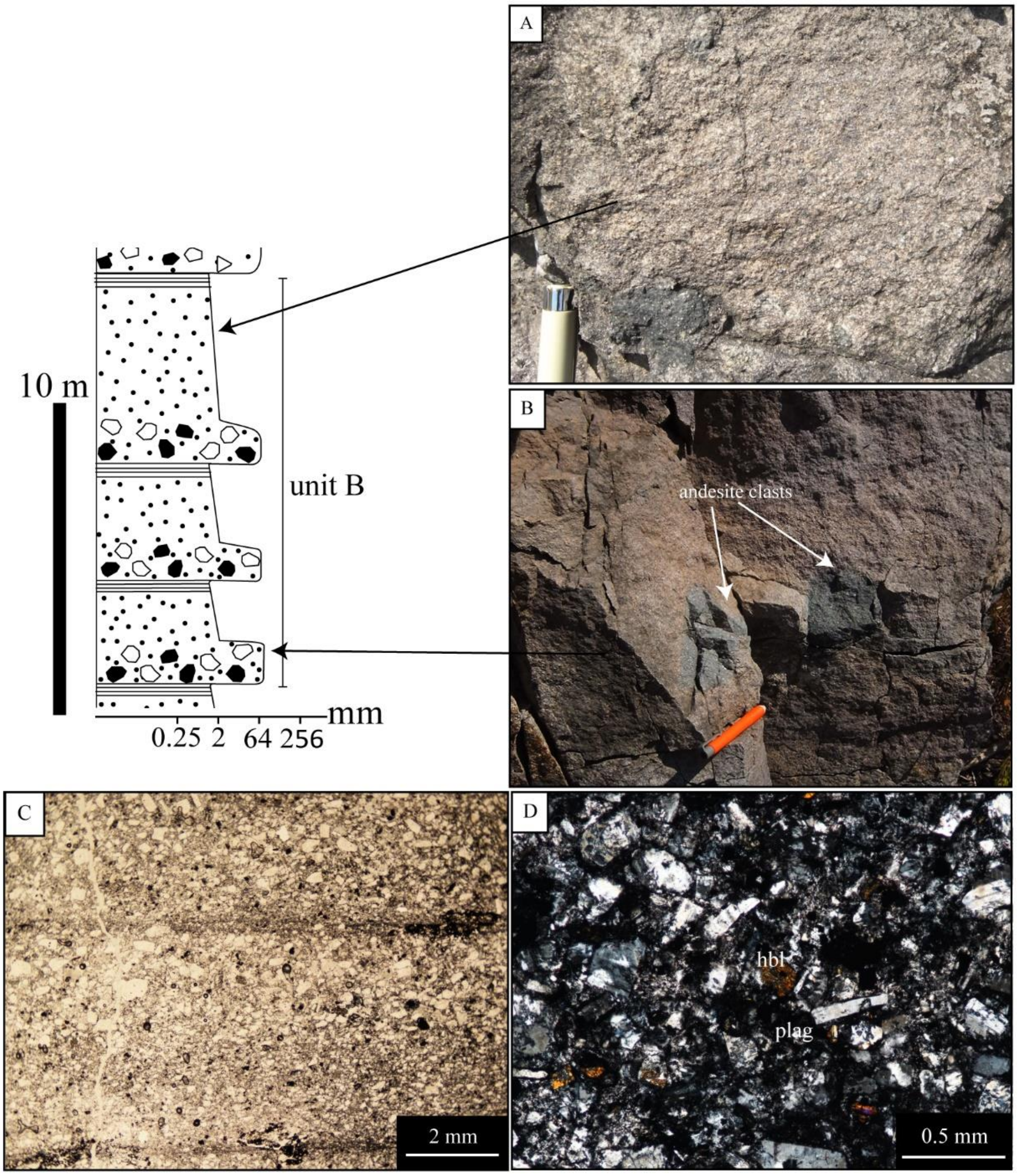

Fig. 3.18 Characteristic of crystal-rich andesitic sandstone unit. (A) Photograph of crystal-rich andesitic sandstone (B) Photograph of crystal-rich volcanic sandstone containing large clasts. (C) Photomicrograph of crystal-rich andesitic sandstone showing variation of grained size indicating lamination. (D) Photomicrograph of andesitic sandstone showing fine-grained of plagioclase crystals and hornblende. Abbreviation; hbl=Hornblende, plag=Plagioclase.

3.3.3 Unit C: Polymictic intermediate breccia

Unit C is the uppermost unit of the Khok Khli volcanic sequence (Fig. 3.19). It has a sharp contact with underlying crystal-rich andesitic sandstone. The total thickness of this unit is about 20 meters. It is characterized by thick to very thick polymictic intermediate breccia beds, particularly at the upper part of the sequence. At the lower part, it is interbedded with thin to medium beds of crystal-rich andesitic sandstone. The relationships can be observed on the western side of the section.

At the upper part of the unit, polymictic intermediate breccia is clast-supported. Clasts are pebble to boulder size ranging from 4-25 cm, angular to subangular, and clasts are poorly sorted (Fig. 3.19A). Clast consists of plagioclase andesite, hornblende-plagioclase andesite, pyroxene-plagioclase basaltic andesite.

These clasts are surrounded by a purplish-brown matrix, which is the sand size and consists of feldspar (Fig. 3.20A and B). Under the microscope, the matrix consists mainly of plagioclase, hornblende, and glass. Plagioclase grains are subhedral with their sizes are 0.1-0.5 mm. The clasts are of andesitic composition, which shows a porphyritic texture. Their phenocrysts are fine-grained feldspar which grain sizes are 0.1-0.5 mm, and are surrounded by fine-grained groundmass (Fig. 3.20C and D).

The crystal-rich andesitic sandstone that interbedded with polymictic intermediate breccia shows lamination (Fig. 3.19B). This laminated andesitic sandstone has a similar mineral composition as the crystal-rich andesitic sandstone of unit B. In addition, at the lower part of unit C, the polymictic intermediate breccia tends to have a smaller class size in comparison to the upper part. Here clasts are pebble to cobble in size ranging from 4-8 cm (Fig. 3.19C).

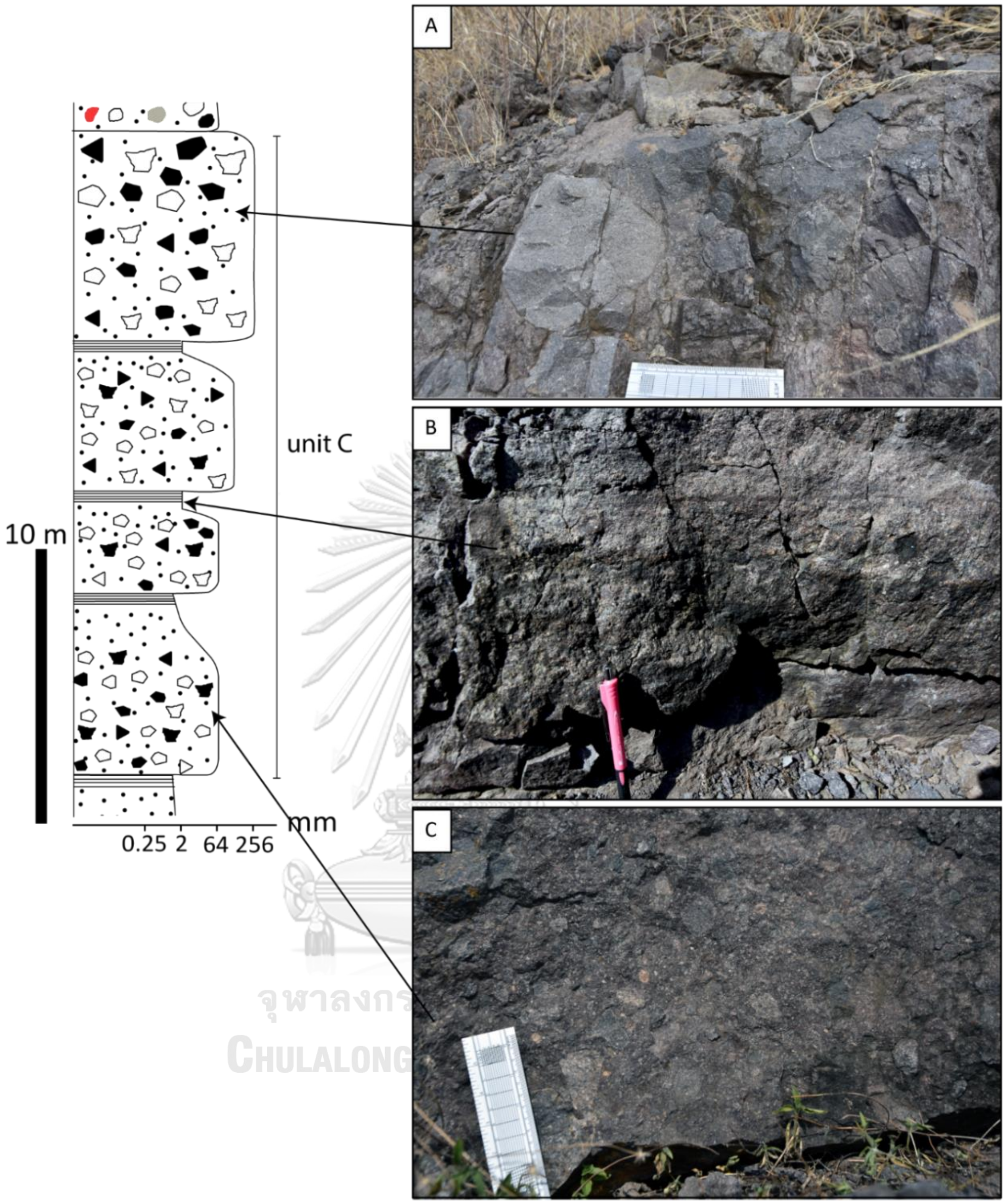

Fig. 3.19 Characteristic of polymictic intermediate breccia unit. (A) Photograph of polymictic intermediate breccia outcrop in the upper part of the unit. (B) Photograph of crytal-rich andesitic sandstone. (C) Photograph of polymictic intermediate breccia in the lower part of the unit.

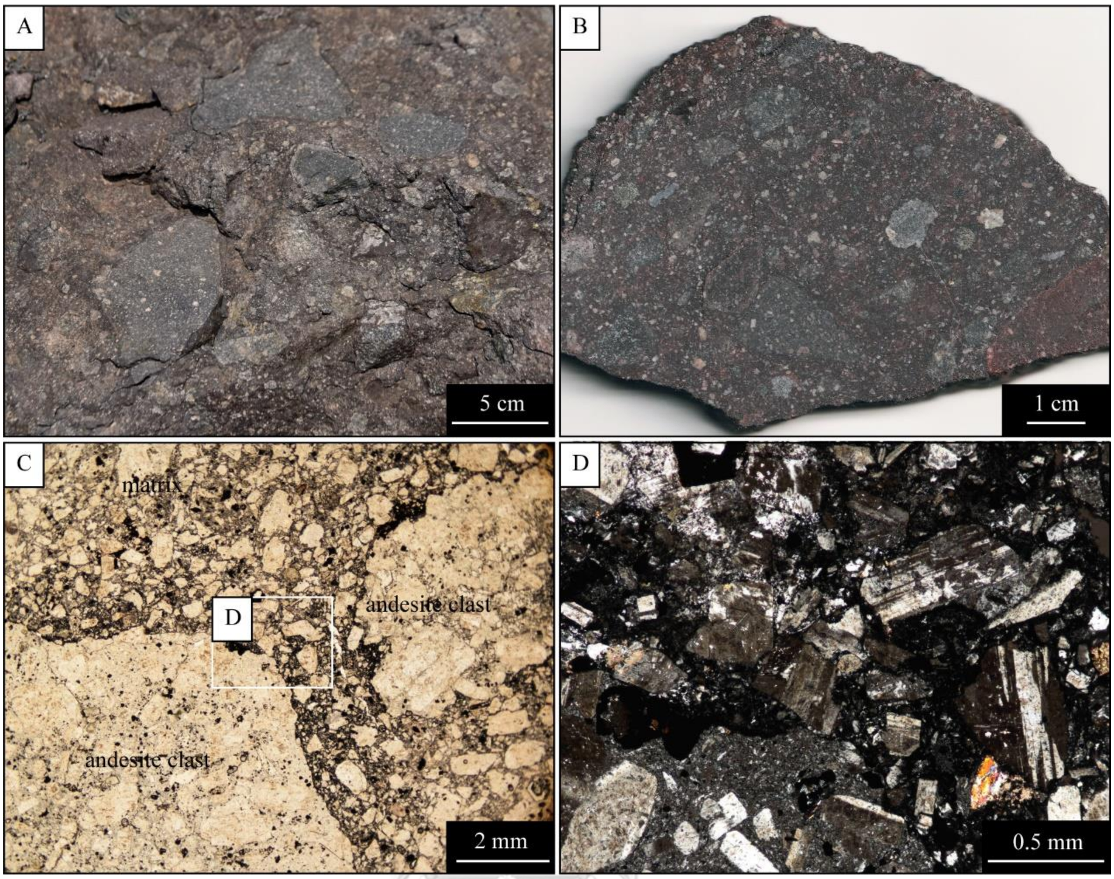

Fig. 3.20 Characteristic of polymictic intermediate breccia unit. (A) Photograph of outcrop-scale showing large clasts sitting in matrix of similar composition. Note matrix of purplish brown color (B) Photograph of rock slab-cut showing subangular to subrounded andesite and basaltic andesite clasts in purplish brown color matrix showing in Fig. A. (C) Photomicrograph of polymictic intermediate breccia showing small andesite clasts sitting in matrix laying between large clasts. (D) Photomicrograph from area given in Fig. C showing matrix containing feldspar (mostly plagioclases) and hornblende and small rock fragments.

The uppermost of polymictic intermediate breccia is the sharp contact between volcanic breccia (Unit C) and clastic sedimentary rocks (Unit V). The polymictic conglomerate is observed to be eastward extending. It is characterized by clasts mixed with different rocks such as porphyritic andesite, mudstone, and limestone, which are surrounded by a sandy matrix cemented by carbonate (Fig. 3.21).

Fig. 3.21 The contact between Khok Khli volcanics and clastic sedimentary rocks. (A) Photograph of contact between polymictic volcanic breccia and polymictic conglomerate. (B) Photograph of andesite clast of polymictic intermediate breccia unit. (C) Photograph of polymictic conglomerate showing porphyritic andesite and clastic rocks as clasts.

3.3.4 Clastic sedimentary rocks (Unit V)

The clastic sedimentary rocks are excluded from the Khok Khli volcanics. They are part of Kuttaphet sandstone (Unit V). They overlie the volcanic sequence with sharp contact. The clastic sedimentary rocks at this section compose of polymictic conglomerate, conglomeratic sandstone, and coarse-grained sandstone. The thickness of this unit is about 25 meters. At the lower part, the polymictic conglomerate is clast-supported. Clasts compose of porphyritic andesite, mudstone, and limestone (Fig. 3.22B). However, in the upper part of the unit, it is clast-supported and becomes conglomeratic sandstone. Volcanics fragments seem to absent in the upper part (Fig. 3.22A). This polymictic conglomerate is considered as a basal conglomerate of Khorat Group that is dominantly overlain by light brown fine-grained sandstone.

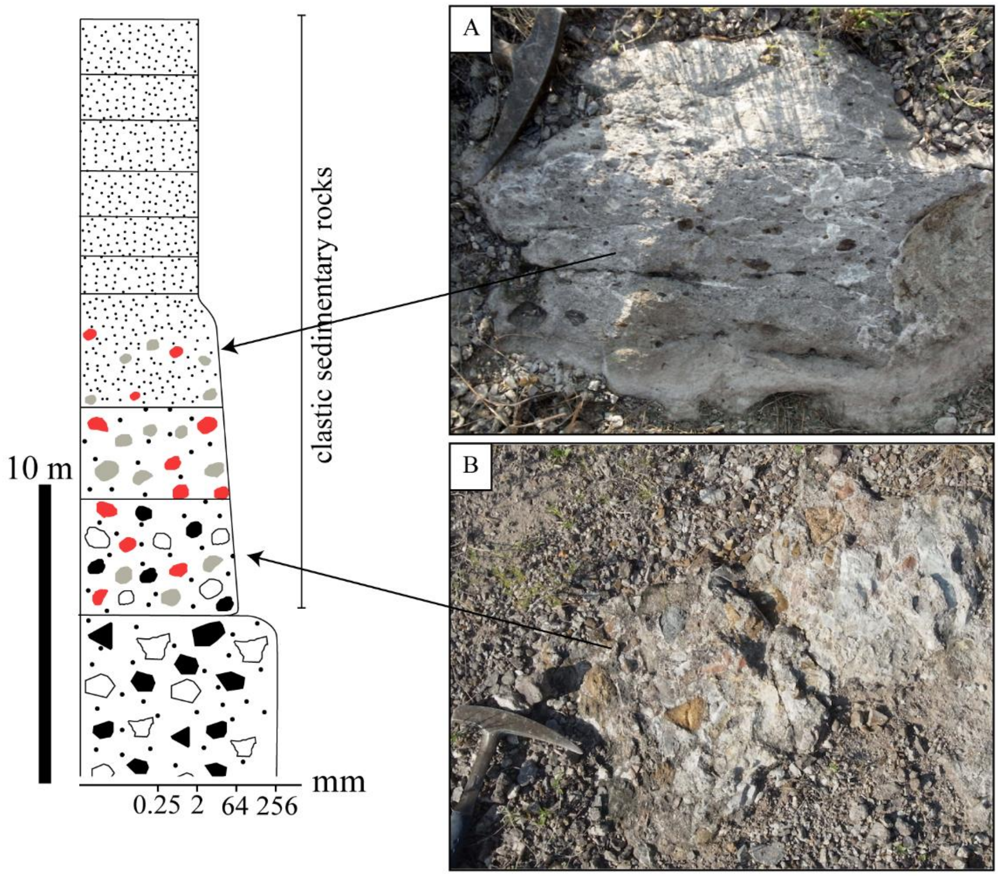

Fig. 3.22 Characteristic of clastic sedimentary rock unit. (A) Photograph of conglomeratic sandstone. (B) Photograph of polymictic conglomerate.

Chapter 4
Petrography of volcanic rocks

4.1 Introduction

This chapter details the petrographic descriptions of volcanic rocks in the Lam Sonthi area focused on volcanic rocks for further geochemical study. This study includes field classification, and representative samples were selected for petrographic investigation. The study has focused on Unit III (Khao Ruak volcanics) and Unit IV (Kuttaphet volcanics and Khok Khli volcanics), where there are suitable lava and breccia clasts suitable for whole-rock geochemistry study.

4.2 Petrography of volcanic rocks

4.2.1 Khao Ruak volcanics

The Khao Ruak volcanics (Unit III) comprise of pyroxene-plagioclase andesite, andesitic breccia, hornblende andesitic breccia, and crystal-rich andesitic sandstone (see chapter 3). Pyroxene-plagioclase andesite (lava) and clasts of andesitic breccia were selected for a detailed petrographic study. In this study, the pyroxene-plagioclase andesite (lava) and larger clasts of andesitic breccia were used for petrochemistry analyses, and the details are given below:

Pyroxene-plagioclase andesite

Pyroxene-plagioclase andesite (lava) cropped out in the eastern side of Khao Ruak mountains at Ban Nong Pradu To, Ban Khao Din, and Ban Chong Ko (Fig. 3.1). The rock is greenish-grey to dark grey, porphyritic texture containing about 10-20% phenocrysts of feldspars and mafic minerals setting in the finer-grained groundmass (Fig. 4.1A and B). Under the microscope, the phenocrysts of pyroxene-plagioclase andesite are plagioclase, pyroxene (mostly clinopyroxene), and hornblende. The grain size of plagioclase can be varying from 0.4 to 1.5 mm and predominantly of euhedral crystal shape. Pyroxene phenocrysts have grain sizes ranging from 0.3-1 mm. They show euhedral to subhedral crystal shape. A few samples display hornblende phenocryst, which shows euhedral to subhedral crystal shape. Their grain size is ranging from 0.5-1 mm. The groundmass dominantly consists of fine-grained (<1 mm), acicular plagioclase crystal (Fig. 4.1C).

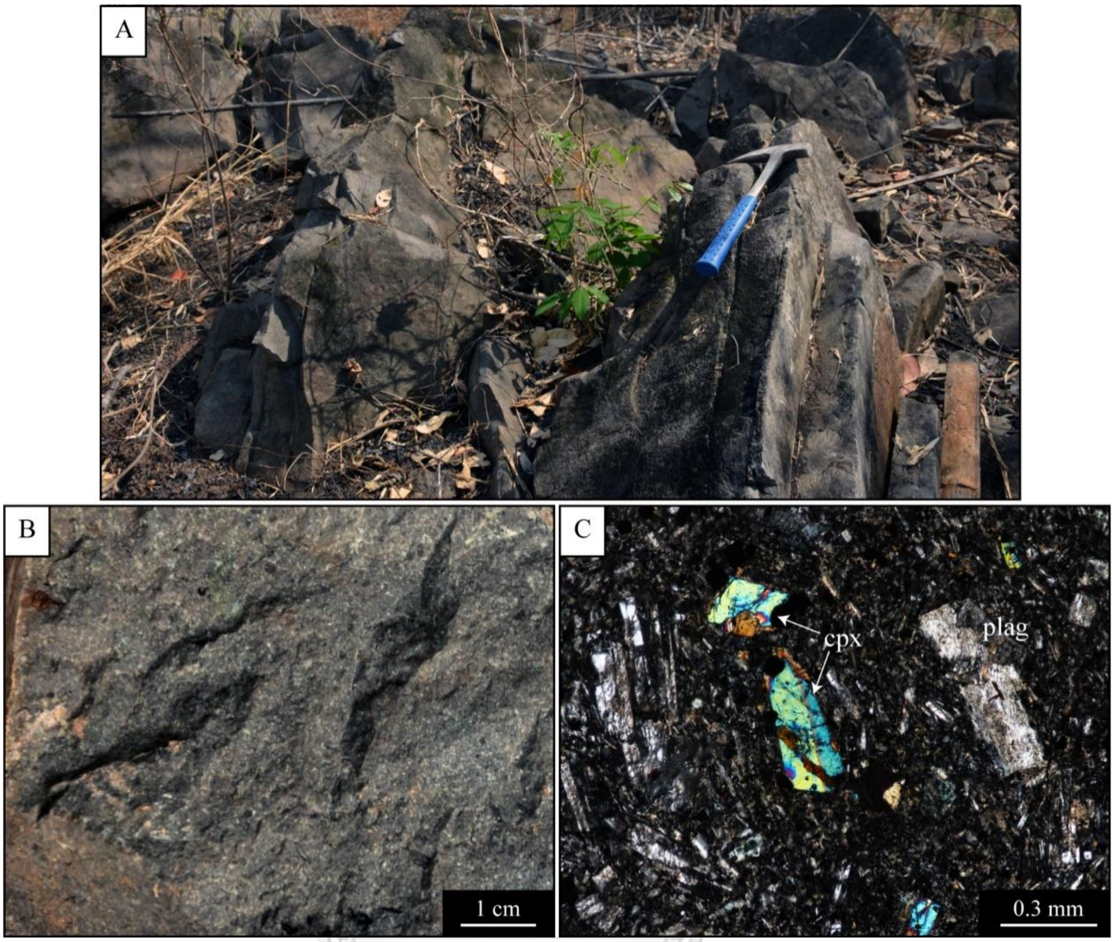

Fig. 4.1 Characteristic of pyroxene-plagioclase andesite. (A) Photograph of an outcrop of andesite. (B) Photograph of andesite showing phenocrysts of mafic minerals (pyroxene) in dark grey groundmass. (C) Photomicrograph showing plagioclase and clinopyroxene phenocrysts in fine-grained groundmass of similar composition. Abbreviation; cpx = Clinopyroxene, plag = Plagioclase.

The pyroxene-plagioclase andesite consists of both as lava and clasts (clast of andesitic breccia). The andesitic breccia clasts are dark grey to grey and are typically characterized by porphyritic texture. Clasts are sub-angular to sub-rounded ranging in size from 10-20 cm (Fig. 4.2A). These pyroxene-plagioclase andesite clasts constitute about 20-25% phenocrysts mainly of feldspar and mafic mineral phenocrysts (pyroxene and hornblende) setting in a finer-grained groundmass (Fig. 4.2B). Under the microscope, the pyroxene phenocrysts were confirmed as mostly clinopyroxene. Most phenocrysts have been identified as plagioclase and ranging in size from 0.5-1 mm and euhedral to subhedral crystal shape. Clinopyroxene phenocrysts are ranging from 0.1-0.3 mm and show subhedral crystal shape. Under the microscope, the rock displays a seriate texture (Fig. 4.2C).

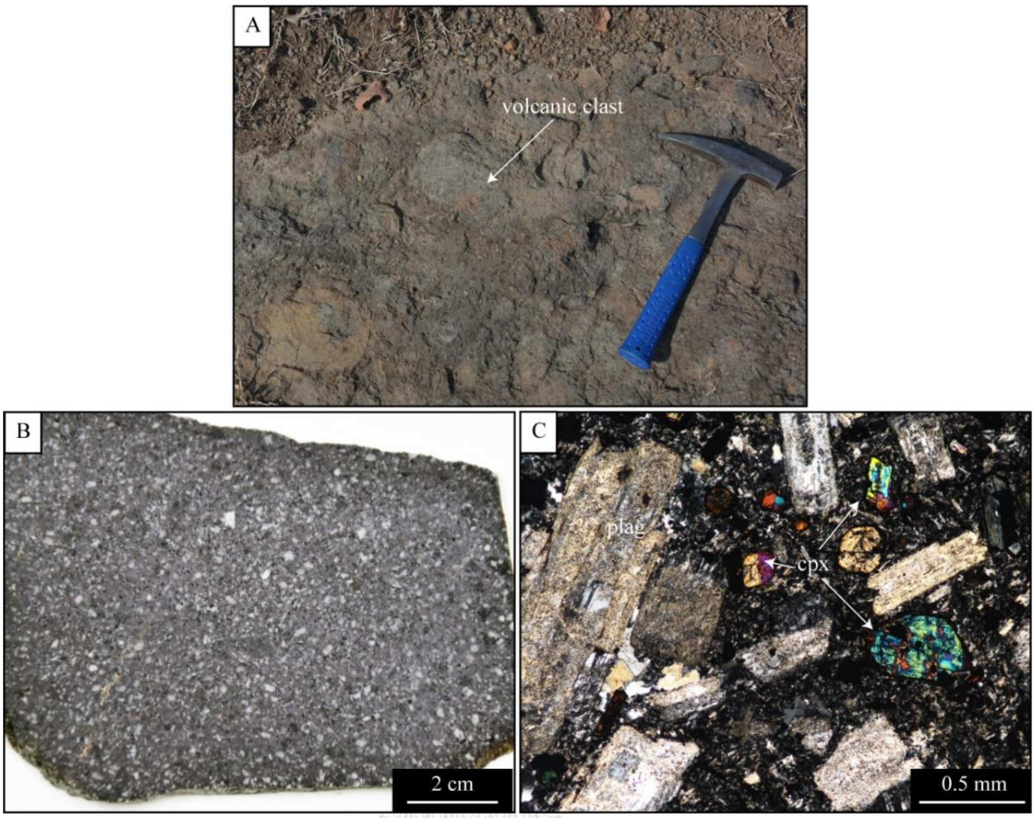

Fig. 4.2 Characteristic of a clast of andesitic breccia. (A) photograph of an outcrop of andesitic breccia showing andesite sub-angular clasts in dark grey matrix. (B) Photograph of a large andesite clast showing a typical andesite texture in which phenocrysts of feldspars and mafic minerals sitting in finer groundmass. (C) Photomicrograph of andesite showing clinopyroxene and plagioclase phenocrysts are surrounded by fine-grained groundmass. Abbreviation; cpx=Clinopyroxene, plag= Plagioclase.

4.2.2 Kuttaphet volcanics

The rocks of Kuttaphet volcanics are characterized by polymictic intermediate breccia (see chapter 3), and samples were collected from outcrop (Fig. 3.1). For petrochemistry study, larger clasts of plagioclase andesite and pyroxene-plagioclase andesite were selected. Detailed petrography description for each rock types are provided below:

Plagioclase andesite

Plagioclase andesite clasts of polymictic intermediate breccia is pinkish grey to grey containing 10-20% phenocrysts setting in the finer-grained groundmass. Phenocrysts predominantly consist of feldspars (Fig. 4.3A). Under the microscope, the phenocrysts of plagioclase andesite are mainly plagioclase with a few of quartz and opaque mineral. Plagioclase phenocrysts are ranging from 0.2-0.5 mm. They show euhedral to subhedral crystal shape. The phenocrysts are surrounded by fine-grained groundmass, which shows seriate texture (Fig. 4.3B).

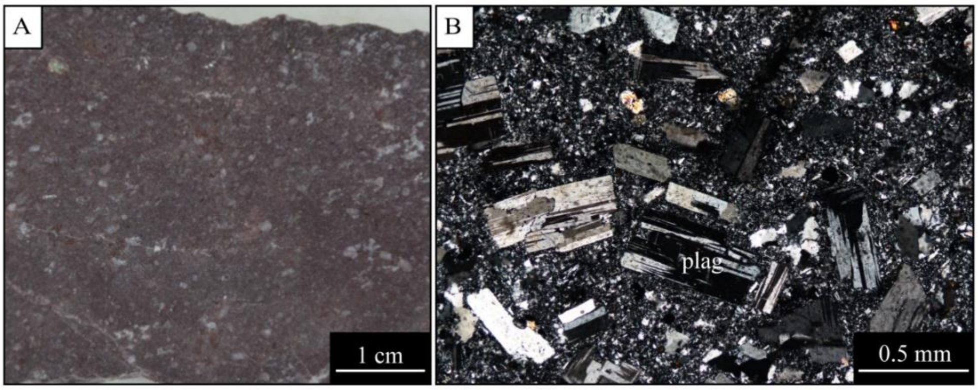

Fig. 4.3 Characteristic of plagioclase andesite clast. (A) Photograph of andesite showing feldspar phyric in pinkish grey groundmass. (B) Photomicrograph of plagioclase andesite showing plagioclase phenocrysts in fine-grained groundmass. Abbreviation; plag=plagioclase.

Pyroxene-plagioclase andesite

Pyroxene-plagioclase andesite is the second type of polymictic intermediate breccia clasts found at the Kuttaphet reservoir. The rock is grey to dark grey, which contains 10-20% phenocrysts setting in the finer-grained groundmass. Phenocrysts dominantly consist of feldspars and mafic minerals (Fig. 4.4A). Under microscope, the phenocrysts of pyroxene-plagioclase andesite are mainly plagioclase and pyroxene (mostly clinopyroxene). Plagioclase phenocrysts are ranging from 0.2-0.8 mm. They show euhedral to subhedral crystal shape. Pyroxene phenocrysts have grain sizes ranging from 0.2-0.6 mm. they show euhedral to subhedral crystal shape. The groundmass dominantly consists of fine-grained, which shows seriate texture (Fig. 4.4B).

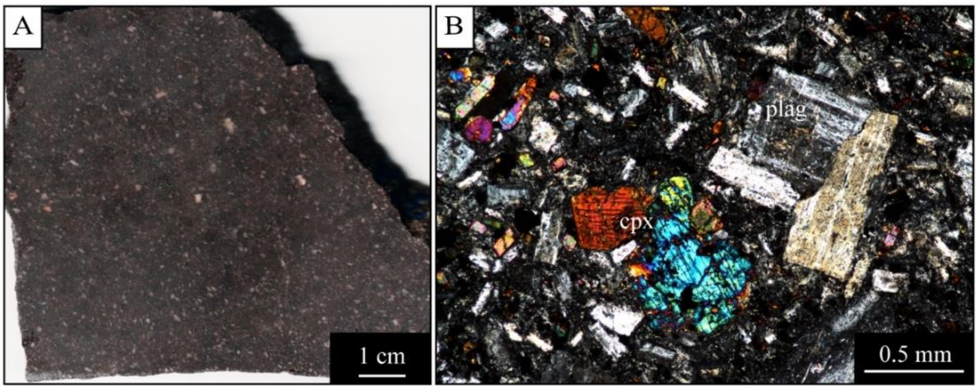

Fig. 4.4 Characteristic of pyroxene-plagioclase andesite clast. (A) Photograph of andesite showing feldspar and mafic minerals phenocrysts. (B) Photomicrograph of pyroxene-plagioclase andesite showing clinopyroxene and plagioclase phenocrysts are surrounded by fine-grained groundmass.

4.2.3 Khok Khli volcanics

Petrochemistry of Khok Khli volcanics is focussed on subunit C (polymictic intermediate breccia). This subunit has suitable clasts for petrography and whole-rock geochemistry study. At least two types of clasts have been identified namely, 1) plagioclase andesite and 2) hornblende-plagioclase andesite.

Plagioclase andesite

Plagioclase andesite clasts are pinkish grey to grey, containing 20-30% phenocrysts setting in finer-grained groundmass. Phenocrysts dominantly consist of feldspars with minor mafic minerals (mostly hornblende; Fig. 4.5A) Some feldspar phenocrysts can be up to 0.5 cm long, whereas hornblende phenocrysts can be up to 0.3 cm in diameter. Under microscope, the feldspar phenocrysts are mainly plagioclase and on the other hand mafic minerals are hornblende (Fig. 4.5B and C). Plagioclase phenocrysts are ranging from 1-5 mm. They are subhedral to euhedral crystal shape (Fig. 4.5B). Hornblende crystals are partly altered to chlorite especially in groundmass. Their grain size is ranging from 0.5-2 mm (Fig. 4.5C). The phenocrysts are surrounded by fine-grained groundmass which shows trachytic texture.

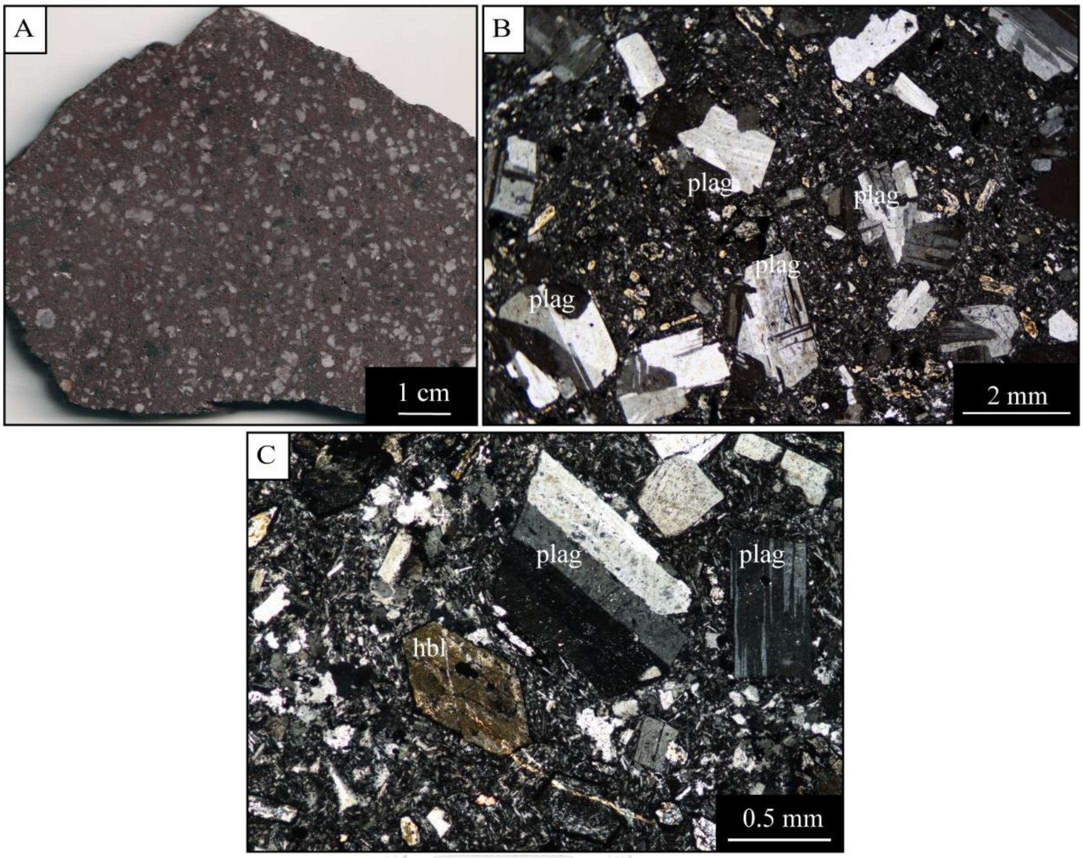

Fig. 4.5 Characteristic of plagioclase andesite clast. (A) Photograph of andesite showing feldspar and mafic minerals phenocryst in pinkish grey groundmass. (B) Photomicrograph of plagioclase andesite showing phenocrysts of plagioclase in fine-grained groundmass. (C) Photomicrograph of plagioclase andesite (B) zoomed up showing fine-grained groundmass surrounded plagioclase grains and a few hornblende grains are found. Abbreviation; plag=plagioclase, hbl=hornblende.

Hornblende-plagioclase andesite

Hornblende-plagioclase andesite is other clast of polymictic intermediate breccia which is selected from the Unit C of Khok Khli volcanics. The rock is pinkish grey to grey which contains 20-30% phenocrysts setting in finer-grained groundmass. Phenocrysts dominantly consist of feldspars and mafic minerals (Fig. 4.6A). Petrographically, the phenocrysts of hornblende-plagioclase andesite are plagioclase and hornblende. Additionally, pyroxene phenocrysts are found in a few samples. Plagioclase phenocrysts are ranging from 0.5-2 mm. They show euhedral to subhedral crystal shape. Hornblende phenocrysts have grain size ranging from 0.2-0.6 mm. they show euhedral to subhedral crystal shape (Fig. 4.6B). The groundmass dominantly consists of fine-grained, plagioclase acicular which shows trachytic texture (Fig. 4.6C).

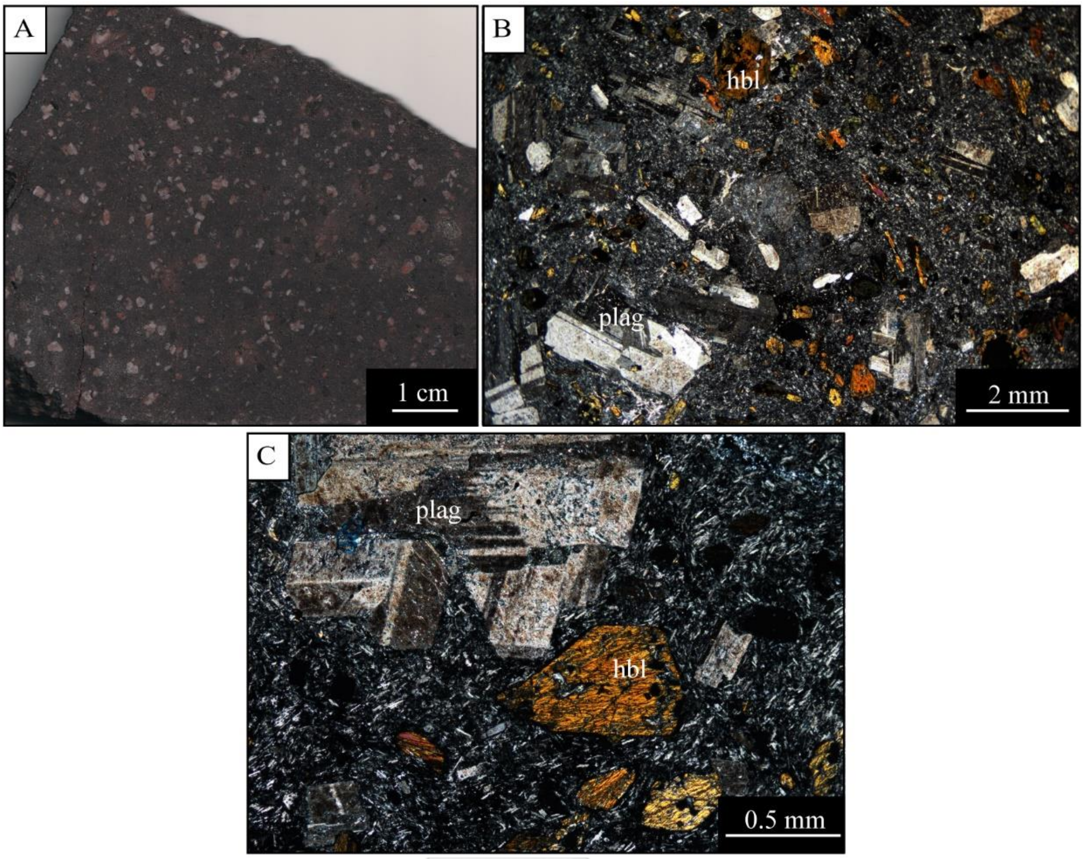

Fig. 4.6 Characteristic of hornblende-plagioclase andesite clast. (A) Photograph of andesite showing feldspar and mafic minerals phenocryst in pinkish grey groundmass. (B) Photomicrograph of hornblende-plagioclase andesite showing phenocrysts of plagioclase and hornblende in fine-grained groundmass. (C) Photomicrograph of hornblende-plagioclase andesite (B) zoomed up showing trachytic groundmass surrounded hornblende and plagioclase grains. Abbreviation; plag=plagioclase, hbl=hornblende.

Chapter 5
Geochemistry of volcanic rocks

5.1 Introduction

This chapter describes the geochemistry of the volcanic rocks in the Lam Sonthi area. There are major elements, trace elements, and rare earth elements analyzed to classify the magmatic group and determine the tectonic setting in the study area.

5.2 Sampling and analytical methods

5.2.1 Sampling

The least-altered volcanic rocks were collected from Khao Ruak volcanics (Unit III) and Lam Sonthi polymictic conglomerate (Unit IV). Samples of Khao Ruak volcanics consist of lava and large breccia clasts. For the Lam Sonthi polymictic conglomerate unit, only large clasts of Kuttaphet volcanics (LST02, LST03, LST04, LST05, LST07, LST08, LST09, LST10) and Khok Khli volcanics (LST22, LST23, LST24, LST25, LST26, LST27, LST31, LST32, LST33, LST34, LST35, LST37, LST38, LST39) (Fig. 5.1) were selected for whole-rock geochemical analysis. Besides, most clasts of Kuttaphet volcanics and Khok Khli volcanics selected for this study are larger than 10 cm in diameters.

Samples of volcanic rocks representing each rock type were selected and underwent a petrographic study to confirm their rock types. The Khao Ruak volcanics can be grouped into pyroxene-plagioclase andesite (lava) and pyroxene-plagioclase andesite (clast). For Kuttaphet volcanics, volcanic clasts include plagioclase andesite and pyroxene-plagioclase andesite, whereas Khok Khli volcanics consist of plagioclase andesite and hornblende-plagioclase andesite. A total of thirty-four samples were selected for XRF whole-rock analysis. They are twelve samples from Khao Ruak volcanics, eight samples from Kuttaphet volcanics, and fourteen samples from Khok Khli volcanics. The nine samples out of thirty-four samples were further analyzed for trace elements and rare earth elements using ICP-MS which are three samples from Khao Ruak volcanics, three samples from Kuttaphet volcanics, and three samples from Khok Khli volcanics.

5.2.2 Analytical method

The major elements were measured from fused discs. In preparation for fused discs, samples were first pulverized by a disc mill to clay size at the Geology Department, Chulalongkorn University. Loss on ignition was determined by heating 1 or 2 grams of sample in a high-temperature furnace at 1,000◦ C for 12 hours and reweighting the samples at the Department of Mineral Resources (DMR). Then samples were mixed 1 gram of powder samples with a few lithium bromides (LiBr) and 5 grams di-lithium tetraborates (Li2B4O7) in a platinum crucible. The mixed materials were fused at the DMR.

Major elements analysis was performed using PANalytical (Zetium) wavelength dispersive X-ray fluorescence spectrometer (WDXRF) at the Department of Mineral Resources (DMR), Thailand. The concentrations were calculated against the calibrations derived from 3 international standard reference materials (JGb-1, GBW03101, and JB-1a).

Trace elements and rare earth element analyses were performed using ICP-MS at the ALS Australia laboratory. The samples were pulverized the same as XRF analysis before mailed to the ALS company. Using 2 grams of each sample were dissolution by acid; then they were fused with Li Borate.

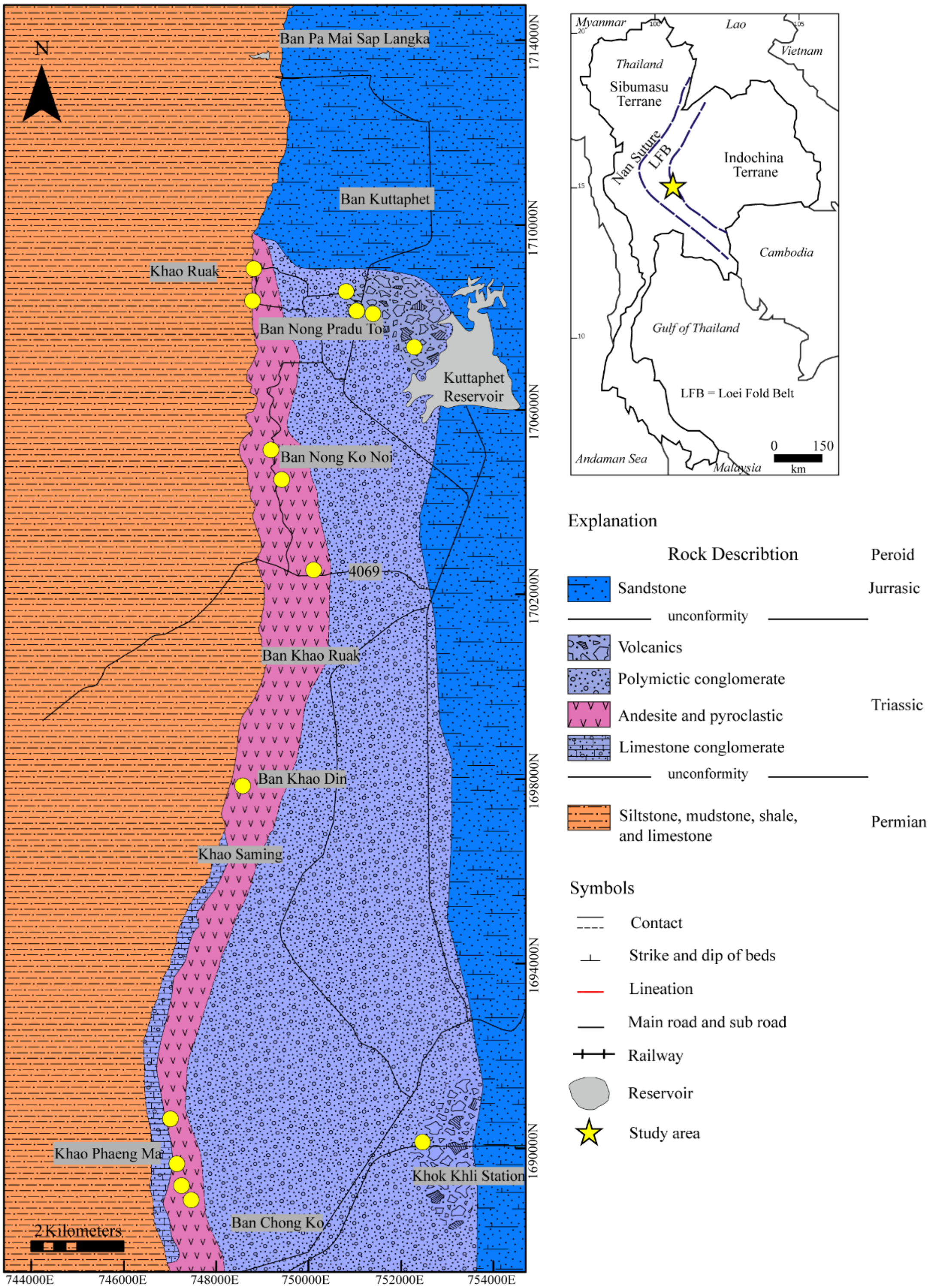

Fig. 5.1 Geological map of the Lam Sonthi area showing sample location for whole-rock geochemical analysis.

5.3 Geochemistry of volcanic rocks in Lam Sonthi area

Whole-rock geochemical data of volcanic rocks in the Lam Sonthi area are shown in Tables 5.1 and 5.2.

5.3.1 Major element geochemistry

In the process of major element analysis, the major oxides have been recalculated into a volatile-free before plotting geochemical data. The volcanic rocks from both units (Unit III and Unit IV, particularly from Kuttaphet volcanics and Khok Khli volcanics) were classified based on their SiO_2 contents. The volcanic rocks of Khao Ruak volcanics have SiO_2 content of 57-64 wt.%. The clasts from Kuttaphet volcanics have SiO_2 content of 60-71 wt.%, whereas the clasts of Khok Khli volcanics have a SiO_2 content of 58-66 wt. % (Fig. 5.2). Based on silica content, majorities of the rocks from the Lam Sonthi area are classified as andesite, excluding one sample (clast) of Khao Ruak volcanics is identified as basaltic andesite and other two samples of Kuttaphet volcanics are classified as dacite to rhyolite compositions.

Based on the petrographic study, the studied volcanic rocks will be categorized into six groups. There are two groups from Khao Ruak volcanics: pyroxene-plagioclase andesite lava and pyroxene-plagioclase andesite clast, and two groups from Kuttaphet volcanics: plagioclase andesite clast and pyroxene-plagioclase andesite clast. The other two groups from Khok Khli volcanics are plagioclase andesite clast and hornblende-plagioclase andesite clast.

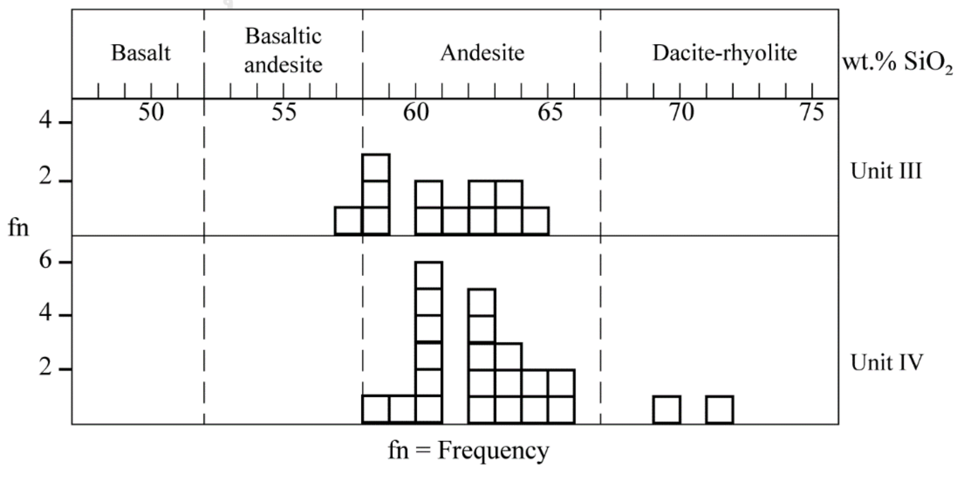

Fig. 5.2 Histogram of whole-rock SiO_2 content for the volcanic rocks from the Lam Sonthi area. The wt.% SiO_2 are classified based on the rock types of Cox et al. (1979).

Diagram proposed by Madeisky (1996) was used to evaluate the degree of alteration of volcanics samples, and the diagram (Fig. 5.3) shows that the majorities of the studied volcanic samples from this study have molar (K+Na+2Ca)/Al values > 1, which are interpreted as unaltered rocks. However, five samples in which the (K+Na+2Ca)/Al values are slightly less than 1 (0.92-0.98), suggesting they are the least altered rocks. Those samples are mostly from Khok Khli volcanics.

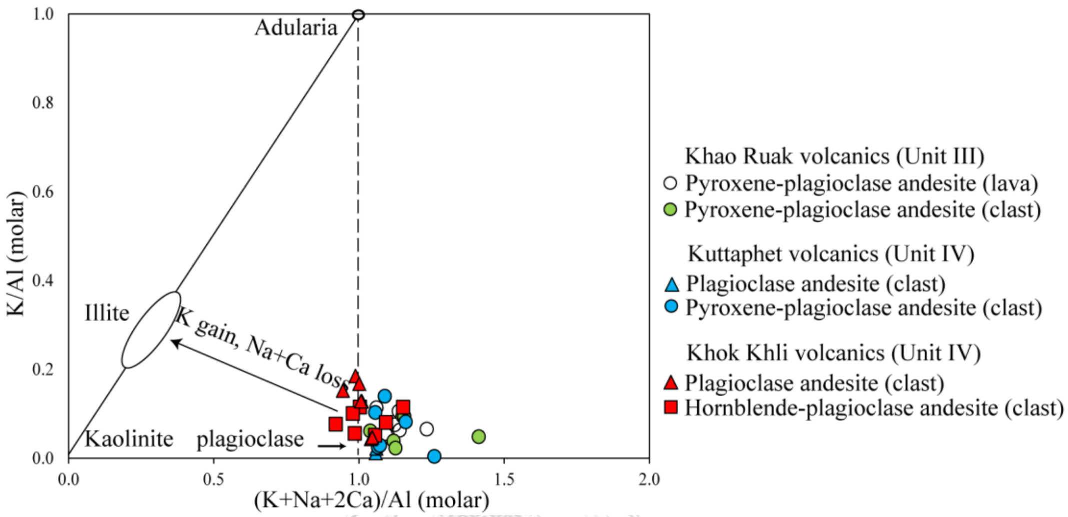

Fig. 5.3 Molar K/Al vs. molar (K+Na+2Ca)/Al (Madeisky, 1996).

The bivariate plots for major oxides against SiO_2 (Fig. 5.4) show the variation of pyroxene-plagioclase andesite of Khao Ruak volcanics can be separated into two magmatic suites. Both the Khao Ruak suite I and Khao Ruak suite II contain samples of clasts and lavas. The Khao Ruak suite I has lower SiO_2 than Khao Ruak Suite II but higher Al_2O_3 and CaO concentrations than Khao Ruak Suite II (Fig. 5.4B and D). However, other major oxides (e.g., TiO_2, MnO, Na_2O, P_2O_5, and K_2O) are similar (Fig. 5.4A, C, E, F, and G). The samples from Kuttaphet volcanics (plagioclase andesite clasts and pyroxene-plagioclase andesite clasts) are distinctive. The plagioclase andesite clasts have higher SiO_2 concentrations than pyroxene-plagioclase andesite clasts but lower TiO_2, Al_2O_3, CaO, P_2O_5, and K_2O concentrations compared to pyroxene-plagioclase andesite clasts (Fig. 5.4A, B, D, F, and G). The sample from Khok Khli volcanics (hornblende-plagioclase andesite clasts and plagioclase andesite clasts) have similar major oxide (e.g., TiO_2, MnO, CaO, Na_2O, P_2O_5, and K_2O) concentrations (Fig. 5.4A, C, D, E, D, and G) but hornblende-plagioclase has lower SiO_2 concentration than plagioclase andesite (Fig. 5.4A, B, C, D, E, F, and G).

In general, the pyroxene-plagioclase andesite of Khao Ruak volcanics (Unit III) both lava and clasts have a lower TiO_2, Na_2O, MnO, and P_2O_5 concentrations than the samples from Kuttaphet volcanics and Khok Khli volcanics (Fig. 5.4A, C, D, and E) but higher CaO concentration (Fig. 5.4F). Whereas pyroxene-plagioclase andesite (clasts) of Kuttaphet volcanics are like of Khok Khli volcanics especially the hornblende-plagioclase andesite with exception of CaO in which the pyroxene-plagioclase andesite of the Kuttaphet volcanics are slightly higher than the Khok Khli volcanics (Fig. 5.4D). For the plagioclase andesite of Kuttaphet volcanics has lower concentration for most of major oxides except Na_2O (Fig. 5.4E). All samples show the trend of Al_2O_3 concentration is decreasing against increasing of SiO_2 concentration (Fig. 5.4B). Diagram of SiO_2 vs K_2O shows most rocks of this study are mainly identified as medium-K with samples plotted in the field of low-K (Fig. 5.4G). However, only the plagioclase andesite (N=2) is clearly low-K.

Table 5.1 Major oxides and loss on ignition of volcanic rocks, Lam Sonthi area, Lop Buri province

ID	Group	Type	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	L.O.I.	Total
LST01	KR1	Lava	61.82	0.53	15.53	5.25	0.06	1.62	5.40	3.77	1.52	0.15	3.86	99.50
LST15	KR1	Lava	62.03	0.49	16.25	5.04	0.09	2.30	3.36	5.65	1.71	0.12	2.45	99.48
LST06	KR2	Lava	57.73	0.58	17.90	6.73	0.11	2.76	6.51	4.08	0.91	0.20	2.01	99.51
LST14	KR2	Lava	58.52	0.62	16.50	6.34	0.10	3.48	5.80	4.10	1.14	0.16	2.70	99.46
LST20	KR2	Lava	58.21	0.68	17.19	6.98	0.10	3.23	6.06	4.56	1.00	0.19	1.26	99.47
LST30	KR2	Lava	59.47	0.61	16.41	6.36	0.07	2.68	6.07	4.95	0.99	0.18	1.52	99.30
LST12	KR3	clast	54.86	0.54	17.25	5.95	0.12	2.50	7.26	6.28	0.77	0.14	3.76	99.42
LST13	KR3	clast	57.13	0.60	17.87	6.78	0.11	2.94	6.89	4.13	0.64	0.19	2.26	99.52
LST16	KR3	clast	58.87	0.58	16.30	6.46	0.11	2.28	3.35	7.24	0.34	0.14	3.57	99.24
LST18	KR3	clast	61.51	0.60	15.90	6.76	0.06	2.09	4.89	4.81	1.39	0.11	1.24	99.36
LST19	KR3	clast	61.42	0.61	16.08	6.89	0.06	1.83	4.91	4.96	1.40	0.12	1.12	99.39
LST29	KR3	clast	62.34	0.53	16.04	5.92	0.06	2.34	3.22	5.98	0.91	0.13	1.68	99.14
LST02	KU1	clast	71.24	0.39	14.29	2.96	0.02	0.41	1.51	7.42	0.16	0.12	0.95	99.46
LST05	KU1	clast	68.18	0.36	14.47	2.72	0.10	1.53	2.11	6.80	0.30	0.12	2.54	99.23
LST03	KU2	clast	59.90	0.67	17.17	5.61	0.07	1.49	4.43	8.21	0.06	0.20	1.59	99.41
LST04	KU2	clast	59.92	0.68	15.82	6.58	0.18	2.35	3.18	6.51	0.36	0.22	3.64	99.43
LST07	KU2	clast	59.68	0.78	17.12	7.07	0.08	1.60	2.74	6.90	1.62	0.27	1.46	99.34
LST08	KU2	clast	61.36	0.69	15.61	6.58	0.13	2.98	2.43	7.22	0.42	0.23	1.73	99.37
LST09	KU2	clast	61.37	0.74	15.78	7.13	0.09	1.84	2.21	6.67	2.03	0.23	1.28	99.37
LST10	KU2	clast	59.36	0.76	16.84	6.97	0.10	1.82	3.09	7.64	1.27	0.24	1.34	99.43
LST22	KK1	clast	61.32	0.74	16.45	6.93	0.10	1.45	1.84	8.01	0.79	0.19	1.43	99.26
LST25	KK1	clast	58.77	0.70	16.57	6.56	0.15	3.75	2.22	6.49	1.76	0.22	2.05	99.23
LST27	KK1	clast	56.85	0.67	16.84	6.13	0.16	3.09	2.86	7.47	1.79	0.21	3.13	99.20
LST31	KK1	clast	59.31	0.68	18.01	6.06	0.10	2.03	1.41	8.63	0.92	0.24	1.83	99.23
LST37	KK1	clast	59.27	0.73	16.51	6.41	0.13	3.76	1.40	6.93	1.17	0.23	2.71	99.24
LST38	KK1	clast	58.36	0.71	17.46	5.89	0.11	2.46	2.48	8.02	1.30	0.21	1.86	98.85
LST39	KK1	clast	61.05	0.71	16.06	6.88	0.12	2.11	1.69	6.71	1.49	0.23	2.03	99.07
LST23	KK2	clast	63.57	0.53	17.94	5.07	0.06	0.21	0.69	10.12	0.72	0.20	0.49	99.60
LST24	KK2	clast	63.73	0.63	15.18	5.94	0.11	1.65	1.51	5.75	2.59	0.21	1.80	99.10
LST26	KK2	clast	63.11	0.79	14.96	7.33	0.10	2.04	1.20	5.88	2.10	0.16	1.70	99.37
LST32	KK2	clast	63.48	0.53	17.88	5.20	0.06	0.21	0.72	10.06	0.77	0.21	0.46	99.59
LST33	KK2	clast	65.25	0.55	13.88	5.68	0.14	2.84	1.20	6.12	1.64	0.24	1.70	99.25
LST34	KK2	clast	65.53	0.55	13.83	5.66	0.14	2.67	1.18	6.08	1.64	0.24	1.65	99.16
LST35	KK2	clast	63.76	0.63	14.89	6.11	0.13	2.01	1.44	5.95	2.30	0.21	1.70	99.14

Note: KR1=Pyroxene-plagioclase andesite lava of Khao Ruak volcanics, KR2=Pyroxene-plagioclase andesite clast of Khao Ruak volcanics, KU1=Plagioclase andesite clast of Kuttaphet volcanics, KU2=Pyroxene-plagioclase andesite clast of Kuttaphet volcanics, KK1=hornblende-plagioclase andesite clast of Khok Khli volcanics, KK2=Plagioclase andesite clast of Khok Khli volcanics

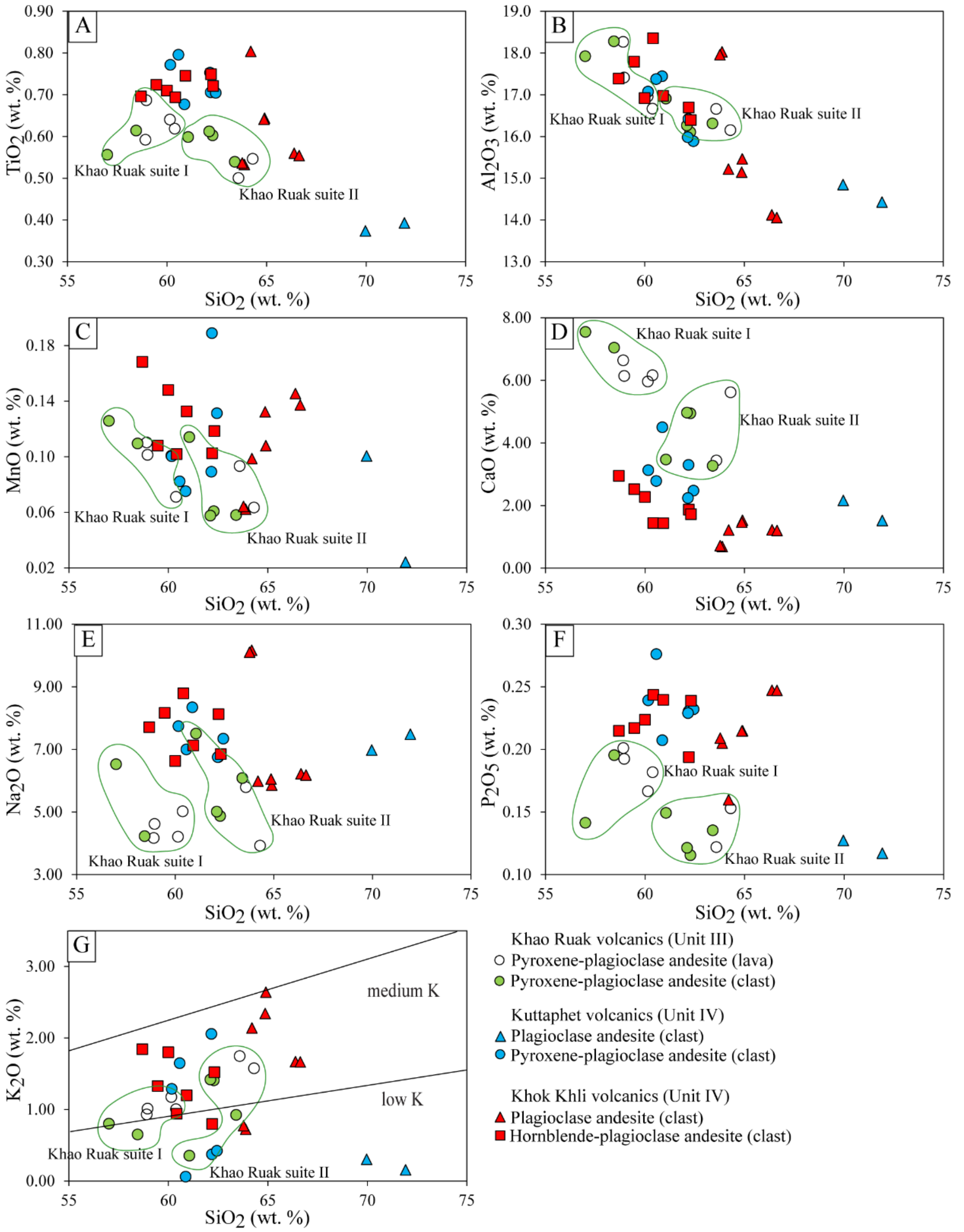

Fig. 5.4 Major oxides binary diagrams plotted against SiO_2. A) TiO_2 vs SiO_2 showing Khao Ruak volcanics have lower concentration. B) Al_2O_3 vs SiO_2 showing trend of Al_2O_3 decreasing against increasing of SiO_2. C) Na_2O vs SiO_2 showing Khao Ruak volcanics have lower concentration. D) MnO vs SiO_2 showing Khao Ruak volcanics have lower concentration. E) P_2O_5 vs SiO_2. F) CaO vs SiO_2 showing Khao Ruak volcanics have higher concentration. G) K_2O vs SiO_2 showing volcanic rocks plotted into medium-K and low-K.

5.3.2 Trace elements geochemistry

Results of trace elements and REEs analyses are given in Table 5.2. The trace elements and rare earth elements (REEs) compositions are used chiefly to determine their tectonic setting's magma affinities. The plots of trace elements against SiO2 (Fig. 5.5) show the variation of pyroxene-plagioclase andesite lava of Khao Ruak volcanics are separated into two magmatic suites consistent with major oxide binary plots. The Khao Ruak volcanic Suite I has Rb, Y, Nb, Zr, and Ce concentrations lower than the Khao Ruak Suite II (Fig. 5.5A, D, E, F, and G), but it has higher V concentration (Fig. 5.5B). The samples of Kuttaphet volcanics show that the pyroxene-plagioclase andesite clast has Rb, V, Sr, Y, Nb, Zr, and Ce concentrations higher than plagioclase andesite clasts (Fig. 5.5A, B, C, D, E, F, and G). The samples from Khok Khli volcanics show the hornblende-plagioclase andesite clasts have higher concentrations of V, Y, Nb, and Zr than the plagioclase andesite clasts (Fig. 5.5 B, D, E, and F).

In general, the LILE such as Rb and Sr of all samples are scattered widely (Fig. 5.5A and C), but V shows a decreasing concentration with increasing SiO2 concentration (Fig. 5.5B). The HFSE, such as Y and Ce concentration of Khao Ruak volcanics (Unit III), is lower than hornblende-plagioclase andesite and plagioclase andesite of Khok Khli volcanics and pyroxene-plagioclase andesite of Kuttaphet volcanics (Fig. 5.5D and G). The Rb, V, Sr, Y, Nb, and Ce concentration of plagioclase andesite from Kuttaphet volcanics is relatively low compare to the rest of the samples (Fig. 5.5A, B, C, D, E, and G). A few samples representative of each group analyzed by the ICP-MS method could not clearly show each group's distinctive characteristics. However, the plots of REE patterns and multi-elements spider diagram give a significant variation in REE pattern.

Table 5.2 Trace elements and rare earth elements of volcanic rocks, Lam Sonthi area, Lop Buri province

ID	LST01	LST15	LST06	LST02	LST05	LST07	LST22	LST25	LST24
Group	KR1	KR1	KR2	KU1	KU1	KU2	KK1	KK1	KK2
Ba	478	427	250	63.7	77.5	687	210	320	993
Ce	30.3	26.8	23.6	32.7	27.1	54.3	34.9	44.7	36.9
Cr	160	90	130	160	140	50	10	20	20
Cs	1.94	0.73	0.26	0.13	0.2	1.76	0.63	0.49	0.79
Dy	3.97	3.7	3.32	3.17	1.84	5.32	4.87	4.86	4.18
Er	2.39	2.28	2.02	1.87	1.13	3.23	3.13	2.87	2.59
Eu	1.03	0.99	1.04	0.98	0.8	1.58	1.32	1.55	1.3
Ga	13.1	17.8	18.7	10.7	10.5	14.3	16	15.8	14.2
Gd	4.1	3.63	3.51	3.82	2.44	5.45	4.6	5.39	4.64
Hf	4.5	4.4	3	3.8	3.7	4.4	3.9	4	3.6
Ho	0.8	0.77	0.66	0.62	0.37	1.06	0.96	0.98	0.86
La	14.5	12.2	10.4	15.3	12.5	24.3	15.1	20.3	17.6
Lu	0.37	0.37	0.29	0.26	0.13	0.45	0.44	0.39	0.37
Nb	2.1	2.7	1.8	1.9	1.8	2.5	2.4	2.3	2.1
Nd	17.4	15.4	14.2	16.8	13.4	27.4	20	24	22.3
Pr	4.1	3.57	3.2	4.1	3.49	6.73	4.72	5.82	5.26
Rb	28.1	32.2	13.3	3.6	8.3	43.3	20.6	38.7	37.2
Sm	3.66	3.29	3.12	3.59	2.43	5.33	4.27	5.18	4.41
Sr	534	676	663	393	544	760	724	467	492
Ta	0.3	0.3	0.2	0.2	0.2	0.2	0.7	0.3	0.5
Tb	0.61	0.58	0.53	0.53	0.32	0.85	0.77	0.79	0.66
Th	4.62	3.45	1.62	4.65	5.2	5.55	3.16	4.86	4.33
Tm	0.35	0.35	0.29	0.24	0.16	0.49	0.45	0.4	0.36
U	1.61	1.31	0.62	1.02	0.8	1.28	0.95	0.91	0.98
V	88	92	142	67	83	118	148	127	102
W	<1	1	<1	<1	<1	<1	258	101	227
Y	22.3	22.1	17.7	18.7	11.5	27.7	27.4	28.4	23
Yb	2.33	2.37	1.89	1.63	0.95	3.09	2.91	2.71	2.39
Zr	159	160	105	142	154	158	151	151	134

Note: KR1=Pyroxene-plagioclase andesite lava of Khao Ruak volcanics, KR2=Pyroxene-plagioclase andesite clast of Khao Ruak volcanics, KU1=Plagioclase andesite clast of Kuttaphet volcanics, KU2=Pyroxene-plagioclase andesite clast of Kuttaphet volcanics, KK1=hornblende-plagioclase andesite clast of Khok Khli volcanics, KK2=Plagioclase andesite clast of Khok Khli volcanics

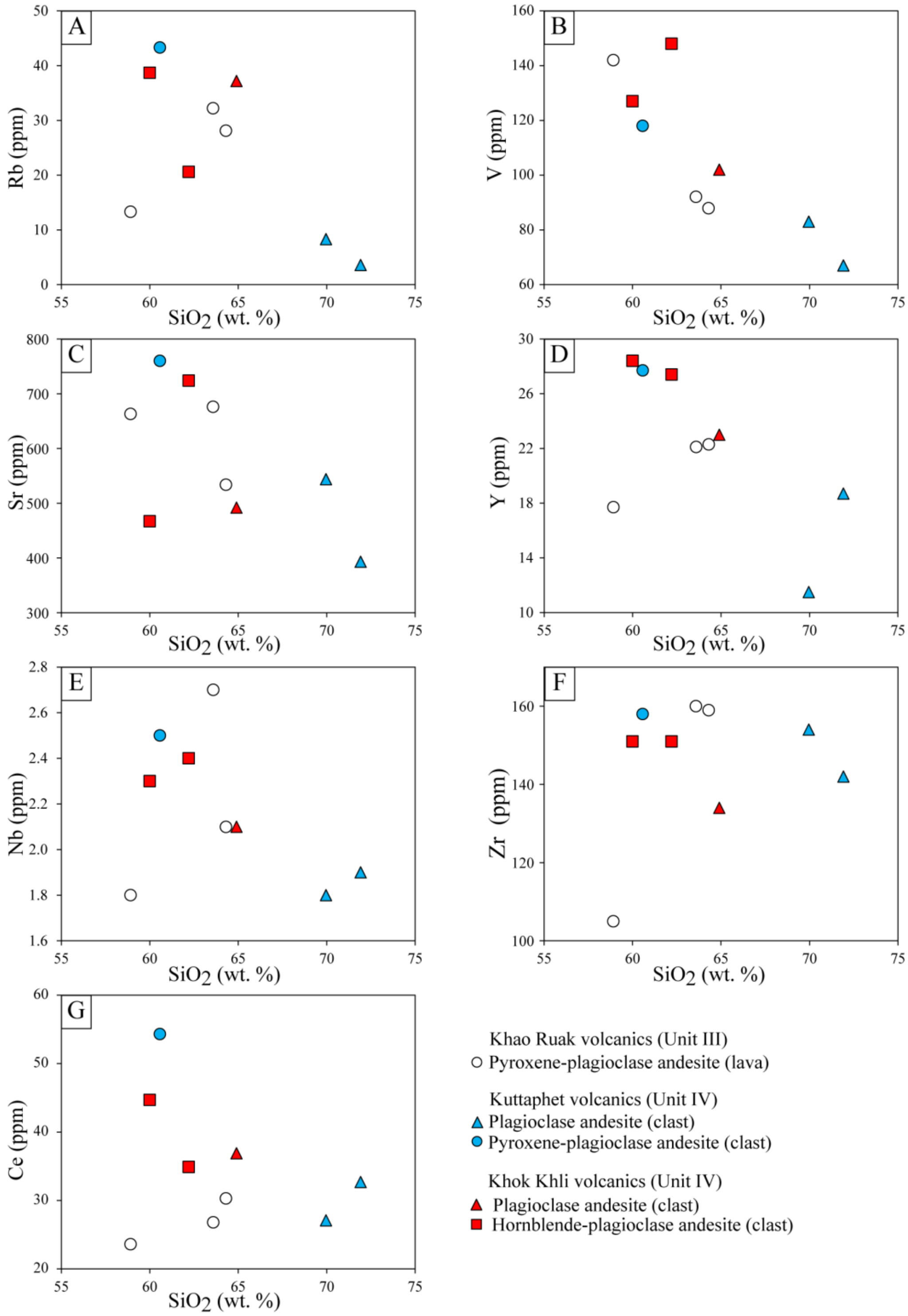

Fig. 5.5 Selected trace elements binary diagram plotted against SiO_2 A) Rb vs. SiO_2 showing Rb concentration scatter widely. B) V vs. SiO_2 showing Khao Ruak volcanics have lower concentration. C) Sr vs. SiO_2 showing Sr concentration scatter widely D) Y vs. SiO_2 showing Khao Ruak volcanics have lower concentration. E) Nb vs. SiO_2 showing pyroxene-plagioclase basaltic andesite has low concentration. F) Zr vs. SiO_2 showing pyroxene-plagioclase basaltic andesite has low concentration. G) Ce vs. SiO_2 showing Khao Ruak volcanics have lower concentration.

5.3.3 Multi element spider diagrams

The N-MORB normalized multi-element patterns (Sun and McDonough, 1989) show negative niobium (Nb) and tantalum (Ta) anomalies (Fig. 5.6), which are the characteristics of magma associated with the subduction zone. The samples from Khao Ruak volcanics, including pyroxene-plagioclase andesite, represent negative Ba, Th, Nb, Pr, and Eu anomalies and the enrichment of Ba, La, and Sr (Fig. 5.6A).

Pyroxene-plagioclase andesite of the Kuttaphet volcanics and the hornblende-plagioclase andesite and plagioclase andesite samples of Khok Khli volcanics show negative Rb, Nb, and Pr depleting and the enrichment of Ba, Ta, La, and Sr (Fig. 5.6B). The rest of plagioclase andesite from Kuttaphet volcanics show negative Rb, Ba Nb, Pr, Nd anomalies, Th, La, and Sr's enrichment HREEs show a slight depletion compared to the other groups, which has a flat pattern (Fig. 5.6B).

5.3.4 Rare earth elements (REEs) geochemistry

REEs variations in the volcanic rocks from the study area are presented by chondrite-normalized patterns (Sun and McDonough, 1989). The diagrams show pyroxene-plagioclase andesite from Khao Ruak volcanics have relatively flat REE patterns, from Sm to Yb with chondrite-normalized Sm/Yb ranged from 1.5-1.8, and slightly LREE enriched with chondrite-normalized La/Sm ranged from 2.1-2.6 (Fig. 5.7A). Pyroxene-plagioclase andesite of Kuttaphet volcanics and the samples from Khok Khli volcanics including hornblende-plagioclase andesite and plagioclase andesite have slightly enriched from Sm to Yb with chondrite-normalized Sm/Yb [herein $(Sm/Yb)_n$] ranged from 1.6-2.1 and slightly enriched with chondrite-normalized La/Sm [herein $(La/Sm)_n$] ranged from 2.3-2.9 (Fig. 5.7B). The rest of plagioclase andesite from Kuttaphet volcanics have enriched from Sm to Yb with chondrite-normalized Sm/Yb ranged from 2.4-2.8 and enriched with chondrite-normalized La/Sm ranged from 2.7-2.3 (Fig. 5.7B).

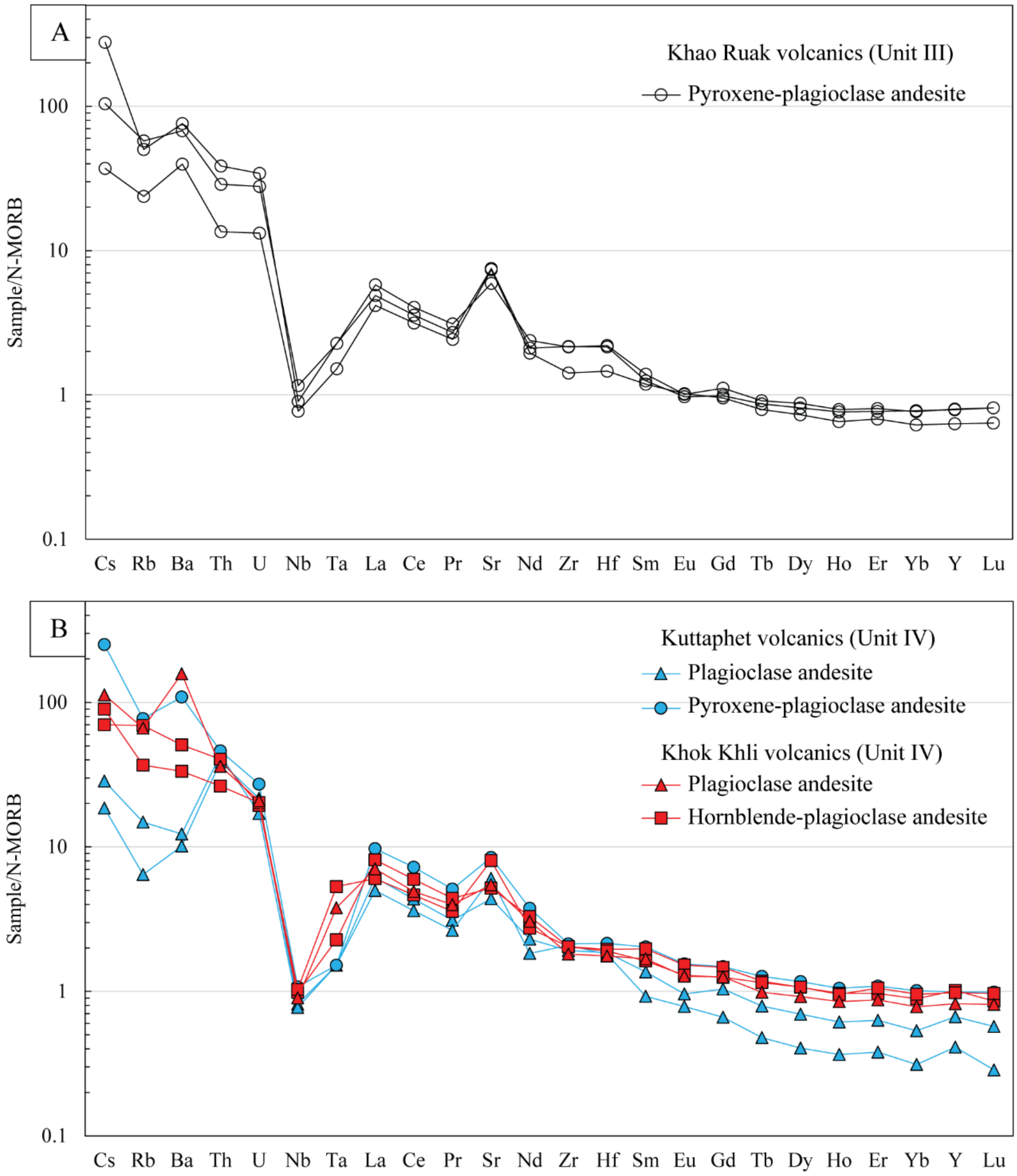

Fig. 5.6 N-MORB normalized trace elements pattern using normalizing of values of Sun and McDonough (1989). (A) Plots of samples from Khao Ruak volcanics. (B) Plots of samples from Kuttaphet volcanics and Khok Khli volcanics.

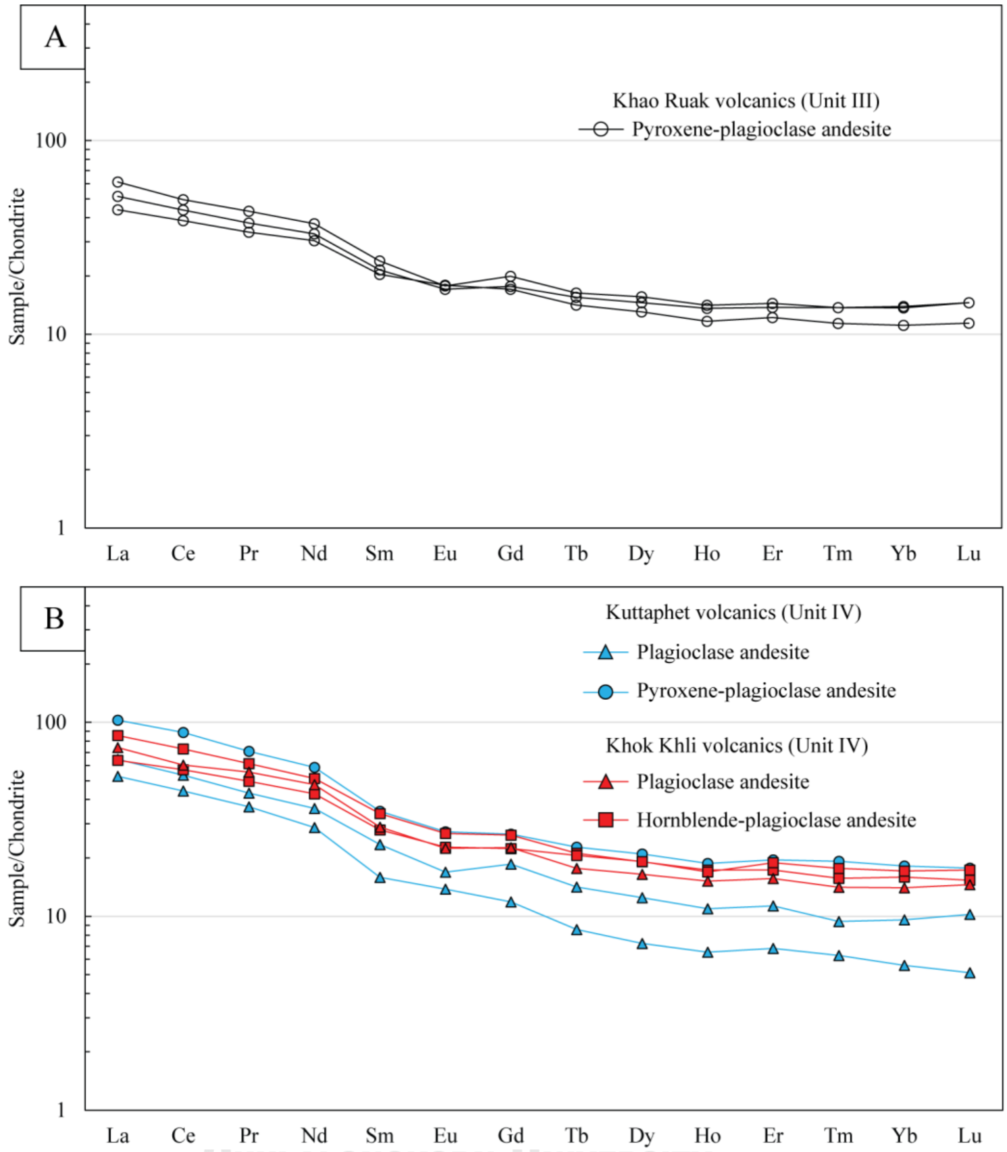

Fig. 5.7 Chondrite-normalized patterns using normalizing of values of Sun and McDonough (1989). (A) Chondrite-normalized plots of samples from Khao Ruak volcanics. (B) Chondrite-normalized plots of samples from Kuttaphet volcanics and Khok Khli volcanics.

5.4 Magma affinity and tectonic setting

Total alkali diagram (TAS) shows the samples from Khao Ruak volcanics are identified as andesite to dacite. In contrast, the samples from Kuttaphet volcanics and Khok Khli volcanics are classified as trachyandesite, trachydacite, and trachyte, excluding two samples plagioclase andesite from Kuttaphet volcanics, were plotted as rhyolite (Fig. 5.8). However, the TAS diagram element is typically mobile during alteration and metamorphism, so the classification diagram using immobile trace elements is more suitable. The representative samples are plotted in the rock classification (Zr/TiO2 vs. Nb/Y) (Fig. 5.9). The diagrams show that all samples from Khao Ruak volcanics and Khok Khli volcanics were identified andesite, excluding a sample of plagioclase andesite from Kuttaphet volcanics plotted in the field of rhyodacite/dacite (Fig. 5.9).

The AFM diagram, a FeO plot, MgO, and the sum of Na2O and K2O shows that all units are typically calc-alkaline series (Fig. 5.10). Furthermore, plotting the discrimination diagram of Th-Hf-Ta, Th-Hf-Nb, and Th-Zr-Nb (Wood and letters, 1980) confirmed that the representative samples in this study are calc-alkaline basalt (Fig. 5.11).

Plotting of Ti against Zr (Fig. 5.12) in the discrimination diagram upon Ti-Zr variation indicates all the rocks in this study area are volcanic arc setting. Furthermore, the chondrite and N-MORB normalized multi-element patterns of the modern volcanic rocks are used to compare with the volcanic rocks of the study area to clarify the tectonic setting. The pyroxene-plagioclase andesites of Khao Ruak volcanics are chemically analogous to the calc-alkaline andesite from the Cay volcano, which is related to the subduction zone (D'Orazio et al., 2003) as shown in Fig. 5.13 and Fig. 5.14. In addition, pyroxene-plagioclase andesite of Kuttaphet volcanics, hornblende-plagioclase andesite, and plagioclase andesite of Khok Khli volcanics also present similar patterns to the volcanic rocks of Khao Ruak volcanics and the volcanic rocks from the Cay volcano, whereas the plagioclase andesites of Kuttaphet volcanic show different pattern in which Rb and Ba are depleted compared to the other samples. This could be implied that pyroxene-plagioclase andesite of Kuttaphet volcanics, hornblende-plagioclase andesite, and plagioclase andesite of Khok Khli volcanics was derived from the magma source with Khao Ruak volcanics.

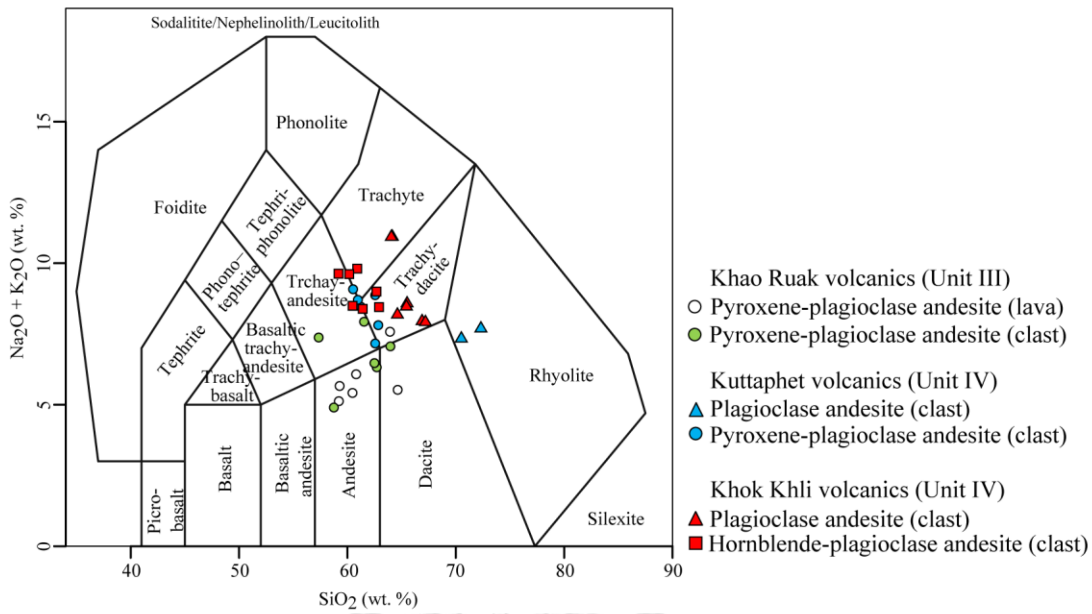

Fig. 5.8 Rocks classified by total alkali vs. SiO_2 (Middlemost, 1994).

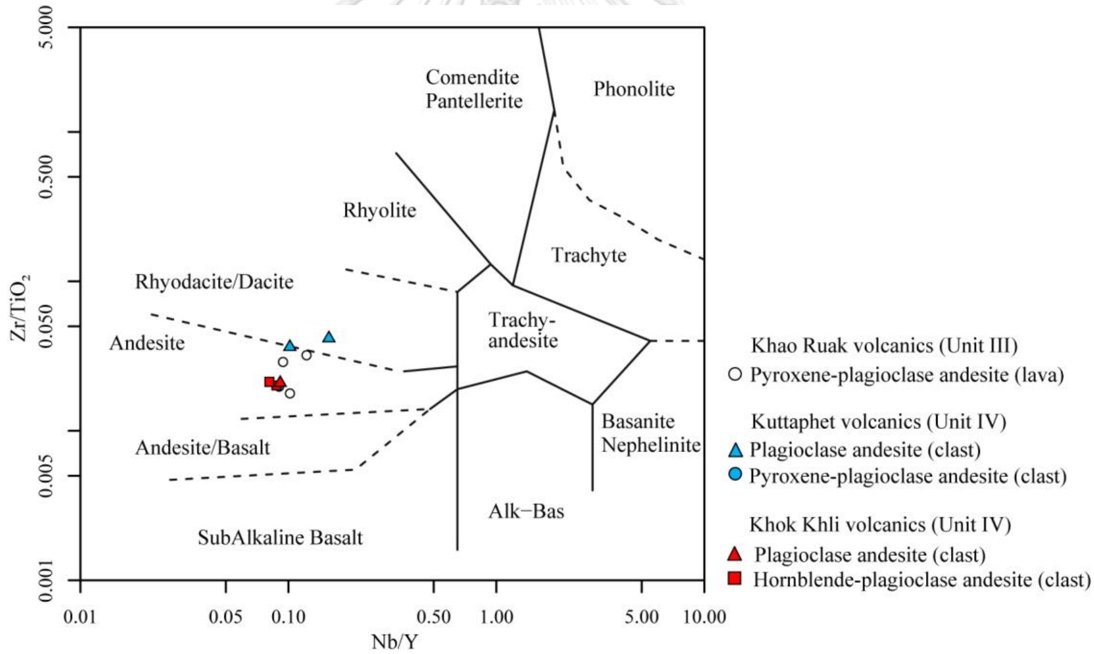

Fig. 5.9 Rocks classified by trace elements plotting of Nb/Y vs. Zr/TiO_2 (Winchester and Floyd, 1977).

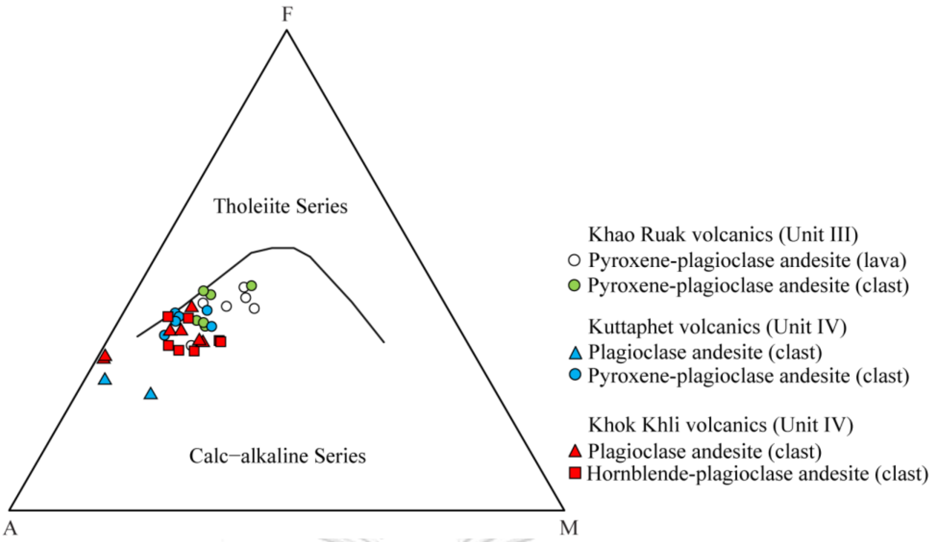

Fig. 5.10 AFM diagram showing volcanic rocks in the Lam Sonthi area are calc-alkaline series (Irvine and Baragar, 1971).

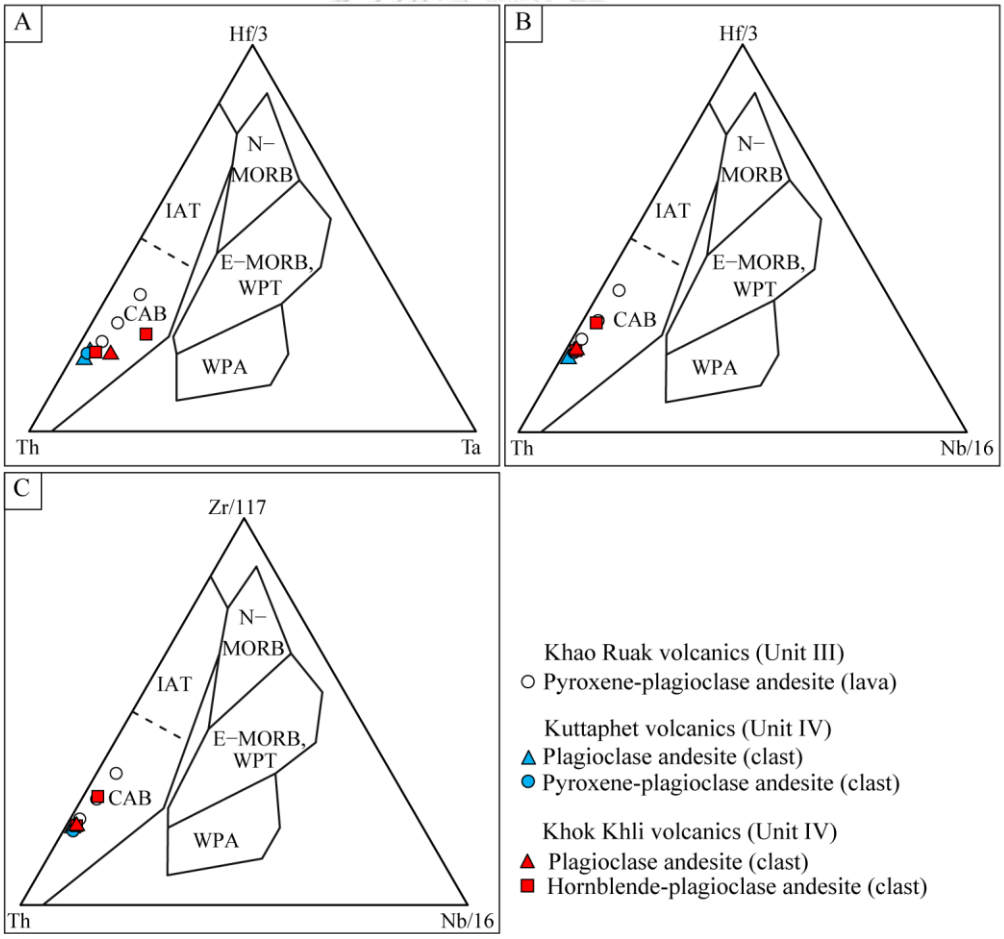

Fig. 5.11 Tectonic discrimination diagrams by Wood (1980): IAT = island-arc basalt, CAB = calc-alkali basalt, N-MORB = normal mid-oceanic ridge basalts, E-MORB = enhanced mid-oceanic ridge basalts, WPT = within-plate tholeiite, WPA = within-plate alkaline.

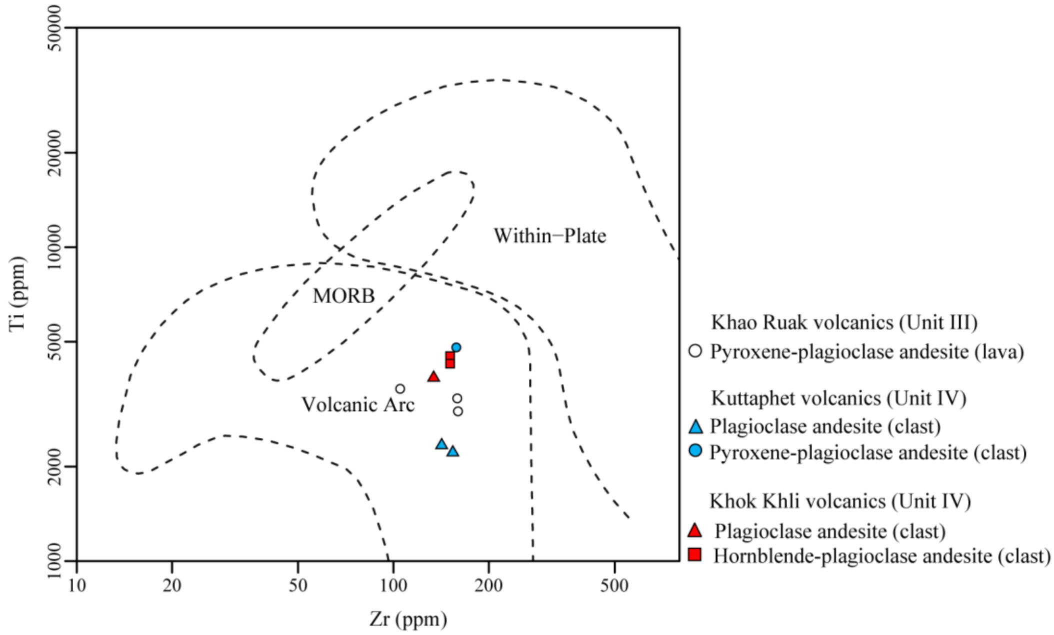

Fig. 5.12 The Ti-Zr discrimination diagrams by (Pearce, 1982): MORB = mid-oceanic ridge basalt.

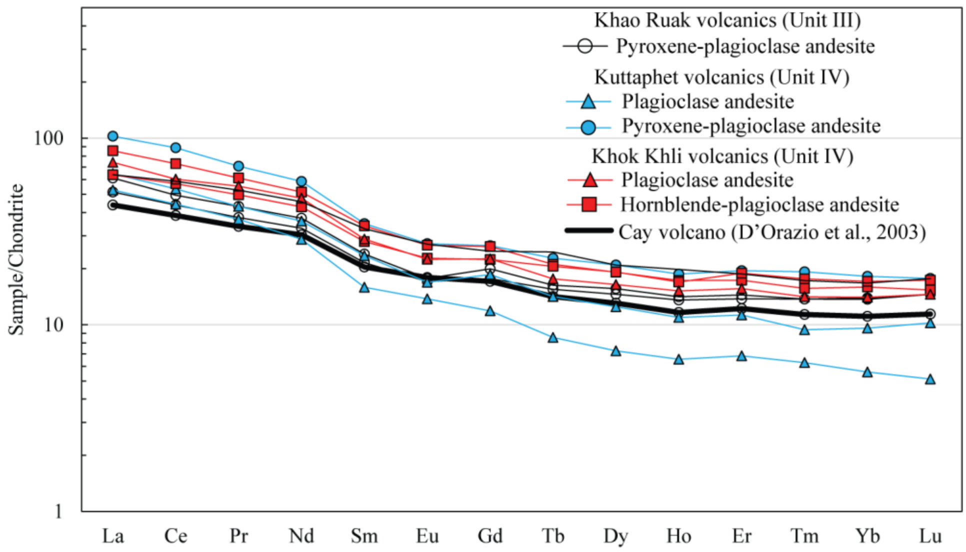

Fig. 5.13 Plots of samples from Lam Sonthi area and andesite from Cay volcano in Chondrite-normalized patterns using normalizing of values of Sun and McDonough (1989).

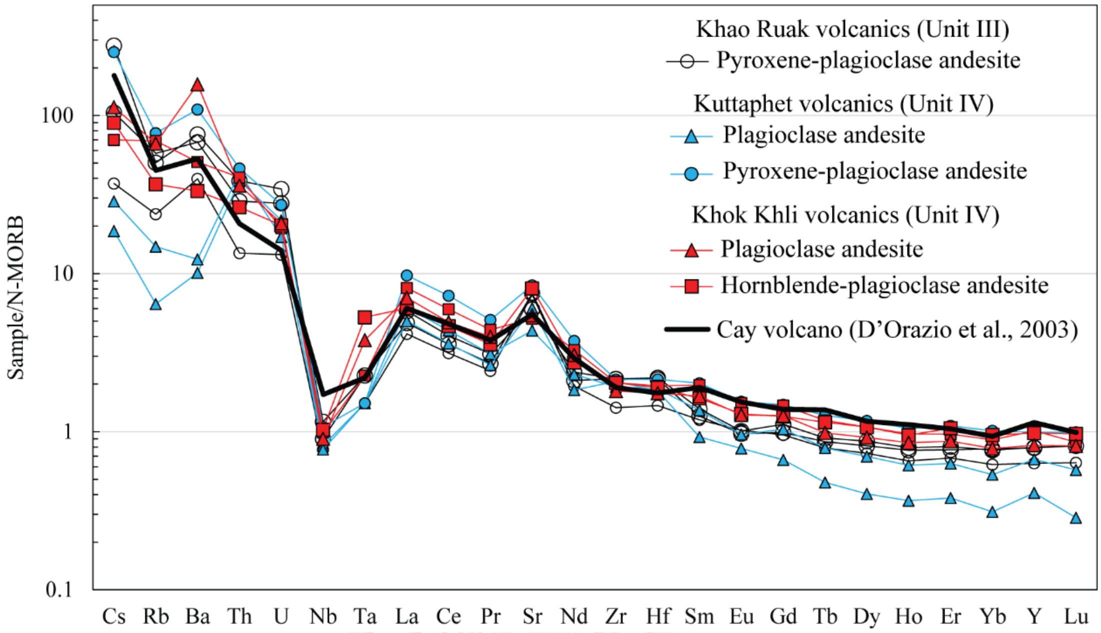

Fig. 5.14 Plots of samples from Lam Sonthi area and andesite from Cay volcano in N-MORB normalized trace elements pattern using normalizing of values of Sun and McDonough (1989).

Chapter 6
Discussion and Summary

6.1 Geology of Lam Sonthi area

Nakornsri (1977, 1981) reported that the sedimentary rocks distributing at Khao Ruak mountains could be correlated with the Khao Luak Formation (Assavapatchara, 2006; Bunopas, 1981; Nakornsri, 1977) of the lower formation of Saraburi Group (Bunopas, 1981). It was suggested to represent the Early Permian age based on fossils of coral *Pseudohuangua* sp. (Nakornsri, 1981). Unit I: Khao Ruak siltstone is observed along with road cut (Road No. 4069) and several places, especially along with the contact with Khao Ruak volcanics (Unit III), suggesting that it mainly consists of mudstone, siltstone, and minor shale. Limestone, where present, tends to occur as lenses from few meters to few tens of meters thick, particularly on the eastern flank of Khao Ruak mountains. Tuffaceous siltstone is locally observed along with the road cut (Road No .4069 location: 748660E and 1702700N). The Khao Luak Formation age is recently reported as 276±7 Ma (Early Permian) from the detrital zircons using the U-Pb zircon age dating technique of sandstones, which was collected from Nong Phai district, Phetchabun province (Hara et al., 2020) far north from the Lam Sonthi area. The Khao Luak Formation was interpreted as formed as the southern continuation of Nam Duk Formation (Ueno and Charoentitirat, 2011) which was a part of back arc basin that has been closed in the end of Permian (Malila et al., 2008; Sone and Metcalfe, 2008). This closure of the Nam Duk basin is believed to have taken place during the Indonesian orogeny I, which caused the hiatus in the Late Permian and Middle Early Triassic (Booth and Sattayarak, 2011).

At the southern part of the area, Khao Phaeng Ma mountains, Unit II: Khao Phaeng Ma conglomerate has a strike almost north-south with steep dipping. The Khao Phaeng Ma conglomerate seems to be truncated at Khao Saming mountains. Further north from this point, the Khao Ruak volcanics come in contact directly on Khao Luak Formation. The contact between Khao Ruak siltstone unit and Khao Phaeng Ma conglomerate unit is sharp. It is interpreted to be a fault contact. The Khao Phaeng Ma conglomerate unit is also overlain by Khao Ruak volcanics striking north-south direction extending for several kilometers and partly overlie the Khao Luak

Formation at the north part. Based on its lithology (e.g., types of clasts and matrix), which mainly consists of limestone and mudstone in the fine-grained clastic matrix, this unit could be originally derived from the clasts and matrix of Khao Luak Formation. Nakornsri (1977, 1981) suggested that this conglomerate could be correlated with Huai Hin Lat Formation.

Unit III: Khao Ruak volcanics consist of andesite, andesitic breccia, hornblende andesitic breccia, and crystal-rich andesitic sandstone. This unit was proposed as Khao Ruak volcanics owing to their distribution area. Small portions of volcanic rocks were previously mapped as the Permo-Triassic volcanic rocks (Vimuktanandana and Thiyaphairach, 2007). Khao Ruak volcanics is clearly overlaying the Lam Sonthi polymictic conglomerate (Unit IV), although there is no clear contact between them. Based on similarities in the geochemical analysis of Khao Ruak and Khok Khli volcanics (the upper part of Unit IV), it could be interpreted as deriving from similar magmatic sources, which may imply that they also have similar ages. Yan et al. (2019) reported the U-Pb zircon ages from Khok Khli volcanics are 204.7±1.4 Ma and 205.1±1.5 Ma (Late Triassic). The age difference between Khao Ruak siltstone and Khao Ruak volcanics inferred the Late Triassic age, presenting the large age gap. This age gap could suggest the unconformity between the two units.

Unit IV: Lam Sonthi polymictic conglomerate was assigned to Phu Kradung Formation (Jurassic) in pre-existing geological maps by DMR (e.g., Nakornsri, 1977; Vimuktanandana and Thiyaphairach, 2007) which included Khao Ruak volcanics (Unit III), Lam Sonthi polymictic conglomerate (Unit IV), and Kuttaphet sandstone (Unit V) of this study. Lam Sonthi polymictic conglomerate (Unit IV) is characterized by multiple clasts types including volcanics (mainly porphyritic andesite), sandstone, siltstone, mudstone, limestone, and fragments of the quartz vein in a matrix of finer sediments of similar component suggesting the involvement of long-distance transportation which could be interpreted as distal from sources. However, it cannot be constrained whether the volcanics clasts are derived from the same sources as of Khao Ruak volcanics. Lam Sonthi polymictic conglomerate unit might be misled to be the same unit with Khao Phaeng Ma conglomerate unit if considered only some aspects of similarities. However, both units are quite distinctive as a Lam Sonthi polymictic conglomerate unit predominantly contains mudstone, sandstone, volcanics, limestone, and quartz fragments/clasts, whereas Khao Phaeng Ma conglomerate unit dominantly contains limestone and mudstone clasts. Additionally, the overlaying of Khao Ruak volcanics on Khao Phaeng Ma conglomerate, suggesting they are separated units. Furthermore, Khao Ruak volcanics and Lam Sonthi polymictic conglomerate are slightly deformed or folded; therefore, Khao Phaeng Ma conglomerate and Lam Sonthi polymictic conglomerate's repetition is less likely. Based on field observation, Kuttaphet volcanics and Khok Khli volcanics could well be developed at the top of the Lam Sonthi polymictic conglomerate as they are locally deposited. However, Kuttaphet volcanics and Khok Khli volcanics discontinue along strike. This makes it difficult to interpret the aerial distribution of the unit.

The Khok Khli volcanics is interpreted to be deposited in the sequential event of turbidity current according to the evidence of mud fragments mixed in the lowest of this sequence (Unit A). However, the upper part of this sequence is interpreted to be resedimented (syn-eruptive) deposition according to the variety of volcanic clasts in the upper of this sequence (Unit C). The Khok Khli volcanics were recently reported to have U-Pb zircon ages of 204.7±1.4 Ma and 205.1±1.5 Ma (Late Triassic) (Yan et al., 2019). However, the samples that were dated did not clearly show their rock types and were literally reported as "fine-grained clastic layer and coarse-grained layer with breccia," herein this study, they could be implied to the crystal-rich andesitic sandstone (Unit B) and the polymictic intermediate breccia (Unit C) respectively. Consequently, these ages could constrain that the depositional age of polymictic conglomerate is not older than the Late Triassic.

Unit V: Kuttaphet sandstone consists of polymictic conglomerate, coarse-grained sandstone, and fine-grained sandstone. They distribute in the eastern part of the Lam Sonthi area through northward. This unit has been previously mapped as Phu Kradung Formation with Early Jurassic's age (Nakornsri, 1977; Vimuktanandana and Thiyaphairach, 2007). Based on the Khok Khli section's stratigraphy, the contact between polymictic intermediate breccia (Unit C) and the polymictic conglomerate is the lowest sequence of this unit (Unit V) was found as a sharp contact. This polymictic conglomerate is inferred to the basement of Khorat Group, Nam Phong Formation, which is recently suggested that it is the lowest sequence of Khorat Group (Sattayarak, Srilulwong, and Pum-Im, 1989). In addition, the Nam Phong Formation is unconformity with the Huai Hin Lat Formation because of Indosinian II or III orogenies (Booth and Sattayarak, 2011). However, the subsurface data defective confirms that the unconformity between volcaniclastic and polymictic conglomerate accurately affects the indosinian orogeny II and III events as thought.

6.2 Volcanic rocks in the Lam Sonthi area

In the Lam Sonthi area, there are three groups of volcanic rocks, which are Khao Ruak volcanics (Unit III), Kuttaphet volcanics, and Khok Khli volcanics. The volcanic rocks include the Kuttaphet volcanics and Khok Khli volcanics, which could be found at the top of Unit IV as the polymictic intermediate breccia. The volcanic rocks of Khao Ruak volcanics consist of clast and lava of pyroxene-plagioclase andesite while selecting Kuttaphet volcanics plagioclase andesite and pyroxene-plagioclase andesite. The other selecting clasts of Khok Khli volcanics consist of plagioclase andesite and hornblende-plagioclase andesite. These volcanic rocks are named based on the mineral constituents observed under the petrographic microscope and their SiO2 concentration from the XRF analysis.

According to significant pyroxene present, the pyroxene-plagioclase andesite might be named as basaltic andesite rather than andesite. However, in this study, the rock names will be based on geochemical analysis over a petrographic study. While the geochemistry of plagioclase andesite clasts from Kuttaphet volcanics is reported as rhyolite composition (Cox et al., 1979 and Middlemost, 1994) but quartz and alkali feldspar, which are the essential minerals of rhyolite (Le Maitre et al., 2002) observing under the microscope, are found less than 20%, so they preferred to be named as andesite.

The geochemistry of pyroxene-plagioclase andesite clasts from Kuttaphet volcanics, plagioclase andesite and hornblende-plagioclase andesite clasts from Khok Khli volcanics are comparing to the characteristic of pyroxene-plagioclase andesite lava from Khao Ruak volcanics. They show the similarity of N-MORB normalized trace elements patterns and Chondrite-normalized patters. In contrast, the plagioclase andesite clasts from Kuttaphet volcanics show a distinctive difference of Rb and Ba depleting in the N-MORB normalized trace elements pattern.

Consequently, pyroxene-plagioclase andesite clast from Kuttaphet volcanics, plagioclase andesite clast, and hornblende-plagioclase andesite clasts from the Khok

Khli volcanics could be implied that they were derived from the magma source, which is similar to pyroxene-plagioclase lava from Khao Ruak volcanics. According to the Late Triassic age of Khok Khli volcanics, it could be implied that the age of Khao Ruak volcanic could be Late Triassic.

6.3 Geochemistry and tectonic implication

The volcanic rocks in the Lam Sonthi area have a calc-alkaline affinity and volcanic arc setting in geochemistry. The chondrite normalized REEs pattern is characterized by slightly LREEs enriched and detectable negative Eu anomaly. The N-MORB normalized pattern indicates enrichment of LILEs (Ca, Rb, Ba, and Sr) as well Th and U over HFSFs (Nb, Ta, Zr, and Hf), which are typically observed in subduction-related magmas (D'Orazio et al., 2003).

The calc-alkaline andesite from the Cay volcano located in the southern volcanic zone of the Andean Cordillera was selected to modern analogous with the Lam Sonthi area samples. It is the effect of the subduction of the oceanic lithosphere under the Pacific margin of South America. The relative concentration of Cs, Rb, Sr, and Ba (mobile fluid elements) and Zr, Nb, Ta, and REEs (immobile fluid elements) indicates a small amount of subducted sediments and slab release fluids in their mantle source (D'Orazio et al., 2003). Since the volcanic rocks in the Lam Sonthi area are similar to calc-alkaline andesite from the Cay volcano, this could be implied that they have formed by magma experienced likely as the Cay volcano and therefore ore it shows similar tectonic environment.

6.4 Age of volcanic rocks

Although in this study the Khao Ruak volcanics have not been dated yet, the interpretation that it is equivalently deposited with Khok Khli volcaniclastic, which was dated and reported as 204-205 Ma (Late Triassic) (Yan et al., 2019) signifies the age of Khao Ruak volcanic, and it should indicate Late Triassic. Additionally, there are other volcanic rocks in the Saraburi-Khao Yai area, which southward from the study area. They might be correlative with the volcanic rocks in the Lam Sonthi area. There are U-Pb zircon ages of the Saraburi-Khao Yai rhyolites present 213-188 Ma (Late Triassic to Early Jurassic) (Meffre et al. cited by (Morley et al., 2013). The other report is the Khao Yai rhyolite, a massive volcanic body in the south of Khao

Khwang Fold-Thrust belt, Saraburi. The rocks were reported to have a U-Pb zircon age of 207.1±2.4 Ma (Late Triassic) (Arboit et al., 2016). Morley et al. (2013) have suggested this Late Triassic age of rhyolite related to Shan-Thai's collision and the combined Sukhothai-Indochina terrane, which also produced the S-type western belt granite in Thailand. In the past ten years, there were few reports of Late Triassic volcanics until recent works by Arboit et al. (2016) and Yang et al. (2019), which focused on ages dating and extended our understanding of Late Triassic volcanics in the Loei Fold Belt.

6.4 Summary

1. The Lam Sonthi area consists of five rock units: Unit I: Khao Ruak siltstone which is correlative to Khao Luak Formation (Early Permian), Unit II: Khao Phaeng Ma conglomerate, Unit III: Khao Ruak volcanics, which their age inferred as Late Triassic, Unit IV: Lam Sonthi polymictic conglomerate which has inferred age of Late Triassic, and Unit V: Kuttaphet sandstone in which the lower sequence could be correlative to Nam Phong Formation as it is considered to be a basement of Khorat Group and the eastward extending sandstone could be correlative to Phu Kradung Formation (Early Jurassic).

2. The volcanic rocks in the Lam Sonthi area show composition is mainly andesite with calc-alkaline affinity, which indicates volcanic arc environment for their formation. Enrichment of LILEs and low abundance of Nb and Ta indicate a subduction-related magmatic setting.

3. The geochemical data indicate that the clasts of Kuttaphet volcanics and Khok Khli volcanics were derived from the similar magma source of the Khao Ruak volcanics, excluding plagioclase andesite clasts of Kuttaphet volcanics.

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